Sustainable Textiles: Production, Processing, Manufacturing & Chemistry

Subramanian Senthilkannan Muthu *Editor*

Sustainable Manufacturing Practices in the Textiles and Fashion Sector

Springer

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This series aims to address all issues related to sustainability through the lifecycles of textiles from manufacturing to consumer behavior through sustainable disposal. Potential topics include but are not limited to: Environmental Footprints of Textile manufacturing; Environmental Life Cycle Assessment of Textile production; Environmental impact models of Textiles and Clothing Supply Chain; Clothing Supply Chain Sustainability; Carbon, energy and water footprints of textile products and in the clothing manufacturing chain; Functional life and reusability of textile products; Biodegradable textile products and the assessment of biodegradability; Waste management in textile industry; Pollution abatement in textile sector; Recycled textile materials and the evaluation of recycling; Consumer behavior in Sustainable Textiles; Eco-design in Clothing & Apparels; Sustainable polymers & fibers in Textiles; Sustainable waste water treatments in Textile manufacturing; Sustainable Textile Chemicals in Textile manufacturing. Innovative fibres, processes, methods and technologies for Sustainable textiles; Development of sustainable, eco-friendly textile products and processes; Environmental standards for textile industry; Modelling of environmental impacts of textile products; Green Chemistry, clean technology and their applications to textiles and clothing sector; Eco-production of Apparels, Energy and Water Efficient textiles. Sustainable Smart textiles & polymers, Sustainable Nano fibers and Textiles; Sustainable Innovations in Textile Chemistry & Manufacturing; Circular Economy, Advances in Sustainable Textiles Manufacturing; Sustainable Luxury & Craftsmanship; Zero Waste Textiles.

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This book is dedicated to:
The lotus feet of my beloved Lord
Pazhaniandavar
My beloved late father
My beloved mother
My beloved wife Karpagam and Daughters
Anu and Karthika
My beloved brother
Last but not least
To everyone working in the textile sector to
make it "SUSTAINABLE"

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Sustainable Manufacturing Practices in Textiles and Fashion

Rupayan Roy, Pravin P. Chavan, Yedu Rajeev, T. Praveenraj, and Prasanth Kolazhi

1 Introduction

The fashion business is renowned for its quick response to shifting consumer preferences and fashions, but it has also come under fire for its detrimental effects on the environment and society (Turker & Altuntas, 2014; Gazzola et al., 2020; Perry & Towers, 2013). Due to the industry's massive resource and energy use, there are substantial volumes of waste produced as well as high levels of greenhouse gas emissions. Additionally, the business has a history of using exploitative labour practises, with low pay and unsanitary working conditions (Chantavanich et al., 2016; Stringer et al., 2016). In response to these problems, there has been an increase in interest in textile and apparel production processes that reduce harmful environmental and societal effects.

The use of eco-friendly materials, production techniques, and supply chain management are examples of sustainable manufacturing methods in the textile and

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apparel industries that reduce their negative environmental effects and encourage social responsibility (Karthik & Gopalakrishnan, 2014; Khandual & Pradhan, 2019; Lee, 2017). Utilising sustainable materials like organic cotton, recycled polyester, and Tencel, energy-efficient production techniques, water conservation techniques, waste reduction and recycling strategies, and moral labour practises are a few examples of these approaches (Singh, 2014). Designing products with a low environmental impact and producing them with consideration for social and human rights are also aspects of sustainable manufacturing methods.

It is impossible to overestimate the significance of sustainable production methods in the textile and apparel industries. With roughly 10% of the world's carbon emissions and major water and other resource use, the fashion sector is one of the most polluting in the world (Bi, 2011; Izumi et al., 2021). As worries about climate change, resource depletion, and environmental degradation continue to mount, the demand for sustainable practises in the fashion business has become more urgent. Fashion firms must change to suit the shifting demands of consumers who now seek eco-friendly and ethical items. Sustainable manufacturing techniques offer corporate advantages like cost savings, improved brand reputation, and higher consumer loyalty in addition to benefits to the environment and society (Clark & York, 2008; Liu et al., 2012; Mefford, 2011).

In addition to focusing on sustainable materials, production techniques, supply chain management, product design and development, and case studies of top fashion businesses, this chapter has offered an overview of sustainable manufacturing methods in textiles and fashion. Due to its strong reliance on natural resources, the fashion industry may engage in environmentally harmful practises. However, this issue may be resolved by using eco-friendly fabrics like Tencel, recycled polyester, and organic cotton (Chen & Burns, 2006). Waste reduction and recycling efforts, water conservation methods, and energy-efficient manufacturing techniques all contribute to reducing negative effects. Supply chain management also requires ethical sourcing and labour practises. Furthermore, the development of sustainable products can make use of closed-loop production methods and eco-design concepts (Hussain & Kamal, 2015; Winkler, 2011).

The advantages of using sustainable manufacturing techniques are demonstrated in case studies of top fashion companies including Patagonia, Levi's, Nike, H&M, and Stella McCartney. Utilising recycled materials and eco-friendly colours are only two examples of Patagonia's environmentally responsible manufacturing techniques. The firm has also started a programme called "Worn Wear" to encourage customers to fix and recycle their apparel. In the final stage, Levi's "Water-Less" production method uses up to 96% less water. Nike has adopted energy-efficient production techniques and employs sustainable materials like recycled polyester. H&M employs recycled materials in their goods and has integrated sustainable supply chain management techniques, including ethical labour and sourcing procedures. The use of sustainable materials and closed-loop production processes are two aspects of Stella McCartney's sustainable product design and development practises (Li & Leonas, 2019; Rathinamoorthy, 2019; Vadicherla & Saravanan, 2015).

In conclusion, minimising the damaging environmental and social effects brought on by the fashion industry requires the employment of sustainable manufacturing techniques in the textile and apparel industries. The use of sustainable materials, energy-efficient manufacturing techniques, waste reduction and recycling, moral labour standards, and sustainable product design and development can have a substantial positive impact on the economy as well as the environment and society. The successful application of sustainable manufacturing techniques and their potential to revolutionise the fashion industry are demonstrated by case studies of top fashion brands. Sustainable manufacturing techniques are essential for the future of the fashion industry due to the rising customer demand for environmentally and ethically responsible products and the urgent need to combat climate change and environmental damage. The fashion industry's transition to sustainability must include sustainable resources. Designers and manufacturers are searching for substitutes for conventional, resource-intensive materials as consumer demand for sustainable fashion increases and environmental worries grow (Todeschini et al., 2017). This chapter will look at the different sustainable materials used in clothing and textiles, their benefits and drawbacks, and examples of contemporary sustainable materials in use.

2 Sustainable Materials

On the path to sustainability, the fashion sector depends heavily on sustainable materials. Designers and manufacturers are searching for substitutes for conventional, resource-intensive materials as consumer demand for sustainable fashion increases and environmental worries grow (Todeschini et al., 2017). This chapter will look at the different sustainable materials used in clothing and textiles, their benefits and drawbacks, and examples of contemporary sustainable materials in use.

2.1 Types of Sustainable Materials Used in Textiles and Fashion

Cotton is a common fabric in the fashion industry; however, conventional cotton farming techniques can be resource-intensive, causing soil erosion, water depletion, and the use of hazardous pesticides (Niinimäki & Hassi, 2011). Organic cotton is farmed without artificial pesticides or fertilisers using eco-friendly practises. Compared to conventional cotton production, this has a lower carbon impact and uses less water.

2.1.1 Recycled Polyester

A typical synthetic fabric used in clothing is polyester; however, it is not biodegradable and can take a very long time to break down. Current plastic is melted down and converted into fibres to create recycled polyester. By using this method, less waste ends up in landfills and less virgin polyester, a petroleum-based substance that increases greenhouse gas emissions, needs to be produced (Siddique et al., 2008).

2.1.2 Tencel

The wood pulp used to make Tencel originates from forests that are responsibly managed. It is made utilising a sustainable closed-loop manufacturing process that recycles solvents and water, reducing waste and pollution (Arana et al., 2020).

2.1.3 Hemp

In comparison to cotton, hemp grows more quickly, uses fewer resources, and is more environmentally friendly. It may be cultivated without the use of pesticides or herbicides because it is naturally resistant to pests (Schumacher et al., 2020).

2.1.4 Linen

The fibres of the flax plant, a renewable resource that requires less water and pesticides than cotton to grow, are used to make linen. Its durability and biodegradability make it a sustainable material for garments and textiles (Dhirhi et al., 2015).

Cotton, polyester, non-cotton cellulosics, polyamide, and polypropylene are amongst the several fibre types utilised in the manufacture of textiles. Wool and silk are listed under “other.” It is important to take note of the global population rise. But since the 2010s, the rate of expansion in textile manufacturing has outpaced the rate of growth in the global population (Fig. 1). The rise of rapid fashion and low-cost manufacturing methods might be blamed for this (Pepper & Truscott, 2021).

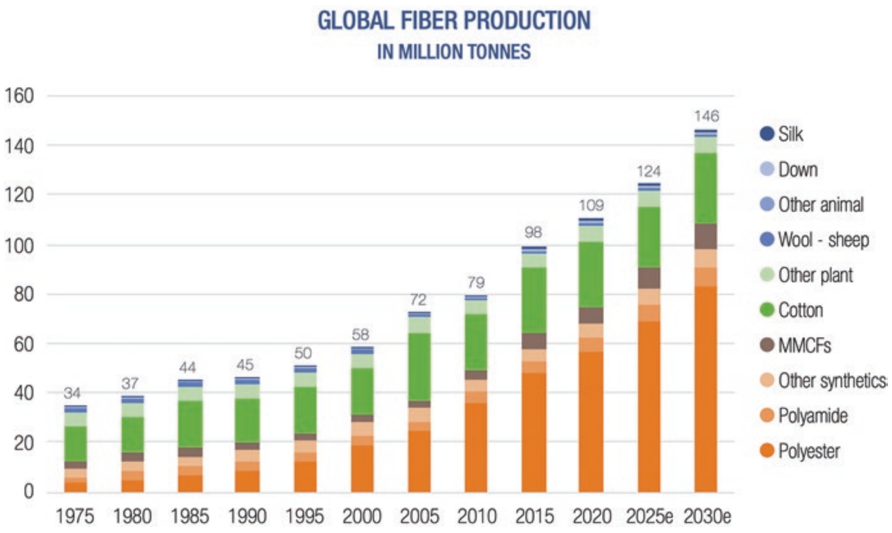

Fig. 1 Growth in global population and textile production by fibre type. (Adopted from Pepper and Truscott (2021))

2.2 Advantages and Disadvantages of Using Sustainable Materials

2.2.1 Advantages

Reduced environmental impact: Sustainable materials are frequently cultivated or produced in ways that have no negative influence on the environment. They produce less waste, need fewer resources, and emit fewer greenhouse emissions (Pepper & Truscott, 2021).

Improved social responsibility: Many sustainable materials help local communities and are manufactured with fair labour conditions, making them an ethical choice (Nayak et al., 2022).

Increased brand reputation: Utilising sustainable materials can enhance a company's reputation amongst consumers who care about the environment and the community, resulting in greater brand loyalty and sales (Ganesan et al., 2009).

2.2.2 Disadvantages

Higher costs: Due to their production processes and scarcity, sustainable materials are frequently more expensive than conventional materials (Ljungberg, 2007).

Limited availability: Some sustainable resources could be hard for businesses to get in big numbers because of their limited supply (Hayles, 2015).

Reduced product performance: In terms of durability, softness, or other features, some sustainable materials might not perform as well as traditional materials, resulting in a lower level of product quality (Suhendro, 2014).

2.3 Examples of Sustainable Materials Used in Textiles and Fashion

2.3.1 Patagonia

Patagonia makes outdoor clothes and equipment using eco-friendly materials like Tencel, organic cotton, and recycled polyester. In order to reduce waste and increase the lifespan of their items, they have also established a programme that encourages customers to mend and reuse their apparel (Lee, 2017).

2.3.2 Levi's

Levi's has included eco-friendly elements into their goods, such as hemp, organic cotton, and recycled denim. They have also incorporated water-saving practises into their manufacturing processes, which has allowed some of their firms to use 96% less water (Nayak et al., 2020).

2.3.3 Adidas

Adidas has introduced a line of eco-friendly footwear that incorporates recycled materials, such as ocean debris, into their designs. By 2020, they have also promised to use entirely organic cotton in their products (Moorhouse & Moorhouse, 2017).

2.3.4 Stella McCartney

Designer Stella McCartney has been a pioneer in eco-friendly clothing. In her collections, she makes use of eco-friendly fabrics including organic cotton, recycled polyester, and vegan leather. Other sustainable initiatives that McCartney has included into her brand include the use of renewable energy in her shops and offices, the implementation of a closed-loop production system, and the promotion of fair labour policies across her supply chain (Milanesi et al., 2022).

3 Sustainable Production Processes

In order to lessen the negative effects of manufacturing on the environment and to ensure a socially responsible supply chain, sustainable production methods are used in the textile and fashion industries. This chapter will discuss some of the crucial techniques employed in environmentally friendly production methods, such as chemical control, waste reduction, water conservation, and energy-efficient manufacturing (Rathore, 2022; Turker & Altuntas, 2014).

3.1 Energy-Efficient Manufacturing Processes

Large amounts of energy are needed to produce textiles and clothing, which adds to greenhouse gas emissions and climate change. By utilising renewable energy sources and streamlining production procedures, energy-efficient manufacturing techniques seek to minimise these adverse effects (Connell & LeHew, 2020; Pimenov et al., 2022).

Sources of Renewable Energy: Compared to conventional fossil fuels, renewable energy sources like solar, wind, and hydropower offer a sustainable alternative. As a means of powering their production facilities, many fashion companies have started to invest in renewable energy (Ahmed et al., 2014). For instance, H&M has put solar panels on the roofs of its stores and distribution centres to provide renewable energy, while Kering Group has vowed to run all of its activities entirely on renewable energy (Lee & Skorski, 2019; Tam & Lung, 2023).

Process Improvement: In order to reduce energy consumption, process optimisation entails finding and removing inefficiencies in manufacturing processes. This can entail making investments in machinery and equipment that is energy-efficient as well as putting in place energy management systems to track and lower energy usage.

3.2 Water Conservation Practices

The production of textiles and clothing depends heavily on water, and this sector is one of the biggest consumers of water worldwide. Through water-saving measures, sustainable manufacturing methods seek to lessen the impact of water usage (Islam et al., 2021).

3.2.1 Water Recycling

Wastewater from manufacturing operations is treated and reused in the recycling of water. By lowering the amount of wastewater released into the environment, this reduces water use and helps to prevent contamination. To lessen their water impact, numerous textile and apparel industries have started to invest in water recycling technology (Jhansi & Mishra, 2013).

3.2.2 Water-Efficient Technologies

Water-saving technology, such low-flow washing and dyeing equipment, aid in lowering the amount of water consumed during production. As they take less water and energy to produce, these technologies can also raise the quality of the final product (Allon & Sofoulis, 2006).

3.2.3 Waste Reduction and Recycling

Significant volumes of waste, such as fabric scraps, packaging materials, and other by-products, are produced during the textile and fashion manufacturing processes. Recycling and waste reduction techniques are used in sustainable production processes to decrease waste (Bhatia et al., 2014).

3.3 Closed-Loop Production Systems

Closed-loop production systems involve designing products and production processes that minimise waste and promote recycling. This can involve using recycled materials, designing products that are easy to disassemble and recycle, and implementing closed-loop supply chains that allow for the recovery and reuse of materials (Jayal et al., 2010).

3.3.1 Waste Reduction Practices

Waste reduction practices involve implementing strategies to reduce waste generation in production processes (Fig. 2). This can include using lean production techniques to reduce excess inventory, implementing reusable packaging and shipping materials, and reducing product returns through better quality control and customer education (Sandin & Peters, 2018).

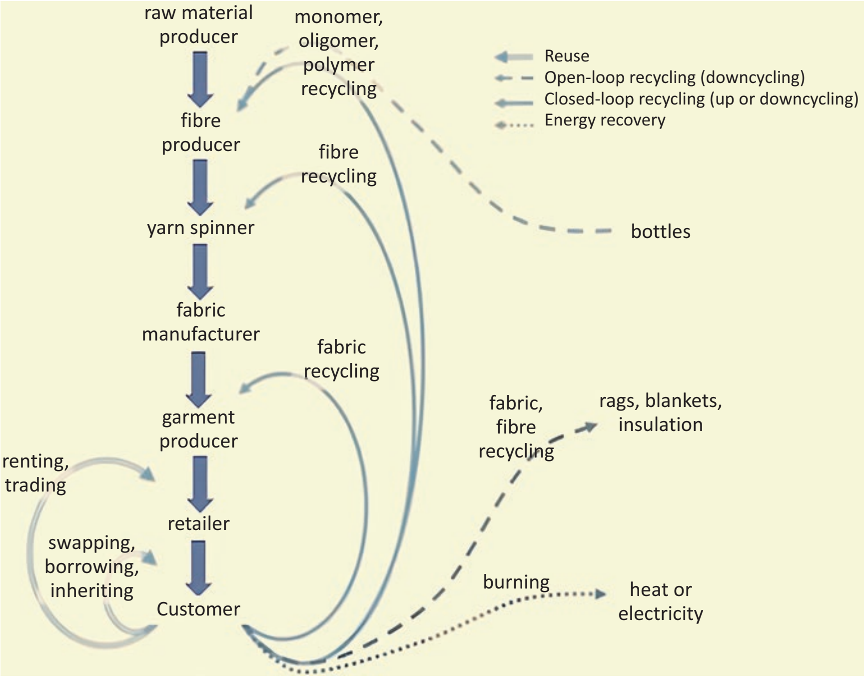

Fig. 2 Different energy-efficient manufacturing processes (Sandin & Peters, 2018)

3.3.2 Chemical Management and Substitution

The use of chemicals in the production of textiles and clothing can have a severe effect on the environment and human health. Through responsible chemical management and replacement, sustainable production techniques seek to lessen the adverse effects of chemicals (Ramphal et al., 2019).

Chemical Control Implementing strategies to reduce the usage of dangerous chemicals in manufacturing processes as well as ensuring proper handling and disposal of these chemicals are all part of responsible chemical management. The Zero Discharge of Hazardous Chemicals (ZDHC) programme, which seeks to remove hazardous chemicals from the textile and fashion supply chain, is one of the chemical management systems that many textile and fashion industries have started to implement.

Chemical Substitution Chemical substitution is switching out dangerous substances for safer ones. This can entail switching to natural dyes from synthetic dyes, utilising vegan leather in place of traditional leather, or employing non-toxic finishing products (Ramphal et al., 2019).

3.4 Examples of Sustainable Production Processes Used in Textiles and Fashion

To lessen their environmental impact and encourage social responsibility, many textile and apparel industries have adopted sustainable production techniques. Several instances include:

3.4.1 Levi's Waterless™ Jeans

In comparison to conventional denim manufacturing, the Levi's Waterless™ brand of jeans uses a great deal less water during the finishing stage of manufacture. Without the use of water-intensive procedures like stone washing or bleach, the Waterless™ technique achieves the required look and finish using a mix of high-pressure air and a misting system. Since it began in 2011, this technique has reportedly conserved more than 3.5 billion litres of water, according to Levi's (Levi Strauss & Co., n.d.).

3.4.2 Nike Flyknit

Nike Flyknit is a sustainable manufacturing method that uses a single thread to make the upper of a shoe, decreasing waste and increasing manufacturing efficiency. The Flyknit method produces an almost seamless upper that is not only more environmentally friendly but also more comfortable and light for the wearer. Nike claims that as compared to conventional cut-and-sew manufacturing techniques, Flyknit production reduces waste by an average of 60% (Kim, 2017).

3.4.3 Adidas Parley Ocean Plastic

In order to produce shoes and clothes, Adidas Parley Ocean Plastic employs recycled plastic that is gathered from the ocean. To help reduce plastic pollution in the oceans, Adidas has teamed up with Parley for the Oceans to collect trash from beaches and coastal towns. The yarn created from this plastic waste can then be utilised to make eco-friendly footwear and apparel. Each pair of Parley shoes, according to Adidas, requires about 11 plastic bottles to make (Adidas America, Inc., 2019).

3.4.4 H&M Conscious Collection

The H&M Conscious Collection is a collection of eco-friendly clothes that employs sustainable materials and manufacturing techniques. The line includes garments manufactured from organic cotton, recycled polyester, and Tencel as well as garments created using environmentally friendly production methods such recycled fabric mixes and water-saving dyeing procedures. Additionally, H&M has put in place a clothing collection service that enables shoppers to contribute worn clothing for recycling or other uses (H&M, 2022).

3.4.5 Patagonia's Worn Wear Programme

With its Worn Wear initiative, Patagonia encourages customers to fix and recycle their clothing rather than throw it away. The programme sells worn Patagonia apparel on their website and offers Patagonia clothing repair services. This initiative lessens the demand for new clothing production and aids in extending the useful life of currently produced apparel, hence lowering waste and fostering sustainability (Patagonia, Inc., 2018).

For the garment business to minimise its environmental impact and promote social responsibility, sustainable production methods are essential. One of the most important ways that textile and fashion companies can achieve sustainability in their production processes is through the use of energy-efficient manufacturing techniques, water conservation techniques, waste reduction and recycling strategies, and chemical management and replacement. Companies can enhance their overall sustainability performance, lower their carbon footprint, and preserve natural resources by putting these ideas into effect. The aforementioned examples show that environmentally friendly production methods can also result in unique and imaginative designs that satisfy consumer desire for eco-friendly products.

4 Sustainable Supply Chain Management

A crucial component of sustainability in the textile and apparel industries is sustainable supply chain management. In order to lessen the industry's detrimental effects on the environment and society, it entails incorporating environmental, social, and economic factors into the supply chain (Gopalakrishnan et al., 2012). Fair labour policies, transparent supply chain management, traceability, and ethical procurement of raw materials are all necessary for the textile and apparel industries. This chapter will cover the significance of managing the supply chain sustainably in the textile and fashion industries and will look at various methods for doing so.

4.1 Ethical Sourcing of Raw Materials

A crucial step in the supply chain for clothing and textiles is the sourcing of raw materials. Raw material source is frequently connected to detrimental social and environmental effects. Purchasing raw materials from manufacturers who follow sustainability requirements is considered ethical sourcing for the textile and fashion industries (Brewer, 2019). To lessen the negative effects of raw material production on the environment, this involves sourcing materials made with sustainable practises. Additionally, it entails buying products from vendors who respect the rights of their employees and use fair labour practises.

4.1.1 Fair Labour Practices

In the textile and apparel industries, fair labour policies are a crucial component of sustainable supply chain management. Many of the products in the fashion business are produced in developing nations, which have a reputation for exploiting their employees (Köksal et al., 2017). Companies must implement rules that support worker safety, just compensation, and favourable working circumstances in order to guarantee fair labour practises across the supply chain. This includes making certain that employees have access to fundamental necessities like health care and education.

4.1.2 Transparency and Traceability

A sustainable supply chain management strategy for the textile and apparel industries must include transparency and traceability. Access to information regarding the supply chain's activities, including its suppliers, procedures, and goods, is referred to as transparency. Traceability is the ability to trace a product's path from its starting point in the supply chain to its final destination. This makes it easier to recognise and lessen negative effects and guarantees that the supply chain runs sustainably and morally. A sustainable supply chain management strategy for the textile and apparel industries must include transparency and traceability. Access to information regarding the supply chain's activities, including its suppliers, procedures, and goods, is referred to as transparency (Sodhi & Tang, 2019). Traceability is the ability to trace a product's path from its starting point in the supply chain to its final destination. This makes it easier to recognise and lessen negative effects and guarantees that the supply chain runs sustainably and morally.

4.2 Collaborative Approaches to Sustainable Supply Chain Management

Sustainable supply chain management requires a collaborative approach involving all stakeholders in the supply chain. This includes suppliers, manufacturers, retailers, consumers, and other stakeholders. Collaboration can help to identify areas of improvement, share best practices, and develop sustainable solutions. Collaborative approaches can also promote transparency and traceability, enabling stakeholders to work together to ensure sustainability in the supply chain (Verghese & Lewis, 2007).

4.2.1 Examples of Sustainable Supply Chain Management in Textiles and Fashion

Sustainable supply chain management techniques have been adopted by numerous textile and apparel firms. The Better Cotton Initiative (BCI), which seeks to increase the sustainability of cotton production globally, is one instance. BCI collaborates with farmers to advance fair labour practises, mitigate the negative environmental effects of cotton production, and promote sustainable farming methods (Partzsch et al., 2019).

The H&M Group is another illustration, with its supply chain-wide implementation of sustainability efforts. Utilising eco-friendly products, cutting back on water use, promoting recycling, and advancing ethical business practises are just a few of H&M's sustainability initiatives. Along with these measures, H&M has also published supplier directories and provided details regarding the environmental effects of its products (Shen, 2014).

The sustainability of the textile and apparel industries depends on sustainable supply chain management. Sustainable supply chain management must prioritise traceability, transparency, ethical raw material procurement, and fair labour practises. Using collaborative strategies with all supply chain participants can aid in achieving sustainability objectives. There has been a large increase in the use of sustainable supply chain management techniques by the textile and fashion industries, but more has to be done to guarantee sustainability throughout the supply chain.

5 Sustainable Product Design and Development

A more ecologically friendly and sustainable fashion sector must start with sustainable product design and development. Closing the manufacturing loop, using eco-design principles, life cycle analysis, product certification, and labelling are all ways to lessen the environmental impact of textile and apparel items. We will go through each of these points in detail and offer illustrations of sustainable product development in the textile and apparel industries in this part.

5.1 Eco-design Principles

According to the principles of eco-design, things should be created keeping the environment in mind from the very beginning. This entails taking into account every stage of the product's lifecycle, from the source of its materials through its eventual disposal (Ikram, 2022). By lowering trash production, energy use, and reliance on non-renewable resources, eco-design seeks to reduce the negative effects of products on the environment. The following are some eco-design guidelines:

Design for durability: The quantity of waste produced can be decreased by designing things to last longer.

Design for recyclability: Waste can be decreased by creating things that can be recycled or repurposed after their useful lives (Braungart et al., 2007).

Design for disassembly: When a product reaches the end of its useful life, recycling or repurposing are more likely to occur (Rios et al., 2015).

Use of sustainable materials: Utilising eco-friendly materials like organic cotton, bamboo, hemp, and recycled polyester can help products have a smaller negative impact on the environment.

Design for energy efficiency: Emissions of greenhouse gases can be decreased by using products that utilise less energy during production or use.

5.2 Life Cycle Assessment (LCA)

A process called life cycle assessment is used to evaluate a product's environmental impact over the course of its full life cycle. It entails examining every step of the supply chain, from sourcing raw materials to production, shipping, consumption, and disposal of the final product (Khasreen et al., 2009). LCA offers a thorough examination of a product's environmental impact, allowing businesses to pinpoint areas for improvement.

5.2.1 Closed-Loop Production Systems

In closed-loop production systems, products are made that can be recycled or used for new purposes once their useful lives are through. This can be done by utilising materials that are simple to separate for recycling or by developing items that use just one material. Closed-loop production techniques can lessen product waste and their negative effects on the environment (Jawahir & Bradley, 2016).

5.2.2 Product Certification and Labelling

Consumer education regarding a product's environmental impact is part of product certification and labelling. Products' environmental and social impacts are disclosed through certifications like the Global Organic Textile Standard (GOTS) and the Cradle-to-Cradle Certified Product Standard (Almeida, 2015). Products' energy efficiency is disclosed on labels like the Energy Star mark and the EU Ecolabel.

5.3 Examples of Sustainable Product Design and Development in Textiles and Fashion

In the textile and fashion industries, there are many examples of sustainable product design and development. Examples include:

5.3.1 Patagonia's Worn Wear Programme

With its Worn Wear initiative, Patagonia encourages customers to fix or recycle their used items. Additionally, the programme offers free repairs for Patagonia products, thereby prolonging their lifespan (Park, 2020).

5.3.2 Adidas' Futurecraft Loop

The Adidas Futurecraft Loop is a closed-loop shoe that may be recycled at the end of its useful life. The shoes can be delivered back to Adidas, where they are disassembled and utilised to make new shoes (Vadakkepatt et al., 2021).

5.3.3 Stella McCartney's Falabella GO Backpack

The Falabella GO backpack by Stella McCartney is constructed of recycled polyester and eco-nylon. The backpack may also be easily disassembled and recycled at the end of its useful life (Stella McCartney, 2023).

5.3.4 Nike's Flyknit Technology

With the help of Nike's Flyknit technology, shoes may be made out of a single piece of material, resulting in less waste and a smaller production-related environmental effect (Fung et al., 2020).

5.3.5 Outer Known's S.E.A. JEANS

S.E.A. JEANS, as they are often called, are a brand of sustainable denim that uses green manufacturing practises and materials in their design. The company developed a sustainable and environmentally friendly product using eco-design concepts and a closed-loop production system (Outerknown, 2023).

6 Case Studies of Sustainable Manufacturing Practices in Textiles and Fashion

The implementation of sustainable practises by businesses across their entire production processes, from sourcing materials to design, manufacturing, and supply chain management, is revealed by case studies of sustainable manufacturing practises in the textile and apparel industries. Here are four examples of well-known fashion companies that have successfully used green manufacturing techniques.

6.1 Case Study 1: Patagonia's Sustainable Manufacturing Practices

Patagonia is a manufacturer of outdoor clothes and equipment that has a long history of supporting green manufacturing methods. The company's goal is to create the finest product with minimal negative impact while also using business to generate ideas for and put into action solutions to the environmental challenge.

The use of recycled materials is one of Patagonia's most significant environmental endeavours. Since 1993, the business has used recycled polyester in its goods, and in 1996 it included recycled nylon. Patagonia wants to minimise its dependency on non-renewable resources by 2025 by using entirely recycled or renewable materials in its products (Ferrara, 2021).

Supply chain management is another area where Patagonia has achieved tremendous advancements. The business introduced the Responsible Wool Standard (RWS) in 2014 with the goal of enhancing the wool industry's policies regarding animal welfare and land management. Additionally, Patagonia purchases sustainable materials like organic cotton from vendors and collaborates with them to uphold fair labour laws and environmental standards.

6.2 Case Study 2: Levi's Waterless Production Process

Since the early 1990s, the well-known denim company Levi's included sustainable principles into its manufacturing procedures. The business introduced its Waterless production method in 2011, which lowers the amount of water used in the manufacture of its jeans.

More than 3.5 billion litres of water have been saved since the introduction of the Waterless procedure, which can save up to 96% less water than conventional denim finishing methods. The method uses less energy and chemicals overall, making it a more sustainable choice (Zhang, 2020).

In an effort to get customers to recycle their old jeans, Levi's has also started a programme. Over 1.5 million pairs of jeans have been recycled by the business, and the recycled denim is used in its manufacturing procedures.

6.3 Case Study 3: Nike's Sustainable Materials and Production Processes

Nike is a well-known sportswear company that has been attempting to use environmentally friendly production methods and materials. Nike's Move to Zero programme, which aims to achieve zero carbon and zero waste in the company's supply chain and goods, is one of the company's major projects.

Recycled polyester, organic cotton, plant-based materials like Tencel, and recycled rubber are just a few of the sustainable components that Nike has been introducing into its products. The business has also made novel materials available, such as Fly leather, which is manufactured from leftover leather and has a smaller carbon footprint than regular leather (Fung et al., 2020).

In addition to employing sustainable materials, Nike has also incorporated a number of sustainable production techniques, such as powering its facilities with renewable energy sources like wind and solar energy, decreasing waste through recycling and reusing initiatives, and using water-saving technologies.

6.4 Case Study 4: H&M's Sustainable Supply Chain Management

A major international retailer of clothing, H&M has been aiming to integrate sustainable practises into every aspect of its supply chain. Products from the company's Conscious Collection are manufactured from eco-friendly materials like Tencel, organic cotton, and recycled polyester.

Additionally, H&M has put in place a number of projects for a more environmentally friendly supply chain, such as the Better Cotton Initiative, which strives to enhance cotton farming methods and lessen the negative effects of cotton production on the environment. Additionally, the business introduced the H&M Global Change Award in 2015, which offers cash to creative businesses developing long-term fixes for the fashion sector (Javed et al., 2020).

Along with using sustainable materials and implementing supply chain improvements, H&M has put in place a recycling programme for its clients. Customers that bring in their old clothes for recycling receive discounts from the business and its uses.

7 Conclusion

In conclusion, the textile and apparel industries are placing an increased emphasis on sustainable manufacturing techniques. The sector has acknowledged the need to lessen its negative effects on the environment and foster social responsibility. Textiles and clothing are made from sustainable materials including organic cotton, recycled polyester, and biodegradable materials. Using sustainable materials has both benefits and cons, but overall, the positives exceed the problems. The textile and apparel industries use a variety of sustainable production techniques, including energy-efficient manufacturing techniques, water conservation techniques, waste reduction and recycling strategies, and chemical management and replacement. Since implementing these procedures, businesses like Levi's, Adidas, and Patagonia have witnessed a considerable decrease in their environmental effect. Promoting social responsibility and lowering industry environmental impact require sustainable supply chain management. Sustainable supply chain management includes a number of important components, including fair labour practises, transparency, and traceability when purchasing raw materials. Sustainable supply chain management techniques have been put into place by businesses including H&M, Patagonia, and Nike.

Sustainable product development requires the use of eco-design concepts, life cycle analysis (LCA), closed-loop production methods, product certification, and labelling. These design concepts have been applied by organisations like Adidas and Stella McCartney, which have created sustainable products that are socially and environmentally responsible. The textile and fashion industries must continue to put high priority on sustainable manufacturing techniques in the future. Businesses must adopt more environmentally friendly production methods, materials, and supply chain management techniques, as well as integrate eco-design ideas into their product development processes. Collaboration between businesses, trade associations, and governmental bodies is crucial for advancing sustainable manufacturing techniques in the sector. The industry can build a more sustainable future for the environment and society at large by cooperating.

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Salt-Free Dyeing of Cellulosic Fibers

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1 Introduction

People have used cellulosic fiber products as clothing and building materials throughout their lives (Tejado et al., 2012). With the production of synthetic fibers, there has been a decrease in the use of cellulosic fibers, but the fact that these fibers remain intact in nature for a long time and increase environmental pollution has encouraged people to use cellulosic fibers again.

Reactive, direct, sulfur, and vat dyestuffs are generally used for dyeing cellulosic fibers. Among these dyes, reactive dyestuffs are the most common dyestuffs that dye cellulose fibers. While dyeing, salt, soda, and surfactants are used besides dyestuffs. Salt ensures the binding of the dyestuff to the fiber, and soda provides its fixation to the fiber. The amount of electrolyte to be put into the dyebath varies according to the dyestuff structure and color depth (Xiao et al., 2017). However, the use of high salt has become an important factor that greatly affects the biochemistry of aquatic life by increasing the load of the wastewater resulting from dyeing, causing more pollution, high COD/BOD values, and the salinity of the rivers (Ashenafi et al., 2020). Various studies have been carried out to eliminate these negative effects.

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The first of these studies is the use of cationic reactive dyestuffs for the elimination and reduction of salt (Srikulkit & Santifuengkul, 2000). Although this dyestuff group offers salt-free dyeing, it could not be used due to its low light fastness (Ma et al., 2005). Xiao et al. (2017) demonstrated that better fastness properties could be achieved by synthesizing three cationic reactive dyestuffs containing azobenzene group and using less salt (Xiao et al., 2017).

Another second work is to cationicize fabrics made from cellulosic fibers. Cationization process is the preliminary preparation made to improve the affinity between dye and fiber (Ma et al., 2005). In the studies, it was observed that the cationization process increased the uptake of anionic dyes and also the fixation of the dyestuffs to the fiber without the use of salt (Ezgi et al., 2013).

In Ashenafi et al.'s (2020) study, using 5 g/L chitosan, cotton fabric was cationized by processing at 60, 70, and 80 °C temperatures for 15, 30, and 45 min, respectively, cationization times. At the end of the study, both the dyeing time was shortened and high fastness was obtained (Ashenafi et al., 2020).

With this section, it is aimed to provide readers with a detailed perspective on the use of salt in the textile sector and the studies to be carried out without the use of salt. In this chapter, cationization process and salt-free dyeing processes are referred. In the first chapter, cellulosic fibers and annual consumption of these fibers are mentioned. Then, dyestuffs that can dye cellulosic fibers and chemicals used in dyeing processes are mentioned. Then, alternative chemicals that can be used instead of salt in the dyeing bath and salt recovery are explained. In the last chapter, cationization and salt-free dyeing processes are mentioned and the book section is finished. In today's world where sustainability gains importance, it will pave the way for future studies in order to reduce the waste load of textile waste water, to use less chemicals and also not to be used in other chemicals that will be put into the reactive dyeing bath.

2 Cellulosic Fibers

2.1 Cellulosic Fiber Properties

Cellulose, one of the renewable resources (Cai et al., 2010) and the main source of which is from plants, is found in fungi, algae, animals, and minerals in nature (Rojas, 2016), and its annual production by nature is 10^{11}–10^{12} tons (Zhao et al., 2007). In particular, cellulose obtained from plants has a biodegradable, recyclable, sustainable, zero carbon footprint (Ardanuy et al., 2015; Li et al., 2019). In addition, its easy availability in nature has increased its use in food and pharmaceutical products (Kolářová et al., 2013).

Cellulose, whose chemical structure was first introduced by Haword (Ardıç, 2007), is a polymer formed by the end-to-end addition of glucose units with the formula $(C_6H_{10}O_5)_n$ and linked by 1,4-β glucosidic bonds (Zhao et al., 2007; Kirci, 2001; Ramamoorthy et al., 2015; Bulut & Erdoğan, 2011). 1,4-β glucosidic bonds are linked by 180° rotation in the chain axis (Rojas, 2016). There are three OH groups on the cellulose chain that hold the glucose molecules together (Gümüşkaya, 2005); these groups connect the cellulose macromolecules with hydrogen bridges (Bulut & Erdoğan, 2011). In addition, OH groups also make the fiber hydrophilic (Kirci, 2001).

Although the main components of natural fibers (such as cotton, flax, hemp, ramie) are cellulose, they also contain components such as lignin, hemicellulose, and pectin in their structure (Bulut & Erdoğan, 2011). For this reason, natural fibers are also known as lignocellulosic fibers (Ardanuy et al., 2015). The distribution of these components differs in the fibers. While determining the moisture absorption, biodegradation, and thermal properties of hemicellulose fiber (Bulut & Erdoğan, 2011), lignin protects the fiber against microbial degradation (Ramamoorthy et al., 2015). Hemicellulose contains hydroxyl and acetyl groups, while lignin contains phenylpropane units (Bulut & Erdoğan, 2011). In addition, lignin is regarded as a thermoplastic polymer with a glass transition temperature of 90 °C and a melting temperature of 170 °C (Kalia et al., 2011).

The most well-known fibers among natural fibers are cotton, linen, hemp, ramie, and jute. Cotton fiber, which belongs to the Gossypium genus in the Malvaceae family (Qin & Zhu, 2011; Narayan Hegde, 2022), is one of the most portentous natural fibers and is largely used in the textile industry (Abhishek et al., 2005; Wang et al., 2020; Fang et al., 2021) and constitutes one of the mainstays of the global economy (Wilkins & Arpat, 2005). Cotton fiber is a seed fiber. The average fiber length of the treated cotton fiber is 1–6 cm (Seher & Eren, 2020). Especially the improved softness, breathability, and absorbency properties make this fiber the most preferred fiber (Mahbubul Bashar & Khan, 2013). Despite these advantages, there are also several disadvantages. These disadvantages are low gloss, high wrinkle formation, microbial degradation, and consumption of large amounts of water, energy, and chemicals (Fang et al., 2021; Mahbubul Bashar & Khan, 2013).

Flax fiber is a stem fiber belonging to the Linum genus and Linaceae family (Jhala & Hall, 2010; Akin, 2013), known for its low cost and high strength properties (Qin & Zhu, 2011). The average fiber length ranges from 20 to 35 mm (Körlü & Bozaci, 2006). Compared to its quick drying feature, the fabrics produced with this fiber show a lot of wrinkling (Dumanoğlu, 2020). Due to its hard structure, flax is subjected to various finishing processes, which improves the low flexibility and high stiffness properties of flax (Manaia et al., 2019). Its use, especially in the field of composites, has started to become widespread today.

Hemp is a 1-year natural fiber belonging to the Cannabis sativa species in the Cannabinacea family, its origin dates back to 850 BC, and it can grow very quickly and has versatile usage possibilities (Seher & Eren, 2020; Jhala & Hall, 2010; Manaia et al., 2019; Şahinbaşkan, 2019; Başer & Bozoğlu, 2020; Yıldırım & Çalışkan, 2020; Merve & Orhan, 2020). The average fiber length varies between 40 and 45 mm (Seher & Eren, 2020). Protection against UV radiation, being aseptic and anti-allergic, high absorbency, and pilling resistance are the main features of this fiber (Kostic et al., 2008; Pejic et al., 2008; Schumacher et al., 2020; Kertmen & Yildirim, 2022). In addition, since no chemicals are used in its production, it also has the feature of environmentally friendly fiber (Şahinbaşkan, 2019). It is a fiber that finds use in various textile products (shirts, trousers, towels, curtains, carpets, upholstery fabrics, etc.), automotive industry, construction industry, and cosmetics industry (Seher & Eren, 2020; Şahinbaşkan, 2019).

Ramie fibers, also known as Chinese Grass, are obtained from a herbaceous perennial plant (Lu et al., 2006; Zhou et al., 2017). The average ramie fiber length varies between 60 and 500 mm (Nam & Netravali, 2006). This fiber, which is more durable compared to linen, hemp, and cotton fibers, has gained popularity in the textile market with its high strength, good moisture absorption, biodegradability, excellent microbial resistance, good gloss, and high annual production properties (Zhou et al., 2017; Kalita et al., 2013; Li et al., 2016; Yuan et al., 2016; Handika et al., 2021). Low thermal stability and poor flame retardancy are disadvantages of ramie fibers (Handika et al., 2021). It is widely used in textile, health, and composite fields (Li & Yu, 2014).

Jute fiber is a bast fiber obtained from Corchorus plants, one of the Tiliaceae families (Duan et al., 2017; Singh et al., 2018). The average length of jute fibers is 160–360 cm (Seher & Eren, 2020). It ranks second in natural and biodegradable fibers (Wang et al., 2009a, 2019). Since their resistance to heat and fire is higher than other cellulosic fibers, they are frequently used in the field of textile and construction (Singh et al., 2018). Since it is a hard, coarse, and hairy fiber, these properties should be improved by chemical processes before spinning (Wang et al., 2009a). It is especially used in sacks, bags, yarn, and carpet linings (Duan et al., 2017; Shahinur et al., 2022).

The feature that distinguishes cellulosic fibers from each other is the cellulose, hemicellulose, and lignin ratios in their structures. The proportions of these components change the physical and chemical properties of the fibers. For instance, while the amount of lignin is high, it gives a hard handle to the fiber (Şahinbaşkan, 2019), while the high content of hemicellulose increases the resistance of the fibers to water (Şahin, 2020). The ratios of the chemical components contained in the fibers are given in Table 1. In addition, parameters such as fiber orientation and fiber diameter affect the mechanical properties of the fibers. The mechanical properties of the fibers are given in Table 2.

2.2 Annual Consumption

In recent years, with the increase of environmental pollution, countries necessitated the use of sustainable and recyclable raw materials. Especially in the European Union, studies on reducing carbon emissions have led people to use cellulosic fibers. Since the wastes of the cellulosic fibers used are organic and 100% biodegradable, it will also be possible to prevent increasing environmental pollution. When FAO 2018 (https://www.fao.org/faostat/en/#data/QV) data were examined, it

Table 1 Chemical composition ratios of some natural fibers (Ramamoorthy et al., 2015; Bulut & Erdoğan, 2011; Venkatarajan & Athijayamani, 2021)

Fibers	Cellulose (wt%)	Hemicellulose (wt%)	Lignin (wt%)	Pectin (wt%)	Waxes (wt%)	Moisture content (wt%)
Jute	60.9–72.1	14.2–23.3	12–13	0.2	0.5	12.7–13.6
Flax	71	18.6–20.6	2.2	2.3	1.7	8–12
Hemp	70–74	17.9–22.4	3.7–5.7	0.9	0.8	6.2–12
Sisal	66–78	10–14	10–14	10	2	10–22
Kenaf	45–57	21.5	8–13	3–5	–	–
Ramie	68.6–76.2	13.1–16.7	0.6–0.7	1.9	0.3	7.5–17
Banana	63–64	10	5		–	10–12
Pineapple leaf	70–82		5–12.7		–	11.8
Coir	32–43	0.15–0.25	40–45	3–4		8
Cotton	85–90	5.7		0–1	0.6	7.85–8.5

Table 2 Physical and mechanical properties of cellulosic fibers (Bulut & Erdoğan, 2011; Venkatarajan & Athijayamani, 2021)

Fibers	Density (g/cm^3)	Elongation at break (%)	Tensile strength (MPa)	Young's modulus (GPa)	Diameter (μm)	Fiber angle	Polymerization degree
Jute	1.3	1.5–1.8	393–773	26.5	15.9–20.7	8.0°	1920–4700
Flax	1.5	2.7–3.2	345–1035	27.6	17.8–21.6	10.0°	2190–4700
Hemp	–	−1.6	690	–	17.0–22.8	6.2°	2200–4800
Ramie	–	3.6–3.8	400–938	61.4–128	28.1–35.0	7.5°	2660–5800
Cotton	1.5–1.6	7.0–8.0	287–597	5.5–12.6	11.5–17.0	20°–30°	2200–4700

was reported that the world fiber production was 110 million tons in 2018 and 45% of this amount was synthetic fine fibers, 29% natural fibers, 20% synthetic fibers, and 6% cellulosic fibers.

Cotton fiber, which has been grown for more than 5000 years (Narayan Hegde, 2022) and is an important raw material source in the textile sector, food sector, and other sectors, constitutes one of the power sources in international trade (Cevheri & Şahin, 2020) and the high usage areas increase the usability of cotton fiber (Xiao et al., 2017). In the list of cotton producing countries in 2018 (Fig. 1), China is the country with the highest cotton production with a rate of 23% (https://www.fao.org/publications/card/en/c/CB7232EN/). However, the countries with the highest production in 2019–2020 and 2020–2021 are India (24.4%), China (22.2%), the United States (17.4%), Brazil (9.3%), Pakistan (6.1%), Türkiye (3.3%), and Uzbekistan (2.4%) (https://arastirma.tarimorman.gov.tr/tepge; Özüdoğru, 2021). At the same time, when the global fiber export data was examined, it is seen that cotton fiber export is 14,955 billion dollars in 2020, and this amount increased to 18,808 billion

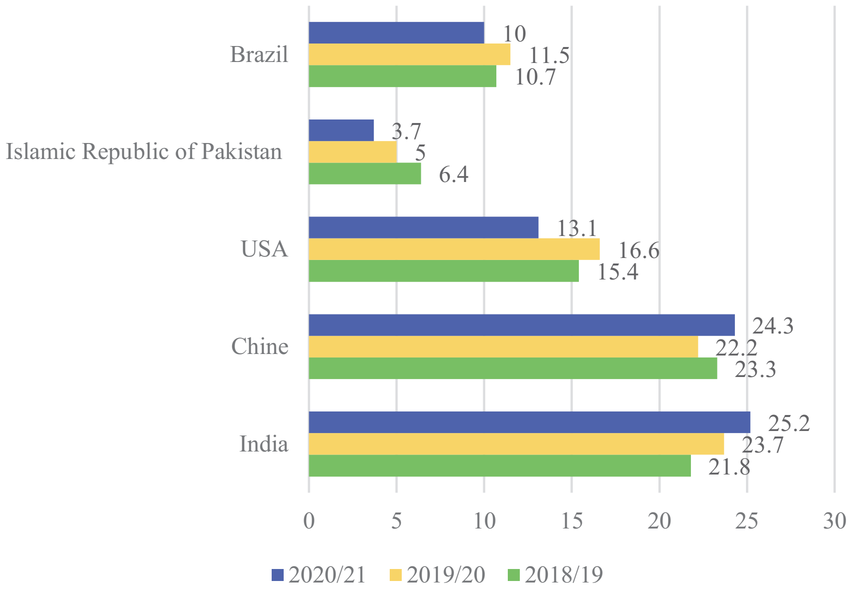


Fig. 1 Countries producing cotton in 2018 (https://arastirma.tarimorman.gov.tr/tepge)

dollars in 2021 (https://www.ithib.org.tr/tr/bilgi-bankasi-raporlar-arastirma-raporlari.html).

In flax production, Canada is one of the main flax-growing countries, while there are countries such as China, Russia, and Egypt in the production of flax for fiber purposes (Jhala & Hall, 2010). However, since flax cultivation areas decreased, flax fiber production was 18% in the nineteenth century, while it decreased to 6% in the twentieth century, and this rate is expected to increase in the following years (Odası, 2020). As shown in Table 3, the production of flax fiber has increased in China and Turkey in the period from 2019 to 2021. More than 90% of the production of ramie fibers is produced in China (Zhou et al., 2017). About 500,000 tons of ramie fiber are produced in China each year (Cheng et al., 2020). The countries that produce the most in jute fibers are Bangladesh, India, China, Nepal, and Thailand. World fiber production varies between 2300×10^3 and 2850×10^3 tons (Shahinur et al., 2022). In hemp fiber production, a total of 142,883 tons of hemp fiber was produced in 2018, and France ranked first with 125,362 tons of hemp fiber production (Başer & Bozoğlu, 2020). As can be seen in Table 3, there has been a decrease in production due to the lack of information and negative point of view in distinguishing between industrial hemp and cannabis used in cannabis production in other countries producing hemp except France (Aydoğan et al., 2020).

Ramamoorthy et al. (2015) stated that a total of 100,000 tons of production in the world consists of 25,000 tons of cotton, 830 tons of flax, 214 tons of hemp, 2300 tons of jute, 100 tons of ramie, and 71,556 tons of other cellulosic fibers (Ramamoorthy et al., 2015).

Table 3 Production data (tons) by country in FAO 2020/2021 (https://www.fao.org/faostat/en/#data/QCL)

Countries	Production year	Flax	Jute	Ramie	Hemp	Cotton lint, Unginnet	Cotton lint, Ginnet
China	2019	17,811.77^{E}	29,200^{E}	57,897^{E}	86,536.54^{E}	23,504,576^{E}	5,889,000^{A}
	2020	22,854.62^{E}	19,300^{E}	59,757.32^{E}	77,176.86^{E}	17,910,606^{E}	5,910,500^{A}
	2021	27,397.32^{E}	15,700^{E}	7652.65^{E}	72,878.18^{E}	17,366,363^{E}	–
India	2019	–	1,709,460^{A}	–	0^{M}	18,558,000^{T}	4,767,140^{A}
	2020	–	1,700,820^{A}	–	0^{M}	17,731,050^{T}	6,131,050^{A}
	2021	–	1,720,000^{A}	–	0^{M}	17,204,000^{T}	–
ABD	2019	–	–	–	–	12,790,218.52^{I}	4,335,440^{A}
	2020	–	–	–	–	9,227,456.35^{I}	3,180,410^{A}
	2021	–	–	–	–	11,246,552.92^{I}	–
Ukraine	2019	540^{A}	–	–	738.68^{I}	–	–
	2020	110^{A}	–	–	738.09^{I}	–	–
	2021	35.23^{I}	–	–	737.51^{I}	–	–
Brazil	2019	–	9^{A}	0^{A}	–	6,893,340^{A}	2,688,403^{A}
	2020	–	1185^{A}	0^{A}	–	7,070,136^{A}	2,757,353^{A}
	2021	–	26^{A}	7.46^{I}		5,712,308^{A}	–
Afghanistan	2019	–	–	–	–	73,120^{A}	24,129^{I}
	2020	–	–	–	–	74,062^{A}	24,440^{I}
	2021	–	–	–	–	72,885.79^{I}	–
Türkiye	2019	2^{A}	–	–	1^{E}	2,200,000^{A}	814,000^{A}
	2020	4^{A}	–	–	1^{E}	1,773,646^{A}	656,251^{A}
	2021	6^{A}	–	–	1.49^{I}	2,250,000^{A}	–
Bangladesh	2019	–	1,600,474^{A}	–	0^{M}	81,000^{E}	27,726^{A}
	2020	–	1,751,635^{A}	–	0^{M}	76,969.54^{I}	32,000^{A}
	2021	–	1,681,938.57^{A}	–	0^{M}	67,000^{E}	–

(continued)

Table 3 (continued)

Countries	Production year	Flax	Jute	Ramie	Hemp	Cotton lint, Unginnet	Cotton lint, Ginnet
France	2019	850,350[A]	–	–	78,050[A]	–	–
	2020	745,570[A]	–	–	102,580[A]	–	–
	2021	678,390[A]	–	–	143,110[A]	–	–

A: official figure, E: estimated value, I: imputed value, T: unofficial value, 0(zero): missing value (data connect exist, not applicable)

3 Dyeing of Cellulosic Fibers

In 1856, William Henry Perkin discovered the first synthetic dyestuff while synthesizing quinine for malaria (Benkhaya et al., 2020). With the production of synthetic dyestuffs, the textile dyeing industry, which has continued its existence with natural resources for more than 4000 years, excluding the last 150 years, constitutes 75% of the global dyestuff market (Benkhaya et al., 2020; Slama et al., 2021). The presence of the textile industry in almost all countries has increased the production of synthetic dyes, and it is estimated that about 10,000 different dyestuffs are used industrially in the world (Slama et al., 2021; Gowri et al., 2014; Keyikoğlu, 2018).

The chromophore groups that give color to the dyestuff absorb the light in the visible region (400–700 nm) and reflect the colors (Keyikoğlu, 2018; Simion Beldean-Galea et al., 2018; Meltem, 2019). Major chromophore groups are azo, carbonyl, methane, nitro and quinoid groups, besides chromophore groups, carboxyl, sulfonate, and hydroxyl. These components are called auxochromes (Keyikoğlu, 2018; El-Nemr, 2012; Choudhury, 2018). According to the structure of the dyestuff, a 5-digit Color Index (CI) number is assigned by the Society of Dyers and Colorists (Aydoğan et al., 2020). This number consists of the application name, color, and identification number of the dyestuff (Gürses et al., 2016). For example, the naming of a dyestuff is as follows: Holacid Fast Red A (trade name), Acid Red 88 (Color Index name), and C.I. 15620 (Color Index number) (Simion Beldean-Galea et al., 2018).

Dyestuffs are complex molecules with at least 5–6 conjugated double bonds and aromatic rings such as benzene and naphthalene (Keyikoğlu, 2018). According to the chemical structures of dyestuffs, it is classified as azo, anthraquinone, indigoid, metal complex, polymethyl, sulfur, aryl carbonium, phthalocyanine, and nitro. According to their dyeing properties, they are classified as reactive, disperse, direct, cube, acidic (anionic), and basic (cationic) dyes (Meltem, 2019).

There are many raw materials in the textile industry. Depending on the structure of the raw materials, the dyestuffs used differ. Figure 2 shows the dyestuffs used in

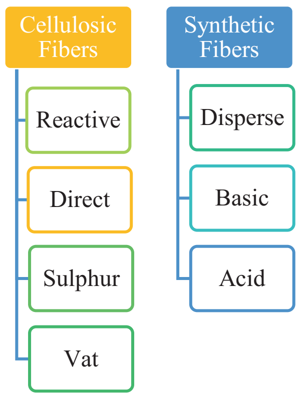


Fig. 2 The dyestuffs used in textile fibers

textiles. While reactive, direct, sulfur, vat, and dyestuffs are used for dyeing cellulosic fibers, disperse, basic, and acid dyes are used for dyeing synthetic fibers (Slama et al., 2021; Simion Beldean-Galea et al., 2018).

3.1 *Dyeing of Cellulosic Fibers and Dyestuffs Use*

3.1.1 Reactive Dye

Procions are the first reactive dyestuff group produced by ICI (Zeneca) company in 1956 (Doyuran, 2010; Öztürk, 2011; Alşan, 2019). It is an important class of dyestuffs preferred for dyeing cellulosic fibers such as cotton and linen (Öztürk, 2011; Özdemir & Tutak, 2013). Unlike other dyestuffs, it is the only dye class that contains atoms and molecules such as Cl, F, SO_2, and $CH_2{=}CH_2$, which form strong covalent bonds by reacting with the molecules on the fiber (Doyuran, 2010; Öztürk, 2011; Alşan, 2019; Özdemir & Tutak, 2016; Akyol, 2022). Due to the strong covalent bond formed between the fiber and the dyestuff, high wet fastnesses are obtained in dyeing (Slama et al., 2021; Giwa & Ogunribido, 2012). A covalent bond is formed between reactive dyestuffs and cellulose fiber according to the following reaction (Doyuran, 2010).

$$\text{Selüloz} - \text{OH} + \text{Cl} - \text{R} - \text{BM} \rightarrow \text{Selüloz} - \text{O} - \text{R} - \text{BM} + \text{HCl}$$

Their molecular weights generally vary between 69 and 221 g/mol, and they penetrate the fiber quickly due to their small molecular structure (Öztürk, 2011; Alşan, 2019). Its features such as having bright colors, being easily soluble in water, high wet and washing fastness, and energy saving as it can be dyed in the cold have made this dyestuff group the most used dyestuff class in dyeing cellulosic fibers (Simion Beldean-Galea et al., 2018; Choudhury, 2018; Doyuran, 2010; Öztürk, 2011; Alşan, 2019; Ojstršek et al., 2008). It has a wide range of color gamuts of reactive dyestuffs used especially for obtaining blue, red, orange, and yellow colors (Doyuran, 2010; Alşan, 2019). Despite the advantages of dyeing with reactive dyestuffs, there are also various disadvantages. For example, poor chlorine fastness, using too much water in the aftertreatment greatly increases the cost and the wastewater rate (Doyuran, 2010). At the same time, the reactive group on the reactive dyestuff interacts with the −OH groups on the cellulosic fibers. In addition, it also reacts with −OH groups in the structure of water, reducing the yield of dyestuff as hydrolysis and causing a decrease in wet fastnesses (Meltem, 2019).

The typical structure of reactive dyestuffs includes reactive-bridge-chromophore and solubilizing groups (Öztürk, 2011; Eren et al., 2007). Figure 3 shows the reactive dye structure. The reactive group on the reactive dye forms a covalent bond with the groups on the textile surface. There are three important groups as reactive groups: dyes containing triazine group, dyestuffs containing vinyl sulfone group, and dyestuffs containing bifunctional groups by carrying the same dyestuff

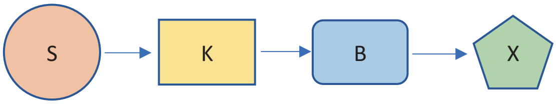


Fig. 3 Reactive dyestuff structure. Q: Resolution providing group; X: Reactive group; K: Chromophore group; B: Bridge group

molecule with these two groups (Şahinbaşkan, 2010). The bridge group connects groups such as −NH−, −CO−, $-SO_2-$ with the reactive group and the colored groups on the molecule, while the solubilizing group provides the solubility of the reactive dyestuffs, the chromophore group gives color to the dye group (Meltem, 2019; Öztürk, 2011).

On the chromophore group, there are azo, anthroquinone, triphenodioxazine, or copper phthalocyanine chromophores to contribute to the color of the dyestuff on the textile surface (Alşan, 2019; Ojstršek et al., 2008). Chromophore groups of dyestuffs are given in Table 4. Azo-structured chromophores constitute the most important color-giving group, and half of the chromophores are in this structure (Meltem, 2019).

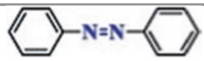
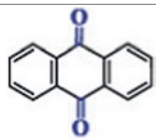
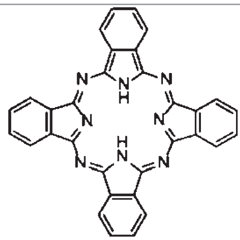
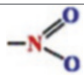
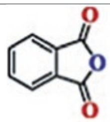
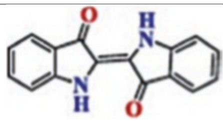
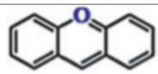
3.1.2 Direct Dye

It is a large molecule, anionic dyestuff group that does not require the use of chemical fixatives and can be easily applied to cellulosic fibers (Keyikoğlu, 2018; Choudhury, 2018; Şenel et al., 2012). It can be applied directly to cellulose fibers in a warm, neutral, or slightly alkaline environment (Simion Beldean-Galea et al., 2018). The ambient temperature is increased to 80 °C (Şenel et al., 2012). The most important features are that they can be easily dissolved in water and bonded to the textile surface without the need for any chemicals (Keyikoğlu, 2018; Gürses et al., 2016). They are also known as sodium salts of sulfonic and carboxylic acids, and their solubility in water is usually provided by sulfo groups and rarely by carboxy groups (Şenel et al., 2012). Unlike reactive dyestuffs, it has lower electrolyte usage (Gürses et al., 2016). Cheap, easy to apply, and resistant to light are the advantages of direct dyestuffs, but their washing fastness is not very good and many EU countries have banned the use of this dyestuff group due to the release of carcinogenic amines (Keyikoğlu, 2018; Choudhury, 2018). Most direct dyes contain compounds such as stilbene, phthalocyanine, oxazine, quinoline, thiazole, and polyazo (Keyikoğlu, 2018; Gürses et al., 2016).

3.1.3 Sulfur Dye

It is used in the dyeing of cellulosic fibers and textile surfaces obtained from the mixture of these fibers with synthetic fibers. The chromophore group of the dye contains one of the sulfide (−S−), disulfide (−S−S−), and polysulfide (−Sn) bonds

Table 4 Chromophore groups on dyestuffs (Benkhaya et al., 2020; Özdemir & Tutak, 2016; El Harfi & El Harfi, 2017; Yaneva et al., 2022)

Chromophore	Structure
Azo	
Antrokinon	
Ftalosiyanin	
Nitro	
Phthalein	
Indigoid	
Ksantan	

(Gürses et al., 2016). They are dyestuffs produced by heating aromatic amines and phenols using sulfur or sodium polysulfide (Keyikoğlu, 2018; Simion Beldean-Galea et al., 2018; Gürses et al., 2016). The water-insoluble sulfur dyestuff is made soluble in water by using suitable reducing agent and alkali (Kulandainathan et al., 2007). It is generally preferred for dark color dyeing, which is used for dyeing work clothes (Simion Beldean-Galea et al., 2018; Choudhury, 2018). Washing and light fastness is good.

3.1.4 Vat Dye

It is a group of dyestuffs used for approximately 4000 years, mainly used for dyeing cotton fiber (Keyikoğlu, 2018; Gürses et al., 2016). Vat dyestuffs, which are generally composed of indigoid and antroquinone, are insoluble in water, they are made soluble in water with the help of reducing chemicals in an alkaline environment and are attached to cellulose molecules by van der Walls and hydrogen bonds (Keyikoğlu, 2018; Simion Beldean-Galea et al., 2018; Gürses et al., 2016). Light and washing fastness is very high. Today, it is used to dye blue jeans.

3.2 Chemicals Used in Dyeing and for What Purpose These Chemicals Are Used

Among the cellulosic fibers, especially cotton fiber, while dyeing with reactive dyes, salt is used to increase the substantivity between the dyestuff and the fiber and to ensure that the dyestuff adheres to the textile surface from the dyebath (Doyuran, 2010; Farrell, 2012). When cellulose interacts with water, a negative charge begins to form on the fiber surface (Farrell, 2012). This formation is called the zeta potential; the formation of the zeta potential is affected by the surface and the solution in which the surface is located (Bayraktar, 2011). The anionic reactive dyestuff tends to be repelled from the fiber surface due to its zeta potential (Özdemir, 2014; Khatri et al., 2015). To minimize this tendency, NaCl or Na_2SO_3 is added to the dyebath. Na+ ion dissolves in water and enters the fiber/water interface between anionic dyestuff and anionic fiber, reducing electrostatic repulsion and increasing dye uptake (Khatri et al., 2015; Chattopadhyay et al., 2007; Arivithamani & Dev, 2017). The amount of salt to be poured into the dye bath varies according to the color darkness and the dyestuff structure. For example, while 10–30 g/L is required for light colors, 50 g/L salt is used for dark colors and not all of the salt is consumed in the dye bath, causing the formation of salty wastewater containing high electrolyte substances (Doyuran, 2010; Ma et al., 2020a; Pei et al., 2022). It increases the salinity of the rivers in the wastewater generated as a result of dyeing and endangers the aquatic life (Singha et al., 2012). Salt recovery systems have been developed to overcome this problem, alternatives to salt have been used, and most importantly, dyeing experiments have been carried out in which salt is not used. Salt recovery will be discussed in Sect. 3.3, alternatives to salt in Sect. 3.4, and salt-free dyeing will be discussed in Sect. 4.

In order to fix the dyestuffs on the fiber, alkalis such as sodium carbonate (Na_2CO_3) or sodium hydroxide (NaOH) are used (Eren et al., 2007; Arivithamani & Dev, 2017; Niu et al., 2022). Cellulose needs to react, dyestuffs need high pH ratios to make covalent bonds on the fiber and become reactive (Doyuran, 2010; Ahmed, 2005). The amount of soda added to the dyebath also varies according to the alkaline composition, dyeing method, and dyestuff group (Khatri et al., 2015).

In addition to the use of salt and alkali in the dyeing of cellulosic fibers, defoamer to prevent foaming, ions such as Ca2+ and Fe2+ in the water affect the dyeing quality, so ion scavengers are added to the dyebath to prevent the interference of these ions (Eren et al., 2007; Ölmez et al., 2006). In addition, surfactants are used to distribute the dyestuff evenly on the textile surface (Gül & Yildiz, 2020).

3.3 Salt Recovery

Water is one of the most basic natural resources to meet the needs of living things, and depending on the increase in population, water use in agriculture, industry, and domestic consumption increases considerably (Burgaç & Yavuz, 2021; Partal et al., 2022).

It is estimated that this increase in water use will cause depletion of fresh water resources and water scarcity in the coming years. The textile sector is one of the sectors that use fresh water resources. A large amount of water is used in pretreatment, dyeing, and printing processes, and it is thought to use 200–400 L of water per kilogram (Riera-Torres et al., 2010). Textile wastewater contains organic substances, surfactants, and toxic substances. In addition to these substances, textile wastewater contains high levels of salt. They contain approximately 6.0% NaCl or 5.6% Na_2SO_4 by weight (Lin et al., 2016; Thamaraiselvan et al., 2018; Ye et al., 2020). This high percentage of salty dyeing waters must be treated in order to be recycled and reused.

Membrane technologies, chemical oxidation, biological treatment, advanced oxidation methods are used for wastewater treatment, but the treatment method with membrane technologies is the widely used technology for salt recovery from wastewater (Riera-Torres et al., 2010; Yurtsever et al., 2020). Membrane technology ensures the separation of the dyestuff and auxiliary chemicals in the dye bath, thereby reducing the COD value (Chollom et al., 2015). Membranes are the elements that separate the components according to their molecular sizes, allow the desired components to pass, while holding the unwanted components (Baburşah, 2004). Microfiltration, ultrafiltration, nanofiltration, and reverse osmosis are the main membrane technologies used in the textile industry (Koyuncu, 2001; Giwa & Ogunribido, 2012).

Microfiltration is the oldest and least efficient system in membrane technologies (Demiral, 2008; Kayacan, 2010; Büyükdere, 2008). They are membranes that hold particles ranging in diameter from 0.05 to 10 μm (Giwa & Ogunribido, 2012; Kayacan, 2010). The flow is parallel to the membrane surface. It requires constant regeneration as it is quickly clogged by the retained particles (Baburşah, 2004).

Ultrafiltration has a tighter holding capacity than microfiltration (Giwa & Ogunribido, 2012). Substances with a molecular weight of 1000–1,000,000 are retained. In addition, salts, proteins ranging in size between 10^{-3} and 10^{-1} μm, viruses, and organic substances are also retained (Büyükdere, 2008).

Nanofiltration is a pressure-driven membrane between reverse osmosis and ultrafiltration processes that traps organic compounds with a relatively molecular weight of 700–1000 salts, as well as large molecular ions such as dyeing aids (Yurtsever et al., 2020; Chollom et al., 2015; Genceli et al., 2021). It is generally used in drinking water treatment, industrial wastewater treatment, hardness removal, pesticide and herbicide removal from water (Büyükdere, 2008; Genceli et al., 2021). In addition, loose nanofiltration membranes are a type of membrane that allows the passage of NaCl at a high rate due to its loose surface structure and enables the fractionation of NaCl (Ye et al., 2020).

In the reverse osmosis principle, it is based on the principle that the solution of two different concentrations passes from the medium of low density to the side of higher density, until the ionic equilibrium is achieved by using a semipermeable membrane (Baburşah, 2004; Kayacan, 2010; Büyükdere, 2008). It is a membrane system that can remove all dissolved substances and metal ions from water, providing the most advanced and highest removal efficiency among membrane processes, with an operating range of 0.1–1 nm, an application pressure of between 15 and 75 bar (Giwa & Ogunribido, 2012; Büyükdere, 2008).

3.4 Environmentally Friendly Alternatives to Salt

In dyeing cellulosic fibers, salts such as sodium sulfate or sodium chloride are used in high proportions to provide dye fixation. Since the waste water generated at the end of dyeing contains high levels of salt, it harms the environment. For this reason, dyeing studies have been carried out using various environmentally friendly salts in order to reduce the use of salt. Environmentally friendly salts are biodegradable chemicals that affect the ionization of the dyestuff and increase its binding to cellulose. It is generally composed of sodium salts of magnesium acetate, tetrasodium edate, trisodium citrate, polycarboxylic acid (Genceli et al., 2021).

Magnesium acetate is an environmentally friendly salt that is biodegradable, can be easily removed from wastewater by adjusting the pH of the solution, and is used 20% less in reactive dyeing than sodium chloride (Genceli et al., 2021).

Tetrasodium edate is a biodegradable, non-toxic, environmentally friendly salt type (Ahmed, 2005; El-Shishtawy et al., 2007; Aysha et al., 2022). Due to its high alkalinity, it causes the dyestuffs to hydrolyze in the dyebath, so adding too much sodium hydroxide to the dyebath makes it difficult to control the dyeing (Genceli et al., 2021; Guan et al., 2007).

Polycarboxylic acids are biodegradable, inexpensive, readily available, less toxic, high molecular weight weak electrolytes (Genceli et al., 2021; Guan et al., 2007). The use of this salt group has proven to be a more effective class in dye uptake than other alternative salts (Ahmed, 2005).

Trisodium citrate is an environmentally friendly salt that suppresses the zeta potential formed on the cellulose fiber and ensures the penetration of dye molecules into the fiber and provides 65–90% dye uptake. In addition, it is used 40–65% less than the amount of salt used in conventional dyeing (Genceli et al., 2021).

4 Salt-Free Dyeing

As mentioned before, salt is used in cotton dyeing to neutralize the negative charge of cotton and overcome the repulsion between the anionic dye molecules and negatively charged cellulosic chains and promote the dye exhaustion. However, the remaining salt in the dyebath is a serious concern from the environmental point of view. Several methods have been explored for salt-free dyeing of cellulosic fibers with anionic dyes, which mainly rely on imparting cationic charge on cotton fibers using various natural or chemical compounds. Salt-free dyeing of cotton using cationization is a promising technique that has gained attention in recent years due to its eco-friendliness and cost-effectiveness. This technique involves the use of cationizing agents to modify the cotton fibers, making them more receptive to dye molecules without the need for salt. The cationized fibers attract the anionic dye molecules, and there will be no need to use salt in the dyebath. Cationization is the process of introducing positively charged groups onto the cotton fibers, which enhances the affinity of the fibers for negatively charged dye molecules. The cationizing agents used for this purpose can be broadly classified into two categories: quaternary ammonium compounds (QACs) and polymeric cationic compounds (PCCs). Various methods employed for cationization and salt-free dyeing of cotton are summarized as follows.

4.1 Cationizing Using Quaternary Ammonium Compounds (QACs)

The most common method for preparation of salt-free dyeable cotton is cationization of the fibers by quaternary ammonium compounds, which carry permanent positive charge irrespective of the dyebath pH value. The binding of the QAC to cotton results in ionic attraction between the fibers and dye molecules and increasing the exhaustion without the need for addition of salt. Generally, there are two types of QACs for application on cotton. One type is composed of a quaternary ammonium group connected to a reactive group which enables it to bond with cellulose under suitable condition. In the second type, the quaternary ammonium group is connected to double bonds, which enables it to bind and polymerize on cotton surface in the presence of suitable initiators. The already prepared cationic polyelectrolytes can also be applied on cotton by exhaustion or pad-dry-cure or pad-batch processes as well (Correia et al., 2020).

CHPTAC (3-chloro-2-hydroxypropyl trimethylammonium chloride) is one of the commonly employed QACs belonging to the type one, which is available at commercial scale. This compound is converted to the fiber reactive 2,3-epoxypropy ltrimethylammonium chloride (EPTAC) in the presence of sodium hydroxide. Under alkaline condition, ether bonds are formed between the epoxy groups of

EPTAC and the hydroxyl groups of cellulose, resulting in the preparation of cationized cotton as shown in Fig. 4 (Hauser & Tabba, 2001).

Hauser and Tabba padded cotton fabric with 50 g/L of CHPTAC (65 wt% solution) and 36 g/L of NaOH (50 wt% solution) at 100% wet pick up and batched for 24 at room temperature while wrapped with a plastic cover. Thorough rinsing and neutralization with dilute acetic acid was followed. The modified fabrics were dyed with different direct and reactive dyes. As shown in Fig. 5, the color strength of cationized cotton was higher when dyed with all reactive and direct dyes used in this study. Comparing the normal and cationized cotton dyed with the same dye, the fastness properties of the cationized cotton were significantly improved. The dyeing of cationized cotton was done at shorter time, using less water and chemicals and consumed less energy (Hauser & Tabba, 2001).

Montazer et al. employed CHPTAC for cationization of cotton using a similar procedure and dyed the cationized cotton with different mono-chlorotriazine, vinyl sulphone, and di-chlorotriazine reactive dyes. Their results showed that the exhaustion rate was over 90% for salt-free dyeing with all reactive dyes (irrespective of the type of reactive group) on cationized cotton, which was much higher than the same dye on untreated cotton fabric in the presence of salt. The cationized cotton exhibited higher color strength and better light fastness compared with the untreated samples (Montazer et al., 2007).

Wang et al. employed a pad-bake method for cationization of cotton with CHPTAC. The optimum concentrations of CHPTAC and sodium hydroxide in padding bath were 8.0 wt% and 1.8 wt%, respectively. The samples were padded with 80% wet pick-up, then baked at 60 °C for 6 min. The total amount of fixed reactive dye on cationized cotton reached 85% without the use of salt, and the color strength of the dyed cationized samplings was improved compared with the untreated cotton samples (Wang et al., 2009b).

Arivithamani and Giri Dev employed an exhaustion method to cationize cotton using CHPTAC in the presence of NaOH (molar ratio of 2:1) at 80 °C. Their results showed that the color strength of the cationized cotton dyed with three reactive dyes (without salt) was twice of the conventionally dyed cotton fabrics dyed with the same reactive dyes (Nallathambi & Venkateshwarapuram Rengaswami, 2016). These authors applied the same process at industrial scale on 5 kg of cotton fabric and dyed the cationized cotton with two reactive dyes without the use of salt. The results confirmed the significant improvement of the color strength of the cationized cotton compared with the conventional dyeing of non-modified cotton. The fastness properties and levelness of the dyeing was also good. The optimum amount of

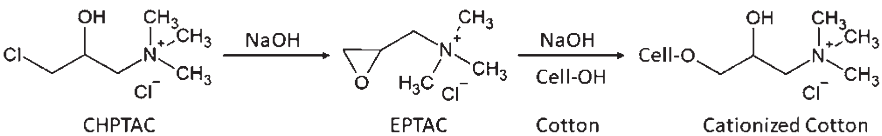


Fig. 4 The mechanism of cationization of cotton using CHPTAC (Hauser & Tabba, 2001)

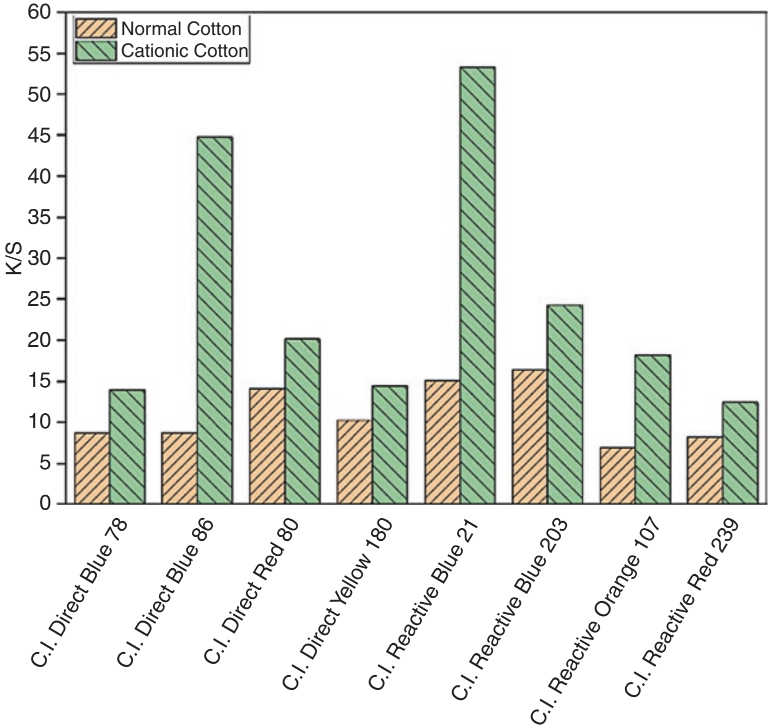


Fig. 5 Color strength of non-modified and cationized cotton dyed with 2% owf of direct and reactive dyes (Hauser & Tabba, 2001)

CHPTAC used in the cationization stage for obtaining the best results in medium shade dyeing was 40 g/L, while it was 80 g/L for dark shades (Arivithamani & Dev, 2017; Arivithamani & Giri Dev, 2018). In another study, the industrially cationized hosiery cotton fabric was salt-free dyed with ultra-deep black shade (9.95% owf) and compared with the non-modified cotton dyed with the same shade by conventional method. The results showed that the color strength was the same for both samples, while the exhaustion was higher in case of cationized cotton (58.2%) compared with the non-modified cotton (51.7%). The total dissolved solid (TDS) and chemical oxygen demand (COD) of the dyebath wastewater were importantly lower in case of the cationized cotton compared with the non-modified cotton (Arivithamani & Giri Dev, 2018). Cationization of viscose fibers with CHPTAC using exhaustion method has been reported by Li et al., and the reactive dye exhaustion, fixation, uniformity, and fastness properties have been improved upon cationization (Li et al., 2022). Cationization of cotton using a commercial cationization agent (Denimcol FIX-OS, CHT, Switzerland) improved the sorption of Methyl Orange on cotton which resulted in the preparation of pH-responsive textile (Kert & Skoko, 2023).

Atiq et al. showed that the cationization of cotton with CHPTAC using a pad-batch method improved the color strength and fastness properties in dyeing with solubilized sulfur black dye (Atiq et al., 2019). Similar method was employed by Setthayanond et al. which imparted salt-free reactive dyeability to cotton fabric (Setthayanond et al., 2023). Cationization of cotton using CHPTAC (30 g/L) in the presence of 10 g/L NaOH by pad-dry process considerably improved the dyeability of cotton with acid dyestuffs, and the exhaustion reached 92% following Langmuir isotherm (Zhai et al., 2022).

In another study, Yu et al. applied CHPTAC on cotton by a pad-irradiation method and dyed the cationized fabric by a pad-steam process as shown schematically in Fig. 6. The cationized cotton showed the same reactive dyeability (without salt) compared with the non-modified cotton dyed with the same dye in a conventional pad-dry-pad-steam method in presence of salt. The levelness and fastness properties were also satisfactory (Yu et al., 2019a). Optimization using response surface methodology showed that the optimal concentration of CHPTAC in this process is 104 g/L, while the molar ratio of NaOH/CHPTAC was 1.02. The optimal microwave power and duration were 537 W and 6 min, respectively (Yu et al., 2019b). Least squares support vector machine (LS-SVM) was also employed to predict the color strength of the dyed cotton fabrics with high efficiency and an error of less than 1% (Tao et al., 2021).

Wang et al. expressed that under optimal condition, CHPTAC can be applied on cotton fabric along with reactive dye in a single pad-steam method and shorten the process duration, increase the color strength and dye fixation. However, the simultaneous application of poly diallyldimethylammonium chloride (PDADMAC) and reactive dye caused the precipitation of the dye causing reduced color strength and uneven dyeing (Wang et al., 2022a).

It is well-known that in conventional reactive dyeing of cotton in presence of alkali and salt, the linkage between the dye molecule and cellulosic chain is formed between reactive group of the dye and hydroxyl groups of the cellulose through nucleophilic substitution or an addition mechanism. Pruś et al. showed that when cotton is modified with CHPTAC and dyed at room temperature without the addition of salt and alkali, the covalent bond was formed between the reactive groups of the dye molecules and the hydroxyl group of CHPTAC instead of the OH groups located on glucopyranose ring (Pruś et al., 2022).

Another approach for cationization of cotton is the graft polymerization of cationic monomer on its surface. For example, when free radicals are created on cotton using potassium persulfate as an initiator, diallyldimethylammonium chloride can

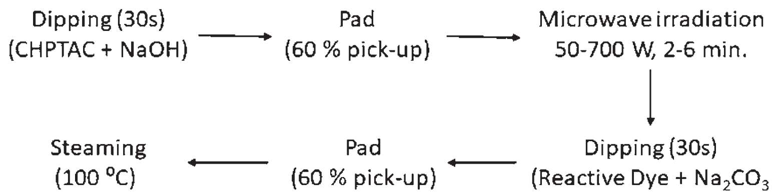


Fig. 6 Schematic presentation of pad-irradiate-pad-steam method for cationization and reactive dyeing of cotton (Yu et al., 2019a)

be subsequently graft polymerized on it using these free radicals. Jareansin et al. used this procedure for cationization of cotton and dyed the modified fabric with bromothymol blue to prepare pH-sensitive fabric as a smart textile for detection of acetic acid and urea in solutions (Jareansin et al., 2019). Meng et al. employed plasma post treatment to generate the free radicals required for polymerization of DADMAC on cotton. The procedure consisted of an immersion stage in DADMAC solution (20–30 wt%), drying at 100–140 °C and atmospheric pressure oxygen plasma post treatment. The salt-free dyeing of cationized cotton with reactive dyes showed better dye uptake and exhaustion rate compared with the conventional procedure (Meng et al., 2021). Helmy et al. investigated the plasma polymerization of DADMAC (7%) on cotton fabric by pre-plasma and post-plasma treatments. Figure 7 shows the mechanism of plasma polymerization of DADMAC on cotton schematically. The cationized samples were dyed with acid dyes. The samples cationized with DADMAC with the aim of pre- or post-plasma treatment showed enhanced dyeability compared with the untreated cotton and fabrics cationized by pad-dry-cure process (Helmy et al., 2017).

Cationization of cotton was studied by free radical initiated graft polymerization of 2-methacryloyloxyethyltrimethyl ammonium chloride in the presence of $K_2S_2O_8$/$NaHSO_3$ as initiator. The modified fabrics were dyed with reactive dyes without the use of salt and exhibited higher than 97% exhaustion with excellent fastness properties (Ma et al., 2020b). In another study, Niu et al. synthesized a bifunctional cationic polymer via free radical polymerization between dimethyl diallyl ammonium chloride and allyl glycidyl ether. The application of the prepared cationic polymer on cotton resulted in salt-free reactive dyeing at low temperature with satisfactory leveling and fastness properties (Niu et al., 2020).

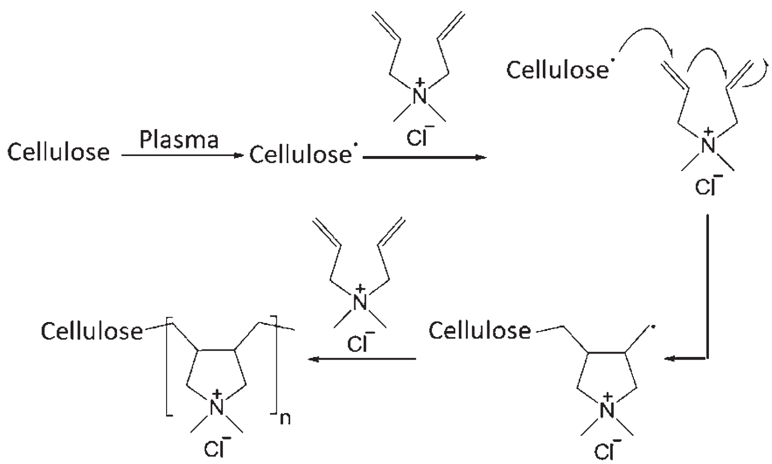


Fig. 7 Schematic presentation of plasma graft polymerization of DADMAC on cotton (Helmy et al., 2017)

Polyaminochlorohydrin quaternary ammonium compounds are also commercially available for cationization of cellulosic fibers. Application of Albafix E (Huntsman, Switzerland) on linen fabric resulted in higher color strength in salt-free dyeing with reactive and direct dyes (Atav, 2017). Cationization of cotton fabric with Cibafix WFF improved its dyeability with direct orange 46 and changed the dyeing isotherm from Freundlich type to Langmuir (Khanjani et al., 2011). In another study, P42 as a commercially available cationic polymer based on Poly[bis(2-chloroethyl) ether-alt-1,3-bis[3-(dimethylamino) propyl] urea] quaternized solution was used for cationization of cotton (Fig. 8). Dielectric barrier discharge plasma (Ar/O_2) was employed as a pretreatment to improve the cationization. Cationized samples were dyed with reactive and acid dyes and compared with greige- and plasma-treated samples. P42-treated sample dyed without salt addition exhibited higher color strength compared with the greige- and plasma-treated samplings dyed using the conventional method. CHPTAC treatment exhibited higher color strength and uniformity compared with P42. However, P42 might be recommended as an alternative due to the safety concerns related to the use of CHPTAC (Correia et al., 2021a). Another study revealed that cationization of cotton using 20 g/L of PDADMAC (Fig. 8) resulted in a color strength comparable with CHPTAC (Correia et al., 2021b).

Tang et al. graft polymerized 2-diethylaminoethyl chloride on cotton under alkaline condition. The modified cotton contained multiple cationic quaternary ammonium moieties and exhibited salt-free dyeing properties (direct, acid, and reactive dyes) with outstanding fastness properties (Tang et al., 2021).

Polyhexamethylene biguanide hydrochloride (PHMB, Fig. 9), a cationic polyelectrolyte, has been applied on cotton fabric using a pad-dry-cure method, and the modified fabrics were dyed with three acid dyes. The cationized fabrics exhibited enhanced dyeability with high levelness and acceptable color fastness properties and antimicrobial activity. The advantage of this method over the conventional dyeing was the recyclability of the dyebath for circular dyeing at room temperature which saves great amounts of water and energy compared with the conventional dyeing processes (Wang et al., 2022b). Wu et al. selectively oxidized cotton surface using 2,2,6,6-tetramethylpiperidine-1-oxygen radical (TEMPO) and sodium hypochlorite to enhance the attachment of Polyhexamethylene guanidine (PHMG) by an exhaustion method. The modified cotton exhibited 30% improvement in exhaustion rate and dye fixation without any change in fastness properties (Wu et al., 2023).

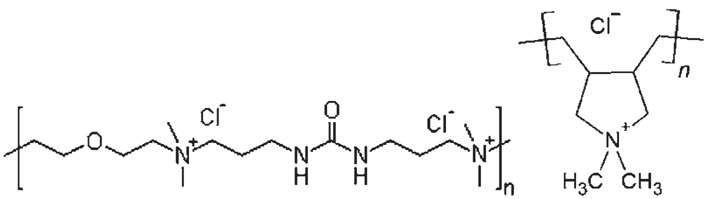


Fig. 8 The structure of P42 (left) and PDADMAC (right)

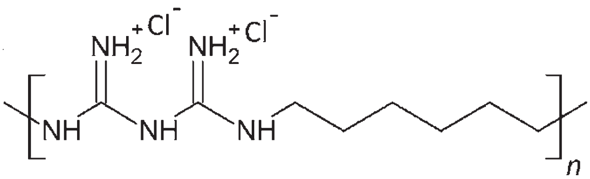


Fig. 9 Structure of polyhexamethylene biguanide hydrochloride

Xia et al. compared the effect of three cationizing agents, namely, CHPTAC, PDADMAC, and polyethyleneimine (PEI) on dyeability of cotton with reactive dyes. All cationizing agents were applied on cotton fabric at the same concentration of 3 g/L using exhaustion method. Selective oxidation was employed as a pretreatment to introduce negative charge on cotton and enhance the adsorption and diffusion of the cationizing agents. In this study, the best salt-free dyeing results were obtained when PEI was applied on oxidized cotton (Xia et al., 2022).

Natural dyes are mainly applied on protein fibers with the aim of metallic and bio mordants. In case of cotton, the affinity for natural dyes is very low and high amounts of metal mordants are needed to obtain moderate color strength using natural dyes. Cationization of cotton is one of the eco-friendlier processes (compared with metal mordanting) which has been considered for enhancement of exhaustion and fastness of natural dyes on cotton. Haddar et al. applied a commercial cationizing agent (Croscolor DRT, Eurodye-CTC, Belgium) on cotton and dyed the modified fabric with different natural dyes such as fennel (Foeniculum vulgare), Gulzuba (Hibiscus mutabilis), grape pomace, and Tamarix aphylla leaves. The cationization improved the dyeability and fastness properties of cotton with the natural dyes and reduced the COD and BOD5 of the remaining dyebath compared with the dyeing in presence of metallic mordants (Haddar et al., 2014a, b; Baaka et al., 2017, 2019). Another study reported the application of Albafix E and Albafix WFF, aqueous solutions of polyaminochlorohydrin quaternary ammonium compound with epoxide end group (Huntsman, Switzerland) on cotton and dyeing with extracts of rose, mate tea, and lavender as natural dyes (Oktav Bulut & Akar, 2012). In another study, Rewin OS, a cationic reactive polyammonium compound from CHT-Bezema (Switzerland), was used for cationization of cotton and improved its dyeability with cochineal natural dye significantly (Čorak et al., 2022). Cationization of cotton using Denimcol FIX-OS (CHT, Switzerland) significantly improved the uptake of goldenrod natural dye compared with the raw and alum-mordanted samples and exhibited the highest fastness properties against washing, light, and rubbing (Topič et al., 2018).

4.2 Cationization Using Bio-based Polymers

Cationic starches are widely used in industries such as cosmetics, paper, wastewater treatment, as well as textiles. Zhang et al. prepared cationic hydrolyzed starch by using 2,3-epoxypropyltrimethyl ammonium chloride. It was applied on cotton using a pad-bake process (100 °C for 10 min) and the modified samples were dyed with reactive dyes by exhaustion method without using salt. The cationized cotton showed better dye exhaustion, fixation, levelness, and fastness properties compared with the non-modified cotton dyed by the conventional dyeing procedure (Zhang et al., 2007a). Ma et al. applied cationic native starch (CNS) and cationic hydrolyzed starch (CHS) (0.1–2.5%) on cotton using a similar process and dyed the modified samples with two reactive dyes. Zeta potential measurements showed that the modified cotton carried positive charge at pH values lower than 8. The CHS-modified cotton samples were dyed successfully without salt and followed Langmuir adsorption isotherm. The results obtained for CHS-modified cotton were significantly better than the non-modified and CNS-modified cotton. Modification with CNS did not show satisfactory results due to the high molecular weight and viscosity of CNS which prevented the dye penetration and fixation (Ma et al., 2012).

Wangatia and Tseghai extracted reactive keratin hydrolysate from cattle hoof and horn and applied it on cotton fabric using pad-dry-cure method. The introduction of amide functional groups on cotton fibers improved the exhaustion of reactive dyes by 6% and increased the color strength by 4% in salt-free dyeing compared with the conventional dyeing in the presence of salt (Wangatia & Tseghai, 2015). Samanta et al. extracted the natural amino acids from soya bean seed waste by acid hydrolysis and applied on cotton fabric by pad-dry-cure process in the presence of $MgCl_2$. The modified cotton exhibited significantly improved exhaustion of reactive dyes when dyed under acidic condition without salt addition (Samanta et al., 2016).

Chitosan is a bio-based polymer carrying amino groups. It can impart salt-free dyeability as well as antibacterial activity to cotton fibers. Haji et al. applied 0.5% chitosan solution on cotton by pad-dry process and improved the attachment through oxygen plasma pre-treatment. The modified cotton samples showed enhanced dyeability and fastness properties with direct and acid dyes without the use of salt (Haji et al., 2016a). Application of chitosan on cotton fabric has improved its dyeability with various natural dyes such as mango leaves (Yanti et al., 2021), weld flowers and walnut shells (Haji, 2020), pomegranate rinds (Haji, 2017), and cotton pods extract (Haji et al., 2016b).

Gelatin, a popular and versatile biopolymer, is derived from collagen, which is one of the most abundant proteins found in animals. It is obtained through the partial hydrolysis of collagen-rich materials, such as bovine bones and porcine skin. Gelatin is widely recognized for its gelling, thickening, stabilizing, and binding properties. As a result, it has a wide range of applications across various industries such as pharmaceuticals, beverages, food, cosmetics, and photography. Gelatin's biocompatibility, low toxicity, and biodegradability make it a favorable choice for tissue engineering, wound healing, and drug delivery systems. Thus, with its unique physical and biological properties, gelatin continues to maintain its prominent position as a widely utilized biopolymer in various applications. The presence of amino groups in the structure of gelatin makes it a candidate for cationization of cotton for salt-free dyeing. Ahmed et al. extracted gelatin from fleshing waste of animal hide and applied it (20 g/L) on cotton by pad-dry method. The cationized cotton was dyed with reactive dyes at acidic medium in the absence of salt, which gave better results than the untreated cotton dyed with conventional method in the presence of alkali and salt (Ahmed et al., 2022).

4.3 Modification Using Other Chemicals

Grafting of amine containing compounds on cotton enables the modified fibers to adsorb anionic dyes through ionic attractions without the need of salt. Poly (vinylamine chloride) with degree of amination of 52.2% (5 g/L) was applied on cotton fabric using a pad-bake method. The cationized cotton exhibited improved salt-free dyeing and fixation with different reactive dyes. The dyeing followed Langmuir isotherm and the uniformity and wash fastness was excellent, while rub fastness was good (Ma et al., 2005).

Amino-terminated hyperbranched polymers (HBP-NH_2) have been also employed for modification of cotton to promote salt-free dyeability with reactive dyes. Zhang et al. synthesized HBP-NH_2 and applied it on cotton using a pad-dry-cure process, which improved the dyeing of cotton with reactive dyes in absence of salt resulting in enhanced fastness properties (Zhang et al., 2007b, 2008).

Poly (propylene imine) dendrimers (PPI) contain several terminal amino groups which upon attachment on cotton can impart salt-free dyeability to the fibers due to the ionic attraction with anionic dyes. Abkenar et al. grafted the PPI dendrimers (G2 and G5) on cotton using citric acid and glutaraldehyde by pad-dry-cure method. The dyeability of modified sampled with direct dyes was significantly improved, enabling salt-free dyeing (Salimpour Abkenar et al., 2015). Other researchers applied a hybrid of chitosan-PPI dendrimer (20% owf) on cotton and obtained salt-free dyeing (Sadeghi-Kiakhani & Safapour, 2015).

Grafting of thiourea on cotton has been reported by Liu and Yao. To introduce epoxy groups, epichlorohydrin was attached to the cellulosic chain through the reaction with the hydroxyl groups of cotton in the presence of NaOH. Then thiourea was reacted with the epoxy groups of epichlorohydrin to introduce amine groups to the cotton fibers. The cotton fibers modified under optimal condition (10 g/L thiourea, 6 g/L NaOH, 40 °C, 60 min) showed significant enhancement in dyeability with reactive dyes without the use of salt and levelness as well as the fastness properties were satisfactory (Liu & Yao, 2011).

Grancarić et al. applied a two-step sol-gel process using amino-functionalized precursor for cationization of cotton. The sols were prepared using tetraethoxysilane (TEOS) and 3-aminopropyltriethoxysilane as precursors and applied, respectively, on cotton fabric by pad-dry-cure method. The amino groups contained in the sol-gel coating promoted the salt-free dyeing of modified cotton with acid dye through ionic interaction with the dye anions (Grancarić et al., 2021). In another study, Zhang et al. applied a silica sol loaded with hyperbranched poly(amidoamine) on cotton to obtain salt-free reactive dyeing property (Zhang et al., 2021).

5 Conclusion

Salt-free dyeing processes in studies related to the dyeing of cellulosic fabrics in the textile sector are as follows:

- Reducing the use of chemicals increases its preferability in terms of being more environmentally friendly and ecological.
- However, cationization of cellulosic textiles is a promising technology for greener dyeing with high potential for industrial-scale applicability.
- Time and energy are saved in dyeing processes, and as a result, cost savings can be achieved.
- In the research and implementation of new dyeing processes, attention should be paid not only to pollution reduction but also to the recycling of water, dyestuffs, chemicals and auxiliaries, and the management of end-products for other applications.

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Sustainable Approaches in Textile-Sizing Process

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1 Introduction

Textile manufacturing stages of wet processing require substantial quantities of water and chemicals, making the textile sector one of the major contributors to water contamination and harmful emissions globally. Sizing process, one of the unique stages of woven textile manufacturing line, is an essential step that imparts extra protection to warp yarns, assisting them to withstand abrasive friction and beat up forces during weaving process. Abrasion resistances to friction and yarn hairiness are crucial factors in weaving process. Evaluation of the effectiveness of the sizing process and also performance of warp yarns and fabrics after sizing is generally carried out on various parameters including elongation, tenacity, initial modulus, breaking force, breakage during weaving process, yarn unevenness, extension during maximum load, abrasion resistance, weight loss during abrasion, fatigue resistance, and yarn hairiness (Ahmed et al., 2021; Kovačević et al., 2019; Singh & Verma, 2017). These characteristics can be significantly managed through a successful sizing procedure. Sizing reduces the yarn's hairiness, which refers to the quantity of protruding fibres, and boosts its abrasion resistance to friction. This improvement leads to lowered frictional force between adjacent warp threads as they are let off the beam and as they pass through the metal components of the weaving machine, subsequently helping to reduce the number of thread breaks during the weaving process on the loom (Gudlin & Kovaevi, 2012). Namely, sizing which serves as a crucial and intricate phase in the fabric manufacturing process contributes to enhance weaving machine performance and promotes energy conservation assisting to minimize adjacent warp thread friction and breakage. However,

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there exist several environmental drawbacks related to sizing process. Water usage and pollution, chemical utilization, energy consumption, generation of waste, and persistence of non-biodegradable materials in the environment are the main concerning drawbacks of the process (Palamutcu, 2015). Starch-based sizing agents, which are utilized for years, are amongst the most common sizing agents, where Polyvinyl alcohol (PVA) has emerged as an alternative to these starch-based agents. Conventional sizing agents, such as natural starches, starch derivatives, carboxymethyl cellulose (CMC), PVA, and polyacrylates size, can be applied individually or in combination depending on warp yarn type (Panda et al., 2021). It is worth emphasizing that the properties expected from a suitable sizing agent are film forming, adding improved adhesion ability to the substrate, providing flexibility, and easy removal from the substrate after weaving operation (Chen et al., 2013; Reddy et al., 2014). In addition, desizing process which involves removing sizing materials before the finishing and dyeing stages of textile production eliminates both subsequently added and naturally existing impurities in the fabrics. It is necessary to transform hydrophobic fibre-yarn-fabric surface into a hydrophilic one before employing any additional wet processing. To overcome the hydrophilic issues and enhance the adhesion and wettability of fabrics, both chemical and mechanical pretreatment procedures may be carried out. In this chapter, sizing process is mentioned in general and the negative effects of the sizing process on the environment are also remarked. Additionally, general information about conventionally used sizing agents is given. Sustainable approaches to sizing/desizing process are discussed in detail under the headings of sustainable innovations in sizing machines, optimization and development of green recipes, reusing of sizing/desizing chemicals, clean and dry technologies for sizing, and clean and dry technologies for textile desizing. Then, novel bio-based biodegradable sizing agents are examined with comprehensive literature review. Finally, future perspectives and trends analysis is made.

2 Environmental Impacts of Sizing/Desizing Process

Both sizing and desizing process requires large amounts of water and heat energy. The discharge of polluted water may cause water contamination unless adequately treated. It is reported that sizing and desizing process correspond to 30% of the water utilization process and produce a similar amount of effluents (Panda et al., 2021). In another study, it is reported that desizing process consumes a significant volume of water, accounting for approximately 40–50% of the total wastewater release of the plant (Palamutcu, 2017). In addition, sizing agents frequently comprise synthetic and natural polymers along with several auxiliary chemicals such as lubricants, softeners, and antistatic agents. The extensive utilization of chemicals can cause adverse environmental impacts including water pollution and soil contamination and may be hazardous to aquatic life. The contamination load of desizing effluent arises from the chemicals utilized in the recipes such as sizing agents themselves, enzymes, surfactants, or alkalis. It has been reported that starch-based sizing agents have chemical oxygen demand (COD) interval of 900–1200 mg O_2/g, where they have biochemical oxygen demand (BOD) interval of 500–600 mg O_2/g. On the other hand, PVA has been reported to have a COD of 1700 mg O_2/g and a BOD interval of 30–80 mg O_2/g. In a similar vein, polyacrylates exhibit a COD interval of 1350–1650 mg O_2/g, while exhibiting a low BOD of 50 mg O_2/g (Chen et al., 2013). Also, the sizing process demands energy for heating the size solution and drying the sized yarns. High energy consumption leads to an increment in greenhouse gas emissions and intensifies global warming. According to an estimation, the average specific electricity consumption for a warping and sizing plant was reported as 0.0073 kWh/kg warp yarn (Palamutcu, 2010). On the other hand, desizing process generates significant amounts of solid waste, including consumed sizing materials and yarn residues. If not managed correctly, these wastes have the possibility of creating further environmental problems. In addition, some sizing agents, particularly synthetic ones, have non-biodegradable nature. Such nature of these agents prompts them to persist in the environment for long periods, which causes ecological damage and contributes to microplastic pollution.

Decreasing heat energy utilization and the environmental impact of the sizing and desizing agents/auxiliary, there are two essential approaches to enhance sustainability aspect of both processes. The one is implementation of innovative approaches in sizing machinery, the other one is search of sustainable processes like optimization of green recipes. Other promising approaches are recycling and/or reusing of sizing/desizing chemicals and/or process water and adopting dry/clean technologies. On the other hand, an emerged sustainable deal is utilization of more sustainable sizing materials of bio-based biodegradable agents.

3 Conventionally Used Sizing Agents

Commonly utilized sizing chemical types including starch and its derivatives, carboxymethyl cellulose (CMC), and synthetic polymers like polyvinyl alcohol (PVA), and acrylic sizing agents are introduced with novel literature.

3.1 Starch

Starch, which is a natural polymer generated from plants such as corn, rice, and potatoes, is one of the oldest and most utilized sizing agents thanks to its low cost, accessibility, and biodegradability. Starch sizing agents are recognized for their film-forming and adhesion properties. However, these agents are considered to provide poor size quality because of several factors such as friable sizing layer and excessively high viscosity (Kabir & Haque, 2022; Xu et al., 2016). Starch can be used pure or in combination with other sizing agents, such as polyvinyl alcohol

(PVA) (Jiang et al., 2019). On the other hand, the price of starch has risen owing to increased demand of the other industries such as food and biofuel, which may be a drawback of this agent in textile sizing processes (Kabir & Haque, 2022; Xu et al., 2016).

3.2 Starch Derivatives

There exist various types of starch derivatives utilized as sizing agents such as carboxymethyl starch (CMS), hydroxyethyl starch (HES), and cationic starches. These derivatives are produced by processes such as etherification, esterification, or oxidation, which alter the chemical structure of starch to obtain desired properties (Yang & Reddy, 2013). These derivatives offer unique advantages over unmodified starch and other traditional sizing agents. CMS is a notable variety of modified starch. The addition of negatively charged functional group disrupts the orderly structure of native starch, which prevents reassociation of gelatinized starch. This modification results in a lower gelatinization temperature and increased solubility. Starch derivative sizing agents exhibit enhanced adhesion, film-forming, and abrasion resistance properties compared to unmodified starch. Starch derivative sizing agents can be applied to a wide range of fibres, including natural fibres like cotton and synthetic fibres (Kovačević et al., 2020; Zhang et al., 2015).

3.3 Polyvinyl Alcohol (PVA)

PVA is a synthetic, water-soluble polymer that exhibits excellent adhesion, film-forming, and abrasion resistance properties. Thanks to its water solubility, removing of PVA in desizing process is easier (Panda et al., 2021; Reddy et al., 2014). These sizing agents can be utilized for various types of fibres, including synthetic fibres and blended fibres, such as cotton/polyester fibres (Panda et al., 2021; Zhang & Li, 2003). Its adaptability enables PVA suitable for different textile applications. PVA may be used pure or in combination with other agents, like starch or CMC, which allows being tailor-made the sizing formulation for specific yarn types and weaving conditions (Hayes & Robinson, 1995; Morsi et al., 2019).

3.4 Carboxymethyl Cellulose (CMC)

CMC is a water-soluble derivative of cellulose. It exhibits excellent adhesion, film strength, and lubricity, making it suitable for wide range of fibres including natural fibres like cotton, silk, and linen, as well as synthetic fibres such as polyester and nylon. Additionally, CMC has good swelling and thickening properties, leading to better penetration of the sizing agent into the yarn structure. CMC can be used pure or in combination with other sizing agents, such as PVA or polyacrylates (Rahman et al., 2021; Sarkodie et al., 2023). This adaptability allows manufacturers to specialize the sizing formulation for specific yarn types and weaving conditions.

3.5 Acrylic Sizing Agent

Acrylic sizing agents comprise a variety of homopolymer, copolymer, or mixture of acrylic monomers. Major category of acrylic sizing agents consists of synthetic agents primarily made of acrylic esters. These sizing agents display outstanding adhesion to hydrophobic synthetic fibres and possess high deformability. There exist three main types of acrylic sizing agents including polyacrylates, polyacrylamid, and polymethyl acrylate. Polyacrylates, which are composed of acrylic acid or its derivatives, exhibit excellent adhesion to hydrophilic fibre, high moisture absorption, and strong stickiness viscosity. It is also reported that they display exceptional sizing performance when combined with a small proportion of modified starch. This compatibility allows the sizing formulation to be tailored to specific yarn types and weaving conditions, ensuring optimal performance. Polyacrylamide type has high moisture absorption capacity, adhesive viscosity, and good adhesion to hydrophilic fibre (Xiao & Zhang, 2009). Although acrylic sizing agents offer various benefits, their synthetic composition may cause some environmental issues. Additionally, their biodegradability may not be as high as natural agents, which can lead to microplastic contamination and other issues.

3.6 Wax

Wax-based sizing agents can be utilized pure or in combination with other agents such as starch, and PVA (Ahmed et al., 2021). To remove wax-based sizing agents from the fabric, solvents can be utilized or the wax can be melted at high temperatures during the desizing process (Goswami et al., 2004). The removal of wax-based sizing agents may require more heat energy and additional chemicals compared to water-soluble sizing agents like starch or polyacrylates, which contributes to the increment of energy consumption and waste generation.

4 Sustainable Approaches to Sizing/Desizing Process

Sustainable approaches to the sizing and desizing processes in the textile industry are becoming increasingly important as the industry shifts towards more eco-friendly practices. These approaches aim to reduce the environmental impact, energy consumption, and resource use associated with sizing and desizing. For this motive, key sustainable approaches can be stated as implementation of innovative technologies on sizing machines, optimization and development of green recipes, reusing of sizing/desizing chemicals, utilization of clean and dry technologies for both sizing and desizing processes, and utilization of bio-based biodegradable sizing agents.

4.1 Sustainable Innovations in Sizing Machines

A typical sizing machine is composed of numerous elements or parts, each with a specific role in the sizing operation. Even though the exact configuration can differ from machine to machine, the primary components generally include creel zone, saw box zone, drying zone, and head stock zone. The creel zone, a crucial part of the sizing machine, greatly influences the characteristics of the sized yarn. The zone involves numerous warper's beams, arranged in various configurations depending on the creel's design. Each warp sheet, originating from a warper's beam, unites to form the final warp sheet that navigates through the size box. As it moves through the size box, the warp sheet picks up size solution, retaining a portion of the solution after compression. The saw box zone is the section where the warp sheet is submerged in the sizing mixture and then subjected to intense pressure. This process ensures a consistent layer of sizing film that is applied across the yarn surface. Upon the application of the sizing mixture, the yarn is then passed over a sequence of heated cylinders, also known as drying cylinders. This process is intended to dry the sizing mixture and cover the surface of the yarn. Following the drying operation, the consolidated warp sheet is separated, allowing the yarns to regain their individual identity prior to being wound onto the weaver's beam (Singh & Verma, 2017).

Today, there exist emerged sustainable innovations that are developed and implemented in sizing machines. These innovations are mainly cantered about three key concepts: improving efficiency, reducing waste, and reducing energy consumption. For this motive, there are several approaches, such as designing energy-efficient machines, integration of water recycling systems, utilization of automatic sizing add-on control, adopting of digitization, and utilization of low liquor technology. New sizing machines are designed to be more energy-efficient, consuming less electricity and heat energy during process, which contribute to reduce the environmental impact (Sino Textile, 2021). Utilization of automatic size pick-up control technology enhances the sizing process by making automatic adjustments based on the yarn type and weaving requirements. Apart from typical sustainable advantages such as reduced wastage of sizing materials, simplifying of desizing, reduced wastewater load, this approach also brings about the quality development of the yarn after sizing, which may even lead to reduction of fabric waste (Pleva Sensors and Controls, 2019). According to a practical experience, it is reported that measuring the size add-on after size box constantly through microwave measurement system reduces by 20% of sizing agents, which brings along less COD load in wastewater

(Pleva Sensors and Controls, 2019). On the other hand, integrating water recycling systems to minimize water waste brings about clean and filters the water utilized in the sizing operation, which enables to reuse of processed water, thus diminishing the need for fresh water.

4.2 Optimization and Development of Green Recipes

Optimization works about sizing formulations to suit specific yarn types and weaving conditions can lead textile industry to a more efficient process implementation. By using the optimized recipe and consecutively reduced amount of sizing agent, it may become possible to decrease both amount of material waste and the environmental load associated with the desizing process.

4.3 Reusing of Sizing/Desizing Chemicals

Implementation of wastewater treatment and chemical recovery systems in sizing/desizing process has great importance in the textile industry due to the increasing importance of sustainability and environmental responsibility. After wastewater treatment, treated water can often be released into the environment or reused in certain cases, where chemicals can then be returned to original processes or used for another purpose after chemical recovery. Herein, wastewater treatment generally focuses on the cleaning of wastewater using physical, chemical, and biological processes, while chemical recovery systems focus on the collection, separation, and purification of waste chemicals. However, constructing a wastewater treatment facility can be quite complex and expensive due to the need to comply with strict government regulations. As such, implementing a chemical recovery system, which enables waste chemicals to reuse, becomes a compelling alternative to traditional wastewater treatment methods in the present day. Adopting a recycling system not only reduces the amount of wastewater generated, but it also provides the extraction of valuable chemicals from the system. However, research investigating the recycling of sizing chemicals, the characteristics of yarn sized with these recycled chemicals, and comparisons to yarn sized with conventional methods is still relatively scarce in the literature and industrial application (Maqsood et al., 2017). For this purpose, PVA is one of the mostly studied sizing agents to recover for reuse. Amongst a variety of treatment processes, ultrafiltration stands out as a conventional membrane separation technique for the recovering of PVA from waste streams, and subsequently facilitates the recycling of water for use in textile process. Maqsood et al. (2017) employed ultrafiltration reverse osmosis technology to recycle the sizing formula, which is composed of 50% recycled PVA and 50% fresh sizing ingredients. They observed that the yarns treated with the conventional sizing recipe exhibited marginally superior tensile strength and elongation compared to those treated with the recycled sizing recipe. On the other hand, it was observed that yarns treated with the recycled sizing recipe displayed better abrasion resistance compared to those treated with the conventional sizing recipe (Maqsood et al., 2017).

Yet, the major drawback of this method is the considerable reduction in flux due to concentration polarization at the surface of membrane utilized in wastewater treatment operation. Additionally, another drawback is fouling, which results from irreversible solute adsorption on the membrane surface and within the membrane pores. So far, the only known methods to restore fouled membranes involve back flushing or chemical cleaning, which disrupt the process but also increase its financial implications. To overcome such a drawback, several studies investigating novel ultrafiltration units such as spinning basket membrane (SBM) module are on-going (Sarkar et al., 2012).

4.4 Clean and Dry Technologies for Sizing

Clean and dry technologies for sizing are innovative approaches aimed at reducing the environmental impact and resource consumption associated with traditional sizing processes. These technologies focus on minimizing water, energy, and chemical usage while maintaining or improving expected sizing performance.

4.4.1 Plasma Treatment

Plasma technology offers a green alternative to conventional chemical treatment processes for modifying surface properties of fibres. Through physical modifications like chain scission, surface etching, and chemical modifications like grafting, cross-linking, and polymerization lead to changes in adhesion potential, wettability capacity, dyeing/printing efficiency, and biocompatibility properties of textile materials. Although plasma treatment has been utilized in textile processing for years, there exists quite limited investigation regarding the effect of plasma treatment on the sizing efficiency of warp yarns. It is reported that treatment time, gas flow rate, and jet-substrate distance are the key parameters that influence the efficiency of treatment (Sun et al., 2011). However, further investigation is essential to optimize this emerging technology for large-scale sizing applications. Sun et al. (2011) designed helium/O_2 atmospheric pressure plasma (APPJ) jet to examine how APPJ treatment affects both the wettability and sizing properties of warp yarn (Sun et al., 2011). They found that helium/O_2 APPJ treatment enhanced the sizing properties of cotton yarn. Sun et al. (2013) developed a sizing system that is a combination of atmospheric pressure plasma and green sizing recipes with glycerol (Sun et al., 2013). They observed that the designed system could improve size pick-up ratio, breaking strength, breaking elongation, and abrasion resistance values of warp yarns about 19.4%, 5.3%, 3.4%, and 169.2%, respectively, when compared to traditional sizing systems utilizing modified starch and PVA. In addition, it is reported that this approach led to a 59.3% reduction in the Zweigle hairiness index value at level 1.

4.4.2 Ultraviolet (UV) Irradiation

UV irradiation is a clean processing technique which is frequently utilized to modify textile surfaces. Investigations have shown that the surface morphology and chemical composition of textile materials, such as polyester, cotton, wool, carbon, and aramid fibre, can be altered after UV irradiation. For the UV treatment of cotton, the introduction of carboxyl groups on the surface of fibre has been reported. UV oxidation etching causes the degradation of cellulose, leading to an increment of roughness in cellulose fibres (Yan et al., 2022). Even though utilization of UV irradiation in textiles has centred around dyeing performance (Bhatti et al., 2014, 2016; Sadeghi-Kiakhani et al., 2020), it is expected that UV irradiation process may also be applicable for improvement of sizing process. Yan et al. (2022) investigated the wettability enhancement of cotton yarns through UV irradiation and proposed a technique for sizing. They observed that the abrasion resistance, breaking strength, and breaking elongation values of UV irradiation pre-treated sized yarns increased about the rate of 20.13%, 20.54%, and 103.49%, respectively, when compared to sized warp yarns without UV irradiation pre-treatment. In addition, 88.23% decrease in hairiness value was reported (Yan et al., 2022).

4.4.3 Foam Sizing

Foam sizing, an old technique, is an alternative to conventional wet sizing utilizing foam with the aim of minimizing wet pickup ratio and saving energy consumption during the drying process of warp yarn. This method promises to reduce water consumption and waste generation. Furthermore, foam sizing offers better manipulation of the application of sizing agents, causing a reduction in chemical usage, and providing more uniform sizing application. In this technique, a high concentrated size formula is mechanically foamed at room temperature and further applied to the yarns by an applicator, which is composed of a horizontal padder. As the foam collapses at the contact point of the padder, yarn is uniformly coated with a lower wet pickup. The add-on ratio is controlled by the blow ratio and the volume of solid existing in the sizing foam mixture. Reduction of wet pickup ratio, energy conservation, and increased production efficiency are the well-known advantages of the process. At low wet pickup rates, less number of bridging risks of yarns and lowered value of yam hairiness are the additional advantages of the technique (Namboodri, 1986). Parameters, such as foaming temperature, stirring speed of foam, the proportion of foaming agent, sizing recipe, and size concentration have significant roles in the process. Despite their importance, limited research has been carried out on these aspects of foam sizing and may be worthy of further investigation (Zhu et al., 2016).

4.4.4 Powder Sizing

Another old technique is powder sizing which involves applying a fine powder of sizing agent to the yarns, followed by heat treatment to melt the powder and form a continuous film on the substrate. This process is a non-aqueous technique where a polymer-sizing agent is applied to a yarn that passes through a fluidized bed of powdered polymer, followed by on-the-spot melting and air cooling. It is reported that yarns treated with a water-soluble polyester-based polymer demonstrated decreased hairiness and a lower occurrence of fabric stitching defects during weaving experiments (Nason, 1988). This method eliminates the need for water as a carrier medium; therefore, it becomes possible to reduce water consumption and wastewater generation.

4.5 Clean and Dry Technologies for Textile Desizing

Clean and dry technologies for textile desizing are designed to reduce the environmental impact and resource consumption volume of traditional desizing process. These cutting-edge approaches focus on reducing water, energy, and chemical consumption while maintaining or improving the effectiveness of desizing process.

4.5.1 Plasma Treatment

Atmospheric pressure plasma treatment has been utilized to modify starch-sized cotton fabric. This treatment changes the surface morphology, creates desizing effect, and enhances wicking and wettability properties of the fabric. Plasma particles interact with the fibre surface, breaking bonds in the sizing agents, which are further eliminated during washing. The increased surface roughness and the presence of functional groups like –OH, –C=O, and C–N lead to enhance hydrophilic characteristics in the fabric. Plasma treatment's accelerated desizing rate results in energy, time, and water savings compared to the regular desizing process (Saleem et al., 2021). Plasma parameters, including plasma voltage, plasma duty cycle, and gas flow rate, have been found to influential factors on the physical properties of textiles such as impurity elimination, whiteness, capillary action, fabric tensile strength, and fabric breaking elongation (Wang et al., 2019). Desizing process of 100% cotton fabric, sized with PVA, has been accomplished using atmospheric plasma treatment with air/helium/oxygen and air/helium mixtures. Surficial chemical modifications, including chain breakage and the development of polar groups, contribute to improving the solubility of PVA in cold water. The air/helium/oxygen plasma mixture was found more substantial impact on PVA desizing than the application of air/helium mixture, due to increased surface oxidation during the air/helium/oxygen plasma treatment (Cai et al., 2003).

4.5.2 Ultrasound-Assisted Desizing

Using ultrasonic energy, ultrasound-assisted desizing facilitates elimination of sizing agents from fabric. Ultrasonic energy can be performed in alone or combination with an enzymatic desizing process to enhance desizing performance of 100% cotton fabric (Şahinbaşkan & Kahraman, 2011). The introduction of ultrasonic energy into fluids results in two main phenomena: heat generation and cavitation. The formation and subsequent collapse of bubbles produced by ultrasonic waves are generally attributed to the bulk of ultrasound's physical and chemical impacts on solid/liquid or liquid/liquid systems. Furthermore, the intense turbulence of the liquid border layer caused by cavitation considerably boosts the movement of sizable enzyme molecules to the fibre surface, leading to an increased overall reaction speed (Thakore & Abate, 2017; Wang et al., 2012). Various process parameters such as ultrasonic power, enzyme concentration, time, temperature, and pH value may be influential on the enzymatic desizing process (Wang et al., 2012). This technique decreases the consumption of water and chemicals, accelerates the desizing procedure, and leads to reduced energy consumption and diminished wastewater production. The utilization of ultrasonic energy can aid in the distribution and penetration of enzymes into the fabric surface and minimize agglomeration of enzyme molecules providing more efficient removal of sizing agents. This integrated approach may result in reduced water consumption and chemical usage, quicker processing durations, and decreased energy demands (Şahinbaşkan & Kahraman, 2011). Also, it is possible to apply ultrasonic waves in a combined process including desizing, scouring, and bleaching (Thakore & Abate, 2017).

4.5.3 Supercritical Carbon Dioxide (CO_2) Desizing

Supercritical fluids (SCFs) are unique substances with distinct physicochemical properties that make them suitable for various applications in physical and chemical processing. In recent years, SCFs, especially supercritical carbon dioxide ($scCO_2$), have seen widespread use in extraction, separation, and purification within the food and pharmaceutical industries. Moreover, SCF technology is gaining attraction in petrochemical and textile sectors. $scCO_2$ mainly acts as a non-polar solvent, which limits its effectiveness in extracting polar solutes and high molecular weight non-polar solutes. To overcome this limitation, co-solvents, typically polar organic solvents like short-chain alcohols, esters, and ketones, can be incorporated to improve $scCO_2$ solubility. Ethanol is considered a promising co-solvent because of its low toxicity and compatibility with $scCO_2$. Previous research on $scCO_2$ has demonstrated that $scCO_2$ is a promising agent for various fabric treatment processes like dyeing and finishing. This includes environmentally friendly pre-treatments like sizing, desizing, and bleaching of cotton, as well as degumming of silk fibres and scouring of polyester, nylon, flax, and wool (Ghanayem & Okubayashi, 2021). Utilizing $scCO_2$ for desizing employs CO_2 in its supercritical state to dissolve and extract sizing agents from surface of sized fabrics. This approach can eliminate the requirement for water and diminishes the use of chemicals. Utilization of $scCO_2$ as a waterless technique creates no wastewater and eliminates the need for energy in drying process of fabrics. Nevertheless, implementing this method necessitates specialized machinery so far and could also entail greater upfront expenses.

4.5.4 Ozone Treatment

Ozone treatment represents an emerging cutting-edge, environmentally friendly desizing technique that employs ozone gas to oxidize and decompose sizing agents from the surface of fabrics. This approach can be employed as a dry or semi-dry procedure, thereby decreasing water and chemical auxiliary consumption. Also, ozone treatment provides additional advantages, such as disinfection and colour removal, which enhance the overall effectiveness of textile processing. Amongst the ozone-assisted pretreatments, bleaching is overwhelmingly prominent in the literature (Ben Hamida et al., 2017; Erdem & İbrahim Bahtiyari, 2018; Paksoy et al., 2020). Ozone functions as a potent oxidizing agent capable of oxidizing organic and inorganic impurities. This reaction involves various intermediate compounds such as peroxides, epoxides, perhydroxyl, and hydroxyl radicals. Some of these intermediates play a role in the bleaching process. Ozone molecules can react in mildly alkaline (pH 9), acidic, and neutral solutions (Panda et al., 2021). However, there exist some studies that investigate a combined process of fabric bleaching and desizing. According to a study on desizing/bleaching of 100% cotton towel fabrics, ozone desizing achieved a specific level of hydrophilicity in towel fabric. However, it was observed that the water absorption attained through traditional desizing processes cannot be fully replicated using this method (Turhan & Soydaş, 2018).

4.5.5 Microwave-Assisted Desizing

Microwave technology has been explored and utilized in variety of textile processes. Microwaves typically have an upper frequency limit of about 300 GHz. Polar substances, such as water, are heated by microwaves through dipole rotation and ionic conduction. Orientation polarization occurs when the dipoles in dielectric materials, like water, reorient themselves under an alternating electric field. In an alternating electric field at microwave frequencies, molecules try to align themselves, leading to intermolecular friction and high speed of back-and-forth molecular movement. This activity generates a substantial amount of heat for quick heating of the textile material. When microwave energy is applied to a material, it disperses evenly, creating heat throughout the entire volume. This volumetric heating enhances the diffusion rate, shortens processing time, and consumes less energy compared to conductive heating (Panda et al., 2021). Using microwave energy in desizing processes involves heating the fabric to facilitate deterioration of sizing agents. This technique can reduce water and chemical consumption while shortening the desizing duration, leading to reduced energy requirements. It is reported that a combined process including desizing, scouring, and bleaching could be completed in 5 min thanks to microwave assistance, achieving the same level of pre-treatment as conventional procedure (Hashem et al., 2014). Microwave-assisted desizing process is reported especially effective when targeting water-soluble and temperature-sensitive sizing agents.

5 Novel Bio-based Biodegradable Sizing Agents

Protein-based or polysaccharide-based sizing agents, such as wheat gluten, corn gluten, dried grains, soy protein, keratin, collagen, casein, chitosan, and alginate, have emerged as potential sizing agents favouring their adhesion performance, film-forming ability, reasonable abrasion resistant characteristics, and biodegradable nature (Xu et al., 2019; Yang et al., 2017; Zhao et al., 2015). One of the earlier work reports that some agents, including soy protein, wheat gluten, and keratin, without modification, resulted in fragile coatings and demonstrated inadequate adhesion to polyester and polyester/cotton yarns, consequently failing to protect warp yarns during high speed weaving operations (Zhao et al., 2015). To cope with such challenges, researchers are focused on process and recipe optimization with modified sizing agents and also combination of novel agents with other conventional sizing agents. These proteins can be utilized in pure or combination with other sizing agents such as starch. In case of combination with starch, it is reported that adding proteins into starch sizing decreases surface tension providing improved wettability of fibre surface, and enhancement at fibre adhesion degree (Sarkodie et al., 2023).

Reddy et al. (2013) proposed a sustainable sizing agent corn distillers dried grains DDGS on cotton, polyester, and polyester/cotton blends. It was concluded that DDGS displayed better abrasion resistance when compared to PVA (Reddy et al., 2013).

Soy protein is another applicable bio-based biodegradable sizing agent. Soy protein is a biodegradable and renewable material originating from soybeans. It has gained attention as a potential sizing agent because of its film-forming and adhesion properties. This novel agent creates a protective layer on the warp yarn surface, reducing friction force and number of warp yarn breakage during weaving process. Additionally, soy protein has water-soluble nature, which simplifies desizing process and lowers the need for aggressive chemicals. Because it is a plant-based, sustainable resource, soy protein utilization can minimize the environmental impact of sizing process. Chen et al. (2013) investigated soy proteins as sizing agents to replace PVA. They found that soy protein displayed a better enhancement in yarn strength and abrasion resistance as compared to PVA sizing agent (Chen et al., 2013).

Zhao et al. (2015) investigated whether soy protein, when modified with specific additives, including diethanolamine, triethanolamine (TEA), ethanolamine, propanolamine, butanolamine, and glycerol, could replace PVA sizing agents for high-speed weaving processes for polyester and polyester/cotton yarns. They observed that additives with multiple hydroxyl groups, non-linear molecular structure, and electrical charge could physically alter the secondary structure of soy protein, which leads to an approximate improvement of 23.6% and 43.3% in sizing adhesion and capacity for hair coverage, respectively, compared to unmodified soy protein. Also, it is concluded that industrial weaving trials revealed that TEA-modified soy protein demonstrated a relative weaving efficiency that was 3% and 10% higher than PVA and chemically modified starch sizing agents on polyester/cotton fabrics, respectively. Another extracted conclusion is that modified soy protein displayed a relative weaving efficiency similar to PVA on polyester fabrics, despite a 3–6% lower add-on (Zhao et al., 2015).

One of the latest study reports that additives with hydroxyl groups, non-linear molecules, and electric charges can be used to physically alter soy protein's structure. Triethanolamine-modified soy protein, known for its potent adhesive property, has emerged as an alternative to synthetic sizing agents like poly(vinyl alcohol). By employing plasticizing agents such as polyols and amines, which share chemical structures with proteins, intermolecular hydrogen bonds can be disrupted, leading to enhanced protein sizing performance (Sarkodie et al., 2023).

Keratin has been explored as another applicable sizing agent. Its unique properties, including adhesion and film-forming abilities, enable it as an attractive option for conventional agents. Moreover, keratin is biodegradable and can be obtained from by-products like poultry feathers or animal hair, making it an environmentally friendly alternative to synthetic sizing agents. Utilization of keratin also encourages a circular economy by up-cycling of waste materials. However, keratin may require working conditions with high add-on. It was stated as polyester/cotton rovings treated with feather keratin exhibited comparable or greater tensile strength to those treated with PVA sizing agents albeit at a slightly increased add-on percentage. Besides, the highest strength that PVA provided on polyester/cotton rovings is reported as 176 N at an add-on of 10%, while keratin agent provided a highest strength of 217 N at an add-on of 18%, but the strength was somewhat diminished (111 N) at an add-on of 10%. On the other hand, it is reported that the abrasion resistance of polyester fabrics processed with keratin size display a significant increase, while the abrasion resistance of polyester/cotton fabrics processed with keratin size display lower compared to those treated with PVA. It is worth noting that when treated with keratin even at add-on rate of 1.9%, the polyester fabrics have significantly improved abrasion resistance, withstanding up to 660 cycles (Reddy et al., 2014).

Another emerging sustainable sizing agent is collagen. Collagen can be derived from a variety of sources including animal by-products like hides, bones, and fish scales. Using these waste materials encourages a circular economy and reduces waste materials. Furthermore, biodegradable characteristics of collagen pose less of an environmental impact when compared to synthetic sizing agents. Also, collagen does not penetrate the yarn and remains on the fibre surface, which may bring about easy removal from the yarn during preparation of textile material for chemical process. In the starch-sizing process, a portion of the starch penetrates the cellulose fibre walls. This results in an excessive use of sizing material, can cause an unnecessary increase in the yarn's linear density, and leads to failure to fully eliminate starch from the woven fabric. However, when collagen sizing solution is used, it enhances the fibre and yarn's morphology, causing the fibres to become more elongated. The collagen sizing layer is only located on the surface of the cotton fibres and doesn't infiltrate the space between the fibres (Rafikov et al., 2020). Rafikov et al. (2020) observed that collagen-based sizing improved microstructure and morphology of cellulose fibres, which decrease sizing agent consumption. They also concluded a 25–35% increase in yarn breaking load and 15–20% reduction in yarn breaking elongation (Rafikov et al., 2020). Rafikov et al. (2020) designed a three-in-one system which is composed of sizing, grafting, and fire-retardant treatment using a collagen solution for cotton yarns. They observed that yarn breaking load increased, where elongation of the yarns decreased by 56% (Rafikov et al., 2020).

Casein, which is a milk protein, has biodegradable nature and exhibits film-forming and adhesion properties on fibre surface. Casein protein having various uses such as coating and adhesive should also be explored as a sizing agent for textile fibres, offering an environmental friendly alternative to synthetic sizing agents (Audic et al., 2003).

Another potential bio-based biodegradable sizing agent is chitosan. Chitosan, polysaccharide-based, is derived from chitin, a natural polymer found in the shells of crustaceans. Stegmaier et al. (2008) reported the biodegradability of chitosan at levels between 80 and 92% after a 28-day period (Stegmaier et al., 2008). Chitosan can be a potential substitute for synthetic sizing agents. With its film-forming and adhesion properties, chitosan has been explored as a potential sizing agent for cellulose-based fibres such as cotton and viscose. Also, it may be utilized to achieve new functionalities in the resulting product such as wound-healing and bacteriostatic characteristics (Stegmaier et al., 2008).

Alginate is another polysaccharide-based natural polymer which is derived from algae species. It consists of β-D-mannuronic acid. Although chemically derived alginic acid does not have solubility in water, its sodium derivative is soluble in water. When dissolved in water, it creates an aqueous solution with a low concentration but high viscosity, making it suitable for sizing cotton and viscose fibre. However, its widespread utilization has diminished because of its high price and weak performance (Patil & Athalye, 2022).

6 Conclusion

Sustainability studies on the sizing and desizing segments, which is one of the most necessary and complex segments of the textile production line, do not take as much attention as the necessity of the sustainable alerted world. However, there are remarkable studies investigating energy efficient and less resource consumption concepts on sizing/desizing processes. These studies are centered about different approaches stated as below. Sizing machine manufacturers try best for energy efficient and less waste water/chemical generated technologies. On the other hand, optimization and development of green recipes is an open subject for research.

Some researchers focus on reusing or recycling both of sizing/desizing chemicals and wastewater. Dry and clean approaches, other innovative methods, contribute to more environmental friendly textile manufacturing by decreasing water, energy, and chemical usage. Main clean and dry-sizing technologies are plasma treatment and UV irradiation. For desizing, ultrasound-assisted desizing, supercritical CO_2 desizing, ozone treatment, and microwave-assisted desizing may be promising key methods. Utilization of bio-based and biodegradable sizing agents, such as wheat gluten, corn gluten, dried grains, soy protein, keratin, collagen, casein, chitosan, and alginate can offer several benefits of biodegradable nature and film forming. By employing these agents, textile manufacturers can contribute to reduction on waste generation, chemical auxiliary consumption, and water contamination. Although there is a considerable amount of work and study on the above-mentioned approaches, more effort should be made to bring the sizing/desizing performance to a level comparable to conventional methods. Also, adaptation of these approaches for sizing and desizing in the textile industry requires persistent research and development efforts to enhance their efficacy and scalability. By incorporating these approaches, textile manufacturers can contribute to a greener and more resource-efficient world.

7 Future Perspectives and Trends

The future perspectives and trends in sustainable approaches for textile sizing/desizing are expected to focus on several key areas. Progressive research and development (R&D) attempts will be vital for refining and optimizing these technologies. R&D activities for sustainable innovations in machinery will include more efficient heating mechanisms, enhanced machinery drive systems and energy recovery mechanisms, integration of water recycling and reusing systems, precision systems to minimize size wastage, developing size recovery and reuse systems, intelligent control systems, predictive maintenance systems, and designing less maintenance required systems. On the other hand, R&D activities for reusing of sizing/desizing chemicals will include the implementation of new technologies and methods for the recovering and reusing of chemicals used in the sizing and desizing processes. This could involve developing enhanced techniques for separation and purification of these chemicals, enabling them to be reused more efficiently. R&D activities for bio-based and biodegradable sizing agents will include exploring novel alternatives to conventional agents, improving their sizing performance, and ensuring their adaptability with a several fibre types and processes. Similarly, R&D activities for dry and clean technologies will include enhancing effectiveness, ensuring adaptability with various fibre types, combining with bio-based biodegradable sizing agents, and lowering costs. In the case of bio-based and biodegradable sizing agents, there will be a tendency to design customized solutions for specific fibre types.

On the other hand, in order to develop implementation of these sustainable approaches, collaborations will be inevitable amongst textile manufacturers, researchers, and technology providers. Such an attempt will promote knowledge exchange, technology transfer, and enhancement approaches for a sustainable textile manufacturing line. As environmental concerns are grooving associated with textile industry, demand for sustainable products and manufacturing methods will be rise. This trend will shift the manufacturers to adopt usage of bio-based and biodegradable sizing agents and dry and clean technologies to fulfil expectations of environmentally alerted consumers. Additionally, implementation of sector-specific international rules and standards concerning sustainable approaches would motivate and lead textile manufacturers to be aware of their responsibility in manufacturing processes.

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Recent Trends in Sustainable Clothing and Textile Manufacturing

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1 Introduction

Clothing and textile manufacturing involves a complex network of organisations such as fibre producers, yarn manufacturers, fabric manufacturers, fabric processing units, and garment manufacturers (Nayak & Padhye, 2015a). Textile fibres are the basic raw materials needed to manufacture clothing and textiles. The fibres can be obtained from natural sources or can be extracted from petroleum sources, hence, known as natural fibres and synthetic fibres, respectively (Kozłowski & Mackiewicz-Talarczyk, 2020). Natural fibres can be obtained from plants (i.e., plant fibres) or animals (animal fibres); whereas synthetic fibres can be manufactured from fossil fuel and natural polymers such as wood (regenerated fibres).

Manufacturing of each of these fibre types has their own impact on the planet. For example, growing of cotton fibres uses significant quantities of chemical fertilisers and water. Growing 1 kilogram of cotton fibre may need up to 20,000 L of water (Fletcher, 2013; Nayak et al., 2023). Hence, the harvesting of natural fibre (i.e., cotton) pollutes the planet in addition to being resource intensive. Although the manufacturing of synthetic fibres does not need chemical fertilisers and large volume of water, the energy consumption is significantly higher. For example, manufacturing of polyester fibres consumes about 369–432 MJ/kg of energy (Nayak, 2022). The energy or electricity is produced mainly by the thermal power, which is generated from coal. The thermal power stations generate large quantities of

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greenhouse gases. Similar to natural fibre production, the synthetic fibre production also pollutes the planet.

Yarn and fabric production also causes environmental pollution. The manufacturing processes for yarns such as ring spinning and open-end spinning consume a significant amount of energy (Nayak, 2019b). The maximum energy is used in the ring spinning process as it involves more steps than the other processes. Rotor and airjet spinning processes are more energy efficient compared to ring spinning due to lower number of steps. Spinning processes also produce significant amount of solid waste mixed with some reusable fibres. Fabric manufacturing can be done mainly by two processes: weaving and knitting, in addition to a third process, nonwoven. Weaving process is more energy intensive than knitting due to requirements of additional steps (such as warping, sizing, and desizing) for weaving. Nonwoven fabrics consume the least amount of energy as fibres can be directly used to make the final product eliminating several steps.

Fabric chemical processing is the major cause of environmental pollution amongst all the processes used for clothing and textile production (Khan et al., 2022). Processes such as scouring, bleaching, mercerisation, and dyeing need significant amount of water, which are finally discarded as wastewater or effluent to the water courses. The wastewater contains several harmful chemicals that are dangerous to aquatic animals. Dyeing process using various synthetic dyes is the major source of chemical pollution (Khattab et al., 2020). In a dyeing process, significant amount of unused dye is exhausted with the effluent to the water courses. Approximately, 20% of the global water pollution is caused by the textile chemical processing, which is the highest amongst the other processes. The fabric chemical processing also involves use of significant amount of energy, which leads to environmental pollution. Figure 1 indicates various environmental impacts of clothing and textile manufacturing.

Clothing manufacturing is the last step where the 2D fabric is converted into 3D garments (Nayak & Padhye, 2015a). In addition to high energy consumption, clothing manufacturing is also labour intensive. Furthermore, large amount of waste is also produced during clothing manufacturing. For example, in a marker planning process, 15–20% of the fabric is wasted as per the marker efficiency. Majority of the clothing and textile manufacturers are located in developing countries, where the legal aspects are not strictly followed. Hence, the manufactures take advantage of the situation and discharge hazardous pollutants to the air and water, leading to large-scale environmental pollution.

In this chapter, various environmental aspects of "sustainable clothing production" in relation to technology upgradation and use of eco-friendly processes in garment manufacturing have been broadly discussed. Using existing data from a variety of resources, and authors' own knowledge, this chapter also discusses the approaches taken by clothing manufacturers in waste management and recycling of hard waste. The use of new processes for chemical processing (such as enzyme application, natural dyeing, and digital printing) and clothing manufacturing (energy saving, waste reduction by the application of lean concepts) to achieve environmental sustainability has also been discussed.

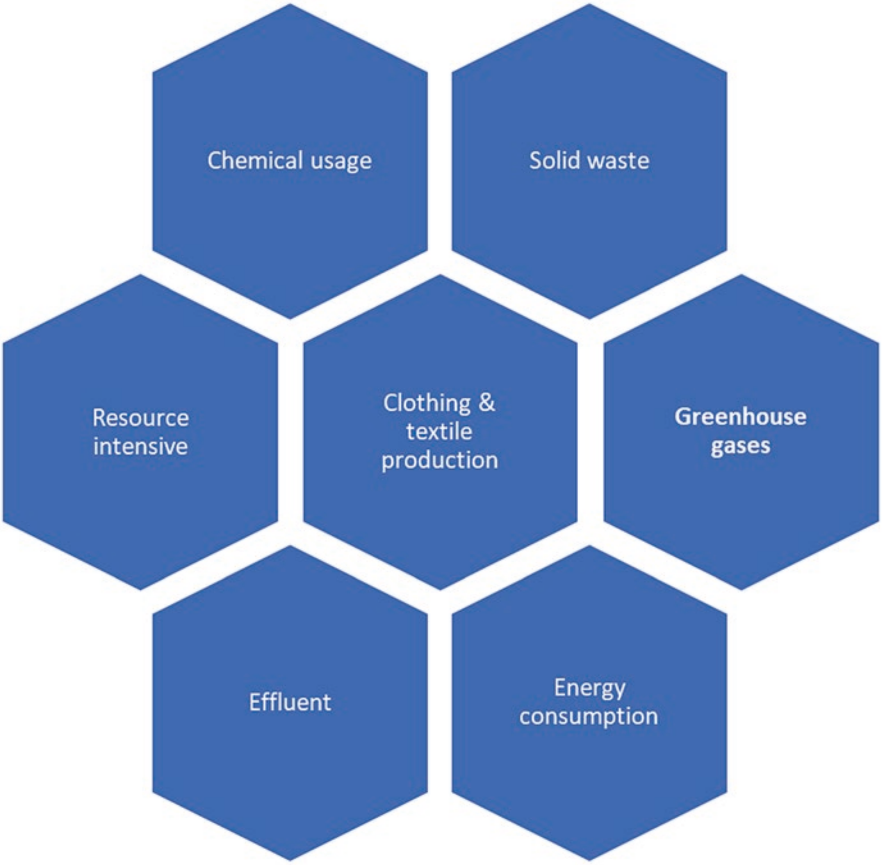

Fig. 1 Various environmental impacts of clothing and textile manufacturing

2 Sustainable Steps in Sewing

Sustainable clothing manufacturing involves various steps that are used to reduce the environmental impacts. Some of the steps include renewable and biodegradable raw material selection, eco-friendly manufacturing processes, green logistics, waste management, and ethical manufacturing practices (Shen et al., 2014; Choudhury, 2014; Nayak et al., 2020b). Furthermore, emerging technologies such as laser, ozone, radio frequency identification (RFID), enzyme applications, and carbon dioxide (CO_2) dyeing are also being used for sustainable clothing manufacturing (Xing et al., 2007; Mahltig et al., 2004; Dubas et al., 2006; Gomes et al., 2013).

Cost competitiveness and globalisation have resulted in shifting of clothing manufacturing from developed countries to developing countries (Nayak et al., 2019). Several clothing and textile manufacturers in the developing countries are equipped with machineries based on traditional technologies. The traditional technologies are energy intensive and produce products with lower productivity. In order to be sustainable, the clothing manufacturers should use energy-efficient tools in spreading, cutting, sewing, and ironing. Furthermore, training of employees on energy efficiency and productivity in addition to using eco-friendly processes can also lead to reduced environmental impacts (Aakko & Koskennurmi-Sivonen, 2013).

To evaluate the environmental footprint (EF) of clothing manufacturing plants, Herva et al. (2008) developed a useful tool. The tool can collect data relating to energy, resources, and waste from various clothing industries. These data can be used to evaluate the environmental footprint of various processes and compare the results. As materials are the main elements in clothing manufacturing, it was discovered that the resources category contributed the most to the final EF (91.33%). Waste accounted for the least amount of contribution (3.35%), while energy usage came in second (5.32%).

The resource or raw material constitutes about 50–80% of the clothing components (Singh & Nijhar, 2015). Hence, the selection of appropriate raw materials is the most impacting step toward the carbon footprint (CFP). The second-most impacting factor is the extensive energy consumption followed by the waste generation. As many developed countries rely on thermal energy source, the CFP of burning coal has been found to be the maximum. Approaches such as energy saving (by technology upgradation, employee's training, use of eco-friendly processes) and waste management (by lean concepts, reducing and recycling waste) can be adopted to achieve sustainability.

The conventional clothing manufacturing practices based on the non-renewable energy sources (such as coal or petroleum source) are unsustainable due to their limited availability and generation of large amount of waste that creates environmental burden (Gwilt, 2011). In the clothing manufacturing industries, electricity is the major source of energy, which is used to drive various machinery, controlling temperature, lighting, and running office equipment. Generally, coal, wood, and fossil fuel are widely used to generate steam for various processes in clothing manufacturing. These processes produce large amount of carbon dioxide and other greenhouses gases. Some industries are shifting to biomass as an alternate source of renewable energy.

Some strategies for saving the usage of water and electricity include using waterless techniques, energy-efficient processes, and renewable energy, which can help to become sustainable in clothing manufacturing (Niinimäki & Hassi, 2011). Figure 2 shows the steps followed in a clothing manufacturing industry, with the indication of energy usage and waste generation. Focusing on these steps to reduce energy consumption and waste generation can reduce total environmental impacts.

2.1 Technology Upgradation

As mentioned earlier, many of the garment industries in developing countries are small and medium-sized enterprises (SMEs) based on the use of traditional technologies (Nayak et al., 2020c). Gereffi and Memedovic (2003) mentioned that the

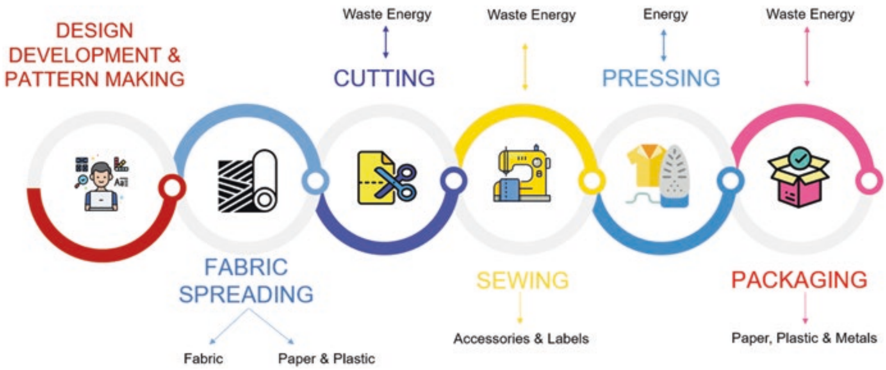

Fig. 2 Flow chart showing various steps in garment manufacturing

productivity in Bangladesh is around 50% lower than China due to the use of traditional technologies in Bangladesh. Similar reports have been published in Vietnam and Sri Lankan garment industries (Knutsen, 2004). The use of traditional technologies has disadvantages such as low productivity, poor-quality, high-energy usage, and higher lead time. In many developing countries, the garment production is featured by low wages, unskilled workers, and sweatshop working conditions (Scott, 2006).

A recent publication by Nayak and Padhye (2018) reported that the garment industries around the world are switching towards automation in the garment manufacturing process. Automation can help in reducing the human intervention, improve the process efficiency and quality consistency of products (Jana, 2018). There are two types of technological advancements such as hardware technologies and software technologies. The hardware technologies include automation in spreading and cutting, semi-automatic sewing, robotics-assisted material handling, and technology-assisted quality control. Similarly, the software technologies include various software such as computer-aided design (CAD), computer-aided manufacturing (CAM), enterprise resource planning (ERP) software, and other software for inventory management (Kumar et al., 1999; Nayak & Padhye, 2018). Some of the new technologies such as RFID and IoT (Internet Of Things) are based on two types of technologies.

2.1.1 Application of Laser

LASER (Light Amplification by Stimulated Emission of Radiation) is a form of electromagnetic radiation produced by changing the energy states within the atoms of certain materials. There has been increased use of laser in the clothing manufacturing sector since the nineteenth century. Various laser applications in clothing manufacturing included laser-cutting; welded garment production (Hung et al., 2020); 3D-body scanning (Lee & Xu, 2020); designing, engraving, and creating various effects in denim (such as patterns, whiskering, and turnout effects) (Nayak et al., 2022c).

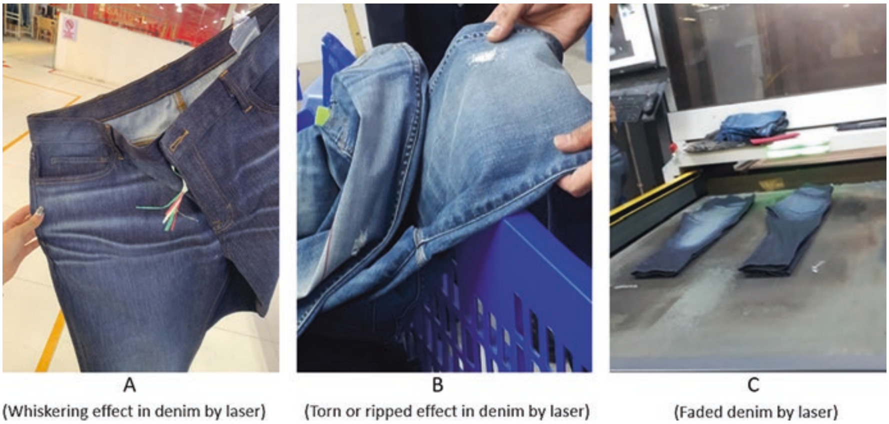

Fig. 3 Some effects produced by applying laser in denim garments

Laser technique is waterless; hence, it is free from the negative environmental impacts of the traditional techniques, which uses large amount of water (Kan, 2014). One such example is the replacement of the traditional denim washing with laser technology for fading denim colour (Nayak et al., 2008). Generally, denim is subjected to chemical washing for fading colour, which has significant amount of environmental impact as the effluent is discharged to the ecosystem. Use of laser can eliminate the environmental problems associated with traditional techniques. Furthermore, laser fading consumes less energy and produces more intrinsic designs. Recently, the denim engraving with laser has emerged, in which the use of lasers replaces previous denim engraving technologies, the resulting in a sophisticated level (Nayak et al., 2022c). Hence, the application of laser in denim combines low cost with better performance and eliminates the use of large volumes of water leading to environmental pollution. Some of the applications of laser in denim manufacturing are shown in Fig. 3.

2.1.2 RFID and Sustainability

Radio frequency identification (RFID) is based on radio waves to automatically identify objects or animals (Nayak et al., 2007; Rekik et al., 2008). In the drive towards sustainability, RFID is gaining popularity to track and trace products in the manufacturing and distribution process. The use of barcode technology can be completely replaced with RFID in several clothing and textile applications (Nayak, 2019a). RFID technology can be implemented to achieve the TBL of sustainability. For example, improved inventory management, increased data accuracy, reduced waste, and reduced shrinkage are some of the benefits relating to environmental sustainability (Denuwara et al., 2019).

For any product, traceability and brand transparency are the major drivers of sustainability in order to reduce the carbon footprints and/or exploitation of labour. With this technology, people can scan the bar code which is printed on every product and get all information regarding who made, where it was made and about materials, production processes, and work policies. These tags spread awareness amongst consumers by being transparent about their products and how they are made, from start to finish, and they can thus have a complete overview of the product they are about to buy and make an informed decision. At the same time, companies develop a strong relationship with their customers by reinforcing the loyalty of brand. On the other hand, traceability is the ability to track a product throughout its entire life cycle, from raw material stage to the finished product stage.

The use of RFID technology can help to reduce human intervention as it is a contactless technique (Nayak et al., 2015). Unlike bar tags, RFID does not need scanning of objects at point of sight; hence, the amount of labour is significantly reduced. The RFID tags can store larger amount of data compared to barcodes and can work from longer distances. The global fashion brands are using RFID technology in several applications during clothing manufacturing and retailing process. Some major applications of RFID technology include identifying objects, monitoring movement of goods, stock update, inventory management, reducing retail shrinkage, and material requirements planning (Nayak, 2019a).

The major reason for the popularity of RFID technology is the availability of instantaneous and accurate information on the amount of inventory (Nayak et al., 2022a). The application of RFID technology can help to improve the productivity and efficiency, hence, streamline the manufacturing processes. Furthermore, it can be used to avoid stock-out situations or overstocking inventory in retailing operations. Therefore, the cash loss involved with the stock-out and overstock situations can be reduced with the help of RFID. From the above discussions, it is clear that the application of RFID can help to improve the profitability of fashion enterprises in the arena of rising labour and material prices.

2.1.3 Carbon Dioxide Colouration

The traditional textile colouration process has significantly high environmental impact due to use of several synthetic dyes in the water medium. However, the use of carbon dioxide (CO_2) in dyeing reduces the water consumption; hence, it is considered to be a sustainable process (Abou Elmaaty & Abd El-Aziz, 2018). Supercritical carbon dioxide ($scCO_2$) has density similar to liquids and viscosity similar to gas, which helps in dyeing. As shown in Fig. 4, the $scCO_2$ dyeing can be performed at a temperature of 31.1 °C and pressure of 73.8 bar. This process is eco-friendly, non-hazardous, non-toxic, and chemically inert under several conditions. This is a new technology of sustainable dyeing without water and no effluents and a shorter dyeing time. The carbon dioxide used in this process has the advantage of being non-toxic and can be recycled to a very high degree.

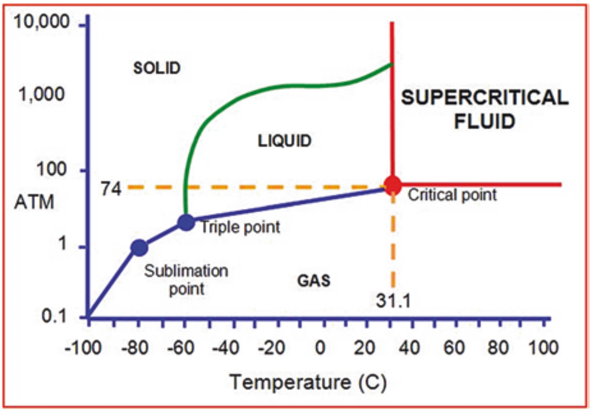

Fig. 4 Phase diagram for carbon dioxide. (Source: Anonymous, 2017)

The major advantage is the scCO_2 dyeing can be applied to the dyeing of polyester, which is hard to dye in the conventional dyeing processes (De Giorgi et al., 2000). This technology can also be used for dyeing cotton fibres with reactive disperse dyes (Özcan et al., 1998), polyester/cotton blended fabrics with reactive and disperse dyes (Maeda et al., 2004), and other natural fibres (Schmidt et al., 2003). The commercial process of dyeing fabric with scCO_2 is known as DyeCoo, where powder dye is inserted into the fabric using CO_2 (Anonymous, 2015). DyeCoo is a waterless technique that reduces energy consumption, which results in more than 98% dye-uptake and reduces chemical consumption by 50% compared to the traditional processes.

2.1.4 Air Dye

Air dye is a breakthrough technology in dyeing industry which uses air instead of water as a dyeing medium (Dhanabalan et al., 2015). The dye is applied through air medium in a jet dyeing machine, which can save water usage, reduce chemicals and effluent problems. Air dye involves the direct transfer of dye into the fabric using specialised machines, which uses reduced energy, and has lower environmental impact. Air dye is a sustainable dyeing technique as it is free from the problems of effluent generation and treatment.

Unlike the traditional dyeing methods, air dye technique saves water courses from getting polluted with the chemicals. In this technology, textile substrates can be dyed and printed by using a single machine as there is no need for steaming, washing, and drying; hence, it saves a significant amount of resources such as water and energy. This technology can be applied to a range of fabrics such as woven and knits. Air dye technology can save up to 95% water and 86% energy usage and reduces the GHG by 84%. While preparing a single garment, up to 170 L of water can be saved.

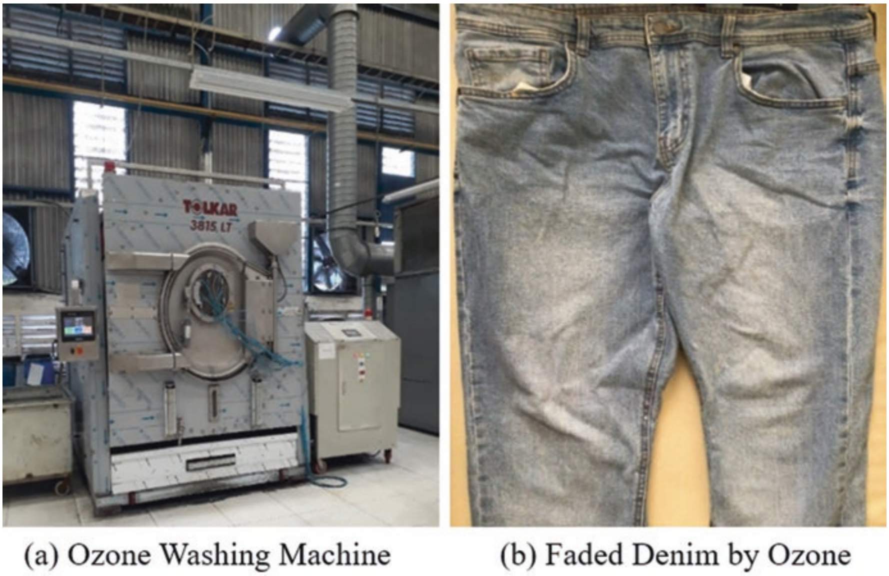

Fig. 5 Ozone application in denim manufacturing: (**a**) ozone washing machine and (**b**) denim faded by ozone

2.1.5 Ozone Applications

Ozone (O_3) is a form of oxygen, which is used to produce faded and patterned denims (Nayak et al., 2022b). Generally, ultraviolet (UV) radiation is applied to oxygen (O_2) to produce ozone for industrial applications. The process of ozone laundering consumes significantly lower amount of water and hence, reduces the environmental impacts (Ben Hmida & Ladhari, 2016). Furthermore, only one or two washes are needed after the colour has been removed by ozone, which saves water. Ozone is increasingly used by several denim manufacturers as a sustainable method to produce colour fading effects in denim (Sarker et al., 2021; Samanta & Konar, 2011). Figure 5 shows some of the ozone applications in denim manufacturing process.

2.2 Use of Eco-friendly Processes

Amongst all the fabric manufacturing steps, textile wet processing produces the highest environmental impacts (Robinson et al., 2001; Correia et al., 1994; Karn & Harada, 2001). Marcucci et al. (2001) established that 200–400 L of water is consumed to manufacture 1 kg of processed fabric leading to generation of effluents. It is a normal practice in many industries in developing countries, where the laws are not strictly monitored to discharge the toxic effluent directly to the nearby water courses. Using eco-friendly chemicals, lower amount of chemicals, enzyme applications, and biotechnology can help in sustainable clothing and textile manufacturing (Roy Choudhury, 2013).

2.2.1 Natural Dyeing

Many of the synthetic dyes are produced from petroleum resources, and they are non-biodegradable. Although the synthetic dyes are readily available at cheaper prices, they are not considered to be sustainable. To resolve this problem, nature has provided us spectrum of dyes from various natural resources such as plants, animals, and minerals (Saxena & Raja, 2014). As animal killing is involved to extract some natural dyes such as Kermes, Tyrian purple, and Cochineal, they are not considered to be sustainable. However, the dyes extracted from plant and mineral sources are sustainable as they are derived from renewable resources and biodegradable. In addition, the residual matter after dye extraction can be used as natural fertiliser, and the effluent treatment is much simpler (Saxena & Raja, 2014).

Natural dyes can be applied to almost all the natural fibres and are friendly to skin and beneficial to health as many of them have medicinal value (Shahid & Mohammad, 2013). Unlike the synthetic dyes, which have been reported for skin irritations (e.g. azo dyes), the fabrics dyed with natural dyes provide several benefits to the wearer due to the medicinal and therapeutic property of the dye sources. The dyeing process is also free from toxic, hazardous chemicals, and harsh dyeing conditions. As natural dyes can absorb the ultraviolet (UV) light from sun, they provide protection from UV, which have been well researched (Feng et al., 2007).

The natural dyed fabrics also provide antibacterial properties, moth repellent properties, and even flame-retardant properties as reported recently (Singh et al., 2005). The traditional dyeing process in many parts of the world was based on natural dyeing before the synthetic dyes were introduced in 1860s. However, the rapid growth of synthetic dyes, easy availability in ready-to-use form, and higher range of colours led to the complete replacement of natural dyes. The growing concern of impact on the environment by the process of dyeing and printing has led the door to switch back to the original source of natural dyes. Table 1 provides an overview of sources of some common natural dyes along with the colours.

In spite of the advantages of using natural dyes as mentioned above, there are several limitations, which prevent wide scale acceptance of these dyes (Shahid & Mohammad, 2013). Three major problems are poor colour fastness, limitations of range of shades, and poor repeatability. The other problems are time consuming natural dye extraction process, natural dyes are not water and energy efficient, applicability to only some fibre groups and poor aesthetics value (Samanta & Konar, 2011). Some of the dyes are sensitive to pH and cannot produce the right colour if the pH is not accurate. These problems have led to the limited application of natural dyes, which account for less than 3% of the total world dye consumption.

To improve these limitations of natural dyeing, many of the recent researchers have focused on various approaches for large-scale applicability. Furthermore, colouration with natural dyes is expensive and labour intensive. The global annual

Table 1 Sources of common natural dyes

Shade	Source	Dye	Botanical name	Comments
Yellow	Plant (root, flower, or fruit)	Turmeric Onionskins Saffron Pomegranate Marigold Myrobolan Teak leaves Golden rod flower	*Curcuma longa* *Allium cepa* *Crocus sativus* *Punica granatum* *Calendula officinalis* *Terminalia chebula* *Tectona grandis* *Solidago grandis*	Yellow natural dyes are the most abundant in nature. Turmeric and saffron can be applied to a range of fibres such as wool, cotton, and silk. Turmeric is the most abundant dye for yellow.
Red	Plant (root, flower, or bark)	Madder (wood) Indian madder or Manjith Safflower Morinda Sappan wood or Brazil wood Puccoon or bloodroot	*Rubia tinctorum* *Rubia cordifolia* *Carthamus tinctorious* *Morinda citrifolia* *Caesalpinia sappan* *Sanguinaria canadensis*	This dye found in abundance next to yellow, both from plants and animals. However, animal sources (Lac, Kermiz, and other insects) are not sustainable. In this group, the dye Sapppan wood can be combined with turmeric to give a range of colours
Orange	(flower or fruit)	One-seeded juniper Dahlia flowers Annatto seeds Balsam flower	*Juniperus monosperma* *Dahlia variabilis* *Bixa Orellana* *Impatiens balsamina*	As the number of sources for orange shade is limited, yellow dyes (i.e. turmeric) can be combined with red dyes (i.e. madder or manjith) to make orange.
Green	Plant (leave and flower)	Tulsi leaves Lily leaves Nettles leaves Bougainvillea flower	*Ocimum sanctum* *Convallaria majalis* *Urtica diocia* *Bougainvillea glabra*	Green dyes are not very common. Blue dyes (i.e. Indigo and woad) are combined with yellow dyes (i.e. turmeric) to produce green dyes.
Blue	Plant (leaves and fruits)	Indigo leaves Pala indigo Woad leaves Knotweed Suntberry seedpods Water lily rhizomes	*Indigofera tinctoria* *Wrightia tinctoria* *Saris rincroria* *Polygonum tinctorium* *Acacia nilotica* *Nymphaea alba*	Indigo is the most popular natural dye for denim. The oldest dyeing place for Indigo dyeing is India. Indigo grows well in tropical conditions found in Asia.
Black or brown	Plant (flower, bark, or fruit)	Cutch Golden dock seeds Eucalyptus bark Black berries Caesalpina chips Alder bark Rofblamala leaves	*Acacia catechu* *Rumex maritmus* *Eucalyptus camaldulensis* *Rubus fructicosus* *Caesalpinia sappan* *Alnus glutinosa* *Loranthus pentapetalus*	Many red and yellow dyes can produce black with iron mordant. The ancient brown dye was derived from the wood of acacia trees. Lac (*Coccus lacca*) can be used, but it is not sustainable.

demand for textile colourants has exceeded 3.2 million tonnes. This huge demand cannot be fulfilled by the natural dyes as huge amount of farming lands are needed, which is used to produce food and livestock. Solving the associated problems and standardising the dyes and dyeing process may help to achieve the environmental benefits of natural dyes.

2.2.2 Digital Printing

The printing of textiles is done mainly by rotary screen printing (60% share), flat bed printing (18%), and conventional screen printing (22%) (Malik et al., 2005). These traditional printing technologies have several limitations, which raises many questions in sustainability context. The traditional technologies are time consuming as large preparation time is involved, additional work of screen development, short lives of screens, generation of toxic waste, and large space needed for storing the screens. As the printing paste in traditional printing uses synthetic dyes and other chemicals, which can be toxic, the preparation process can cause toxic health effects including the toxic remnants.

The digital printing of textiles is a new horizon to overcome the drawbacks in the traditional printing methods. Digital printing uses less space and less hazardous chemicals and results in low waste, which is beneficial to the environment (Cahill, 2006). The finest colour gradations and maximum colour fidelity can be achieved in digital printing. Printing of smaller sample sizes takes less time and is very economical, which can save up to 90% cost. Digital printing does not need large amount of stock, it can save up to 70% of stock material, up to 50% of energy saving, and drastic reduction on water consumption (Malik et al., 2005).

Digital printing consists of inks in cartridges like paper printing, which are ejected through the micro-jets into the substrate or fabric. Subsequently, the substrate is treated to improve the fastness of the print following the sequence of operations as described in Fig. 6. Digital printing is quite simpler as even the images taken by a camera can be directly printed into the fabric without any preparation.

Despite the advantages as described above, digital printing has some disadvantages. The depth of colour and the deepness of the shade cannot be obtained by digital printing as the printer works only up to 15–25 g/m^2 inks (Malik et al., 2005). For large amount of fabric, digital printing may not be economical as the price of each toner is high, which lasts for few fabric rolls. Although digital printing is free from preparation for printing, the printing speed is slow. The clogging of nozzles can lead

Fig. 6 Process sequence for digital printing

to uneven printing. Digital printing is successful for limited verities of fabrics especially of the single fibre fabric. Blends of different fibres can't be printed due to requirement of different fixing conditions for different fibres. Furthermore, it needs skilled people with computer literacy, hence, extra expenditure on training.

2.2.3 Enzyme Applications

Enzymes are biological substances derived from different living organisms. They work as a catalyst to speed up the biochemical reactions. There is a growing application of enzymes in the textile industry as they are free from toxic effects of chemicals. Various enzymes, namely Amylases, Cellulases, Proteases, Glucose, and Pectinases, are used in various clothing and textile applications (Soares et al., 2011). Processes such as desizing, scouring, bleaching, and stonewashing of cotton denim can be achieved with enzyme applications. Enzymes can also be used in biofinishing, to remove pills and fuzz (to improve surface appearance), laundering of garments, and stain removal applications.

The bioprocessing has advantages over traditional processes such as it consumes less energy and less water and generates low number of effluents. Furthermore, enzymes are produced from renewable resources and are biodegradable. Chemical processes using enzymes operate at lower temperature and neutral pH, which can help in low energy consumption and lowers the amount of effluent in several applications. Hence, the applications of enzymes are sustainable in the textile chemical processing. The list of enzymes used for textile chemical processing has been shown in Table 2.

Table 2 List of enzymes used for textile chemical processing

Process	Enzymes tried by researchers	Source	Comments/benefits
Desizing	Amylase	Malt, bacterial, or pancreatic sources	Can be used with or without lipase to remove lipids
Scouring	Pectinase	Plants	Can be mixed with cellulose to improve fabric handle. Unlike the alkali scouring, the effluent of enzyme scouring can be directly discharged to sewage system
Bleaching	Laccases	Plants and fungus	Molecular oxygen facilitates the oxidation of substrates during the enzymatic catalysis
Bleaching (peroxide) after wash	Catalase	Bacteria and fungus	The use of catalase reduces the water consumption and effluent, which increases the sustainability of peroxide bleaching
Dyeing and printing	Laccases	Plants and fungus	Laccases are used together with a chemical mediator

(continued)

Table 2 (continued)

Process	Enzymes tried by researchers	Source	Comments/benefits
Lignin removal	Laccases	Plants and fungus	The most effective mediator is N-heterocycles bearing N–OH groups and in particular N-hydrobenzotriazole (HBT)
Enzymatic dye extraction	Cellulase, amylase, and pectinase	Cellulase: microorganism, Amylase: Malt, bacterial, or pancreatic resources	Cellulase is also widely used in washing detergents and softening of fibres. Amylase, lipase, and pectinase can be used together for simultaneous desizing and scouring

2.3 Employees Training

Garment manufacturing process is labour intensive (Nayak & Padhye, 2015b) and based on traditional techniques. In addition to the technology upgradation as mentioned above, the employees should also be trained on new skills for effective time management, waste reduction, energy saving skills, stress management, and teamwork. The training of employees has shown improvement in the productivity and quality, reduced the number of rejections and lead time (Boothby et al., 2010). Furthermore, training can also improve the skillset for better housekeeping, creating a safe working environment, waste management, emergency management, importance of recycling, and belongingness. This in turn can help in reducing the total waste, process time, and energy consumption and improve the productivity and efficiency.

3 Waste Management

Waste management is a significant problem in clothing and textile manufacturing. Starting from fibre production till the last process of clothing manufacturing, a huge amount of waste is produced by the industries. As suggested by Abdulmalek and Rajgopal (2007), the lean management can be adopted to deal with various process wastes in clothing and textile manufacturing. Similarly, various waste management approaches can be implemented to reduce the hard waste in clothing and textile manufacturing.

3.1 Controlling Waste by Lean Concepts

The fundamental principle of lean manufacturing depends on eliminating process waste by applying several lean tools such as Kaizen, Zidoka, and Muda (Japanese terms used in lean manufacturing) (Bruce et al., 2004). Lean focuses on various wastes such as inventory, waiting, inappropriate processing, excess motion in the manufacturing process, overproduction, repair, and transportation (Nayak et al., 2020a). On focusing on these seven wastes, a clothing manufacturing company can become a lean organisation with higher productivity and efficiency (Benders & Van Bijsterveld, 2000).

3.2 Minimizing Fabric Waste

Various approaches can be taken to reduce the fabric waste. First, improving the marker efficiency to the maximum level by applying various software can reduce fabric waste. The fabric cutting waste can be recycled back to fibres which can be used for filing toys or making other products such as bias tape or piping. Second, following zero waste pattern making approach, where all the fabric can be used to make the garment, can reduce fabric waste (Rissanen, 2013; Townsend & Mills, 2013). Although it is hard to follow for different types of garments, some garments such as Japanese Kimono can be designed in this concept. Designers such as Julian Roberts (2001) and Holly Mcquillan (2000) are working on this concept of zero waste pattern making.

3.3 Controlling Allied Material Waste

The other hard waste generated during garment production such as paper, plastic, fabric remnants, packaging material, and wire coat hangers is generally discarded into landfills leading to the problem of greenhouse gas (GHG) emission (Jha et al., 2008). However, more than 80% of these materials can be recycled back to new packaging material such as packaging paper or plastic packaging material (Metin et al., 2003). The textile hard waste such as cut fabric pieces, third quality rejected garments, or threads can be opened back to fibres and reprocessed into the fabric with slightly inferior properties (Tam & Tam, 2006). The second quality garments, which are rejected during the garment inspection, can be sold in the seconds outlets.

4 Conclusions

The triple bottom line (TBL) of sustainability has been neglected in many developing countries involved in clothing and textile manufacturing. This can be attributed to the globalisation and stiff competition amongst the textile and garment manufacturers globally. In a globally competitive marketplace, the manufactures of clothing and textiles face several challenges due to increased importance of sustainability. Furthermore, the increased international pressure, stricter regulations, and consumer awareness are the driving forces to adopt sustainable practices. This chapter has discussed some of the eco-friendly practices that can be followed to achieve sustainability in the clothing and textile manufacturing process.

The sustainable practices in clothing and textile manufacturing starts from very beginning stage of conceptualisation, where the designers play an influential role by selecting sustainable materials. Technologies such as laser, RFID, DyeCoo, air dyeing, and ozone are used by leading fashion brands to reduce the environmental impacts. Furthermore, enzyme applications, digital printing, natural dyeing, and other greener technologies are used to reduce the amount of toxic chemicals and effluent discharge. The concept of cradle-to-cradle can be applied to textile and garment manufacturing by recycling of old cloths and plastics to new materials, which can avoid the problems of generation of huge piles of landfill. These sustainable approaches can be made successful by the collaborative efforts of fashion retailers, manufacturers, and the consumers. The application of lean management can reduce the process waste and material waste by various principles. Several sustainability benefits can be achieved by the implementation of lean management in the textile and garment industries.

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Take-Back Programs for Fashion Brands' Garments in Sustainable Manufacturing Systems

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1 Introduction

The fashion industry plays a significant role in the global economy in terms of resources' use and social and environmental impact of production, use, and end-of-life. Some fashion companies still adopt a linear business model following the "take-make-waste" logic and produce several garments that end up in landfills at the end of their life cycle (Rathinamoorthy, 2019; Domina & Koch, 1999). Obviously, this growing waste is intrinsically interconnected to the dynamics of the fashion sector that is characterized by an increased number of collections launched each year with a continuous search for lower cost and rapid time. This has been due to two main factors: the spread of the "fast fashion business model" and the fashion democratization process that have made luxury fashion goods more accessible (Arrigo, 2016).

Clothing manufacturing has roughly doubled over the past 15 years to meet the rising demand of the middle class around the world. In the meantime, several issues have arisen such as heavy water usage, pollution from chemicals used in dyeing, and disposal of unsold products through incineration or landfill deposits (Pedersen et al., 2018).

To cope with this very harmful situation for the environment, new sustainable and circular initiatives launched by fashion companies often required a paradigm shift in how fashion products are designed, manufactured, consumed, and disposed (Hvass & Pedersen, 2019). The transition toward a circular economic system involved an emphasis on the control of products and materials throughout their life cycle for firms operating at every level of the fashion supply chain (Wells, 2013;

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Pieroni et al., 2019). In fact, customers' protests have pushed fashion firms toward the adoption of sustainability policies (Jung & Jin, 2016) seeking to move beyond the linear model of "take, make, and waste" (Pedersen et al., 2018).

At the same time, to limit the negative impact deriving from this incessant waste, closed-loop supply chains were developed to reuse and recycle all materials, assessing several processes from the inspection, design, and cleaning of fashion items until to remanufacturing, re-distribution, and disposal (Li, 2013). Closed-loop manufacturing systems for product take-back programs (Andersen et al., 2022) were designed to efficiently break down the collected products, reconstruct and again assemble them. In fact, fashion companies started to launch take-back programs to enable value creation from their second-hand clothes (Stål & Corvellec, 2018). However, downstream supply chain activities and post-retail take-back schemes (Hvass & Pedersen, 2019; Hvass, 2014; Uhrenholt et al., 2022) have gained limited academic attention to date. Therefore, the aim of the chapter is to provide an overview of take-back programs, key elements of closed-loop manufacturing systems, and their challenges for fashion companies.

The chapter is structured as follows: after the Introduction, Sect. 2 presents the circular fashion and post-retail programs; in Sect. 3, take-back programs are explained with some specific fashion brands' cases. Finally, Sect. 4 provides conclusions with future research directions.

2 Circular Fashion and Post-Retail Programs

Over the years, mainstream business model thinking has been criticized for putting too much emphasis on consumers and financial gains (Pedersen et al., 2018). To face these criticisms, new sustainable business models arose, and overall they differ from conventional business models for three main reasons:

- A triple bottom line perspective (Elkington, 2013) that gives priority to economic, social, and environmental value.
- A stakeholder management approach recognizing the existence and relevance of various groups and individuals with influences on business models.
- The adoption of a long-term view (Hvass & Pedersen, 2019; Pedersen et al., 2018).

For a long time, fashion companies have focused their commitment toward circular fashion on reducing the social and ecological impact of upstream supply chain processes and especially of manufacturing. As mentioned in the Introduction, only recently, downstream supply chain issues have gained attention and new activities such second-hand retailing, fashion rental, or recycling have become key components of fashion sustainability (Arrigo, 2022).

In 2018, a survey explored the most relevant aspects of clothing sustainability from the perspective of consumers and highlighted specific aspects of manufacturing. In fact, high quality in terms of durability (for 37% of respondents), absence of hazardous chemicals (28%), labor practices (25%), and the use of recycled materials (23%) resulted to be the most considered aspects for customers. However, also minimized logistics (15%), take-back programs (12%), and second-hand (10%) appeared among the features of clothing sustainability cited by consumers, which consequently recognized their role in circular fashion systems (Statista, 2022). Furthermore, in 2022, the clothing consumption worldwide was approximately 183.8 billion pieces, and according to Statista Consumer Market Outlook, this value was expected to rise in the future years to 197.3 billion pieces in 2026. Therefore, the amount of waste is also assumed to grow steadily, and the implementation of circular fashion programs becomes essential. In fact, circular business models can create value from waste, by turning it into useful and valuable resources for other processes (Bocken et al., 2018). Take-back management is a crucial component of circular business models because it supports the recycling of goods and materials. In addition to closed-loop, reuse, and recycling, other ways such as industrial symbiosis, C2C, and remanufacturing can also be regarded as "circular" (WRAP, 2021).

Past studies have highlighted that although consumers are aware of the opportunity of returning their used garments to fashion companies or even charities, few exploit it (Joung & Park-Poaps, 2013). This may depend on several reasons; however, probably the unawareness about the huge environmental impact deriving from the end-of-life of used clothing can be one of the main causes (Hvass & Pedersen, 2019). Moreover, consumers' environmental or ethical concerns do not always turn into sustainable purchasing behavior (Vehmas et al., 2018; Henninger & Singh, 2017), and their buying decisions are often irrational and not constantly in line with their values (Niinimäki, 2010).

3 An Overview of Take-Back Programs

A take-back program involves taking back a used product to recycle, re-manufacture, or refurbish it (Uhrenholt et al., 2022). Take-back programs launched by fashion companies are particularly useful since they can support both customers' mindsets and the fashion system, by converting consumers into actors within a circular fashion supply chain (Brydges, 2021). Therefore, the collection of used clothing through take-back programs can be considered as a circular business model that exploits the residual value of items – from manufacturer/retailer, to buyers, and then back to manufacturer/retailer (Hvass, 2014; Corvellec & Stål, 2019).

Large fashion companies often develop take-back initiatives since other circular fashion programs such as second-hand retailing or clothing rental would be more expensive and difficult to manage (Hvass & Pedersen, 2019). In take-back programs, fashion companies can collaborate with a non-profit organization or a business collector for in-store garment collection programs (Hvass, 2014). In both situations, the collection partner will sort the gathered textiles and transport them to locations for recycling and reuse. However, fashion companies may also decide to directly realize their own take-back programs, typically restricting donations to own-brand items and with the purpose of learning more about how their goods are used by consumers. Moreover, for online retail, there are currently numerous applications for recycling textiles, and their service providers can collaborate with numerous fashion brands and retailers to offer discount vouchers to final customers or create other special offers (WRAP, 2021).

Several ways to put a take-back program into action exist – the options identified by WRAP, an international NGO working to face the causes of climate change and supporting a sustainable future – can be distinguished in the following take-back schemes:

- *Commercial partnership*: Commercial partners are companies vertically integrated with strong logistics that cover the entire take-back process from the garments' collection, sorting, and transfer to the final reuse and recycling destinations. As a result, they can provide fashion brands with a complete garment collection proposition. The main costs for the fashion brand refer to staff meeting and engagement, since in-store teams' training is necessary before the implementation of the take-back program. Additionally, partnership with a commercial collector enables fashion brands to stay concentrated on their core activities by guaranteeing a professional redistribution, reuse and reuse of items collected in-store. In this way, fashion brands can also increase the store traffic and enhance their customer loyalty by displaying the brand's commitment toward sustainability (Hvass, 2014).
- *Charity partnership*: To facilitate the collection of used products, fashion firms can also enter in partnership with a well-known charity group (Sandberg et al., 2018). Partnerships between charities and fashion brands were already existent in the past; however, traditionally, they were directed to find new uses and markets for unsold or damaged collections (Hvass, 2014). Partnering with a charity could improve customer engagement in a take-back program and at the same time generate more in-country reuse of fashion products through resale in charity shops.
- *Own take-back*: in this case, fashion brands directly manage their post-retail initiatives and take-back programs (Hvass & Pedersen, 2019). Generally, this is more frequent with high-quality luxury fashion items connoted by higher perceived resell values and represents an opportunity for the fashion retailer to capitalize on that value. Fashion retailers launching their own take-back initiatives, beyond high costs for operations, can develop a direct control of reusable garments and materials for recycling programs, resale the collected items directly, and gather insights from the customer use step.
- *Online reuse and recycling applications*: The online reuse and recycling applications connect consumers, collectors, and fashion retailers, offering discounts and incentives to customers to give back their clothing items. The number of these applications is rising with some apps focused only on luxury products with high resale possibilities or unwanted clothing like the "reGain application" (https://regain-app.com). Other apps offer a donation service for men's and women's second-hand such as Thrift+ (https://thrift.plus).

- *Retail landlord-led initiative*: a retail store with the right size (such as a shopping center) can develop a fashion take-back initiative covering all related costs. A similar initiative can be useful to improve customers' awareness about take-back schemes. The owner of the retail environment also supervises the program promotion, but affiliated fashion retailers can also participate. For instance, in 2019, Landsec, one of the largest retail property owners in the United Kingdom, set a textile recycling scheme at its Westgate shopping center in Oxford. This initiative, called "*spring clean, think green*" allowed customers to recycle their old clothing of any brand by leaving them at a recycling point within the shopping center. Then, Landsec launched the initiative across other 14 shopping centers and, as incentive, offered a chance to win gift cards in the prize draw (https://www.recyclingbins.co.uk).

3.1 Fashion Brands Offering Take-Back Programs

In the fashion industry, several brands have developed take-back programs to reinforce their commitment toward sustainability and circular fashion principles. Some examples of fashion brands launching take-back programs are provided below.

- *H&M Garment Collecting Programme*

- The Garment Collecting Programme was launched by H&M in 2013 in collaboration with I:CO, an international provider of circular fashion solutions (https://www.ico-spirit.com). H&M placed recycling boxes in its stores worldwide and, in 2020, was able to collect 18,800 tons of unwanted clothes and textiles equivalent to 94 million T-shirts (www.hm.com). The H&M take-back program unfolds in the following way: customers can give back any unwanted garments to the cashier of an H&M store and receive a voucher to use in a future purchase. Then, once the fashion item is inserted in the garment collection box, the business partner takes control and divides all the collected garments into three categories: rewear (when the items can be sold as second-hand), reuse (when the items cannot be worn again, they will be used to make other products), or recycle (all the remaining items will be shredded into fibers useful to create new things).
- *Zara Clothing Collection Program*
- Zara has launched the Clothing Collection Program to gather and extend the life of used fashion items as part of its social and environmental sustainability commitment. The program for collecting used clothing is developed in collaboration with local non-profit organizations such as Caritas, Red Cross, and China Environmental Protection. Once gathered, the garments are classified and, according to their conditions, can be reused or recycled. Used items will be donated to individuals in need, sold in second-hand stores to support social projects, or recycled into new fibers and textiles (www.zara.com).
- *Patagonia Take-Back Program*

- To contribute to building a circular clothing system, Patagonia developed the Take-Back Program in 2011 to recycle old garments made with cotton, hemp, or linen and support recycling. Customers can return their items into a Patagonia retail store or also can mail it to the company Reno distribution center. Then, collected garments will be sent to a supply chain partner that recycles the materials into new fibers that will be next combined with factory cotton pieces to create the Patagonia Tee-Cycle collection. Additionally, to support items' longevity and avoid CO_2 emissions and garbage, Patagonia organizes the Worn Wear tours each year, where different teams repair zippers, tears, buttons, and much more in different cities (www.patagonia.com).

4 Conclusions and Future Research Directions

Circular fashion, where items are collected and sold as second-hand garments recycled into new fibers, represents a recent phenomenon but also a recent business opportunity (Vehmas et al., 2018). As shown in previous sections, take-back programs have been introduced by large fashion brands often in collaboration with external partners to limit the environmental damages caused by clothing manufacturing and disposable fashion culture (Corvellec & Stål, 2019; Hvass & Pedersen, 2019). However, launching a take-back initiative is not without challenges for fashion companies. In fact, they need to recognize the right partners, make customers aware of this in-store new initiative, and engage them leveraging the retail staff that should be trained to effectively carry out this activity. Additionally, take-back programs also require logistics and traceability challenges to follow the collected items in their subsequent transformations. From the customers' side, despite their interest in social and environmental issues, the latter do not seem to constantly act on their buying decision (Vehmas et al., 2018). Therefore, fashion brands should also train customers, engaging them also with in-store communications and delivering marketing communication campaigns on their offline and online channels.

As stated in the Introduction, take-back initiatives in closed-loop manufacturing systems are very underdeveloped in fashion marketing academic literature to date (Hvass & Pedersen, 2019; Hvass, 2014). In this chapter, an overview of different typologies of take-back programs and challenges for fashion companies has been provided. However, additional future research directions could be developed to better understand the potential of take-back programs. First, the role played by the different actors, fashion brands, charity organizations, and commercial partners taking part in a take-back system could be deepened to know their co-branding and collaboration opportunities. Additionally, a precise assessment of economic and marketing opportunities, with relative costs, of take-back programs is still at an early stage (Uhrenholt et al., 2022) but deserves further development.

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The Awakening of an Environmental-Conscious Fashion Era

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1 The Sustainability Scope of the Fashion Industry

Few industries around the world tour their sustainability credentials more strongly than the fashion industry. Different products, from socks to bags to wedding dresses are being marketed as carbon positive (i.e., from textile fibers production in farming systems), vegan and organic. At the same time, new business models are sold as environmental and sustainability life savers, simply because they include terms like recycling, rental, repair, resale, and other key circular economy strategies. Nevertheless, the sad truth is that the fashion industry constitutes one of the most polluting industries in the world after food, transportation, and energy (Papamichael et al., 2022). This is due to the fact that fashion is a major part of everyday life while stylistic changes, chosen by the key players of fashion brands, drive society into the constant replacement of old or "out of fashion" clothing with new clothes which are trending at the current time. This everlasting cycle of discarding clothing is mostly seen from fast fashion brands (i.e., Zara and Pull n Bear) where, apart from the high

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carbon footprint of clothing, the cheap and affordable prices accompanied by the speedy production add to the narrative of replacing the old with something new (Papamichael et al., 2023a; Yan et al., 2021).

Between 2000 and 2014, more than 150 billion clothes were created annually over the world, with Europe (EU) discarding 2 million tons each year (United Nations Environment Programme, 2018). At the same time, the global revenue of wasted fashion products reaches USD 400 billion with approximately 13 kg/capita consumption (Provin et al., 2021). According to Statista (2022a, b), the textile industry emitted 1 gigaton of carbon dioxide equivalents in 2019, with an estimated increase of emissions up to 1.6 gigatons by 2030. Even before the fashion products reach the consumers, 35% of the materials are lost and wasted throughout the supply chain due to unused stock, false monitoring, changes in design and transportation (CO, 2018; Eunomia, 2020; Papamichael et al., 2023c). The revenue of the global fashion industry increased from 2015 to 2020. After the market recovered from the effects of the coronavirus (COVID-19) pandemic in 2021, excessive inflation in 2022 brought additional challenges to the global garment sector. The cost of production increased, and customer confidence decreased. The worldwide clothing industry is expected to generate 1.53 trillion US dollars in 2022, a little decline from the previous year. However, income is expected to rise to more than 1.7 trillion dollars by 2023 (Fig. 1). China will lead the rankings for the largest value of garment exports in 2021. In terms of the value of garment imports, the United States ranked second only to the European Union (Statista, 2022b).

Given the data, it comes as no surprise that the fashion industry holds 20% of global waste production (EcoFriendly, 2021). Simultaneously, due to overconsumption patterns and lack of sustainable and truly circular end-of-life treatment of products, a lack of space for disposal of fashion items has been created, resulting in

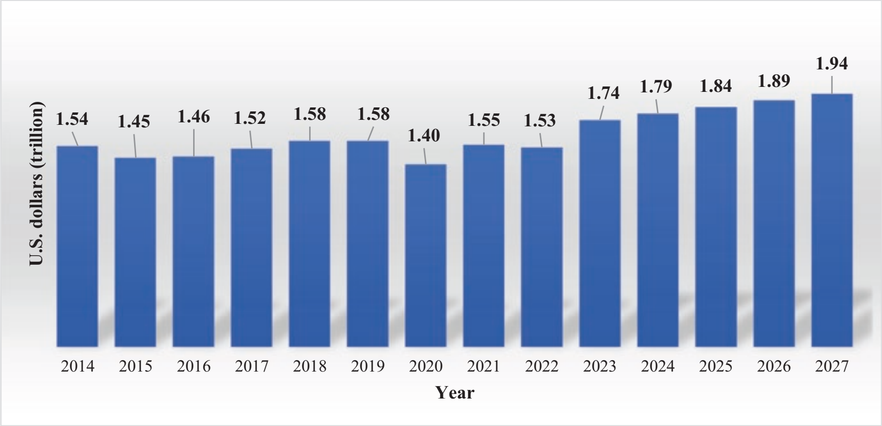

Fig. 1 Revenue of the fashion industry from 2014 to 2027. (Figure created by the authors) (Data from Statista 2022b)

uncontrolled dumping of waste in dry desserts and low income countries (LICs) around the world. Specifically, in 2021, 60,000 tons of fashion wastes were disposed of in north Chile, shipped mainly from the United States, EU, and Canada. Similarly, 140,000 tons are being shipped to Kenya yearly, resulting in approximately 20 million kg of landfill waste per year (Centobelli et al., 2022; EcoWatch, 2021; Papamichael et al., 2023c).

Adverse indirect effects of textile overproduction, however, include microplastic and plastic accumulation (from synthetic fibers) on the floor level of oceans and seas, amounting to 14 million tons. These data constitute 16–35% of global microplastic marine pollution (Cai et al., 2020). It is estimated that if the business as usual (BAU) scenario continues, 22 megatons of textile waste will be added to marine environments by 2050, separate from 148 million tons of waste that will be added further by human kind (Greenpeace, 2016; Papamichael et al., 2023c).

Nonetheless, there is little doubt that the fashion sector is an important actor in the global economy. The fashion sector accounts for almost 3000 billion USD, or more than 2% of the world's gross domestic product (GDP). From 2020 to 2025, the economy's reliance on fashion is predicted to increase from 2.5 trillion USD to 2.5 trillion USD. As a result, there is no issue about removing the industry or the goods created, but rather optimizing and strategically providing activities, business models in the notion of sustainability to limit the sector's risks and effects (Shirvanimoghaddam et al., 2020). According to Ellen MacArthur Foundation (2017), EU countries consume large amounts of textiles while fashion products discarded each year add up to 350 billion Euros. Even though popular business models concerning circular economy like resale, reuse, and renting of clothing showcase a great deal of potential, these strategies do not decouple carbon footprint and environmental benefits. As long as the fashion industry maintains a linear production line, circular fashion vision cannot become a reality. Material innovation and production line optimization from raw material extraction to design, production, consumption, and end-of-life treatment is necessary for the industry to taste the real benefits of a truly circular business approach (Appolloni et al., 2022; Colasante et al., 2022).

This chapter seeks to highlight the major challenges affecting the textile industry, with emphasis on how fashion could facilitate the transition to a sustainable circular economic model. Furthermore, specific proposals and efforts that could contribute to the textile sector meet the targets established by the international and European strategies are provided, with the ultimate goal to shift to a new consumption model. Methods, tools, and indicators for assessing the effectiveness of the fashion industry's initiatives are also discussed. All of the aforementioned knowledge was considered in order to develop a new business model that prioritized changing customer attitudes and behaviors. Finally, effective case studies from different organizations were reviewed.

2 The European Green Deal and SDGs

The European Green Deal in line with the Sustainable Development Goals (SDGs) of the United Nations (UN) direct global efforts toward sustainable development. The SDGs aim to address global social, economic, and environmental challenges and are interconnected (UNDP, 2022). With 169 targets to be met by the year 2030, and over 232 indicators for measuring progress the SDGs were developed to encourage positive outcomes for humanity, the environment, peace, prosperity, and relationships. The SDGs also represent current concerns and threats in the garment and textile value chain. The sustainable production and consumption of textiles are directly related to several of the SDGs. In the literature, the most referred SDGs are the SDG 12 (Sustainable consumption and production), SDG 6 (clean water and sanitation), SDG 13 (climate action), while the least ones are SDG 1 (zero hunger), SDG 3 (good health and well-being), SDG 4 (quality education), and SDG 14 (life below water) (Cai and Choi, 2020) (Fig. 2).

SDG 12 focuses on promoting sustainable consumption and production patterns. As mentioned in Sect. 1, the textile industry has a significant impact on the environment and society, and therefore it is essential to promote sustainable consumption and production of textiles (Gardetti and Senthilkannan Muthu, 2020). SDG 12 is a gateway to many of the other SDGs for the textile industry (Textile_Exchange, 2023). Within SDG 12, target 12.8 stresses the need for people worldwide to "have the relevant information and awareness for sustainable development and lifestyles in harmony with nature" (Papú Carrone, 2020). To make possible this transformation, researchers and practitioners have identified traceability as an essential initial step toward informed decision-making (Global Fashion Agenda, 2021). Traceability

Fig. 2 Fashion's role in the sustainable development goals. (Figure created by the authors)

mechanisms, as a result, provide a potential approach for monitoring and tracking the activities for every actor in the supply chain, thereby strengthening procedures and control through the network and enabling consumer-facing firms to verify their sustainability implies, improving reputation, and securing the battle toward counterfeit. Consumers with purchasing power are able to obtain crucial data about a brand's social and environmental activities through traceability and public transparency (Human Rights Watch, 2017).

SDG 13 aims to take urgent action to combat climate change and its impacts. The textile industry is a significant contributor to greenhouse gas emissions and therefore reducing the environmental impact of textile production and consumption is essential for achieving this goal (Olofsson and Mark-Herbert, 2020). The production of new smart fabric textiles with longer lifetime will help decrease environmental impacts (Júnior et al., 2022). SDG 14 is connected to the conservation and sustainable use of the oceans, seas, and marine resources toward sustainable development. Sustainable textile production and consumption are essential to achieving this objective because the textile industry significantly contributes to ocean pollution through the release of dangerous chemicals and micro-plastics. Similarly, SDG 15 focuses on the protection, restoration, and promotion of sustainable use of terrestrial ecosystems, especially considering land use and soil management. Because the cultivation of cotton and other natural fibers has a significant impact on land use and biodiversity, sustainable textile production and consumption can support sustainable land use. Furthermore, SDG 6 which aims for Clean Water and Sanitation is linked to water consumption and a number of pollutants that can be extracted from textile industry wastewater.

Globally, the industry employs about 26.5 million people, with women making up about 70% of the workforce (Olofsson and Mark-Herbert, 2020). It is obvious that social issues are directly related to SDG 8 and SDG 5. SDG 8 and SDG 5 aim to promote inclusive and sustainable economic growth, full and productive employment, and decent work for all and Gender Equality. The textile industry employs many people, so encouraging sustainable textile production and consumption can help create jobs and boost the economy (Australasian Circular Textile Association, 2020). Another important SDG which with its development can strengthen the other objectives is SDG 17, basically by improving science and technology, and trade rules based on the use of sustainable materials. The literature demonstrates that eco-labeling plays a significant role in addressing the human health and environmental issues in the sector for SDG 3 (Cai and Choi, 2020). Collaboration among the stakeholders is very important as well as promoting working groups, coalitions, and platforms that inspire collective engagement in order to achieve targeted goals (Cai & Choi, 2020; Textile_Exchange, 2023). All stakeholders, including consumers, producers, policymakers, and civil society organizations, must work together to achieve the set goals.

3 Strategy for Sustainable and Circular Textiles (Directive 2022)

Nowadays, European consumption of textiles has the fourth-highest negative effect on the environment and climate change, after food, housing, and transportation. Textiles ranks third in terms of water and land consumption and fifth in terms of raw material utilization and greenhouse gas emissions (European Commission, 2022). As part of the European Green Deal (EGD), the Circular Economy Action Plan (CEAP), Industrial Symbiosis, Plastics Strategy, Zero Pollution action Plan the European Commission is tackling the challenges of the textiles industry and has outlined a new plan to make textiles longer lasting, repairable, reusable, and recyclable. The new EU Strategy for Sustainable and Circular Textiles addresses rapid fashion, waste from textile production, and the depletion of unsold textiles, while also ensuring that their manufacturing is carried out in accordance with human rights. The strategy also aims to develop an enhanced environmentally friendly, viable industry that is more resilient to worldwide crises.

With the goal to meet these objectives, the EU Strategy outlines a forward-looking set of actions: (i) Specify guidelines for textiles to make them endure longer and be easier to repair and recycle. (ii) Introduce additional detailed data as well as a Digital Product Passport to ensure traceability and transparency. (iii) To motivate customers and boost awareness about sustainable fashion, tackle greenwashing. (iv) Reducing excessive production and overconsumption, as well as discouraging the destruction of unused or unsold textiles. (v) Propose obligatory textile Extended Producer Responsibility (EPR) with Fee Eco modulation. (vi) Take action to prevent the inadvertent discharge of microplastics from synthetic textiles. (vii) Restriction of textile waste exports and global promotion of sustainable textiles. (viii) Encourage the adoption of circular business models, which involves the reuse and repair sectors. (ix) Empower organizations and member-states to endorse the strategy's targets (European Commission, 2022) (Fig. 3).

Fig. 3 Key actions in the textiles strategy. (Figure created by the authors)

3.1 Introducing Mandatory Ecodesign Requirements

Prolonging the useful life of textile products is the most efficient strategy for drastically lowering their climatic and environmental impact. Product design is critical to achieving this goal. Color fastness, tear resistance, and the quality of zippers and seams constitute some of the most typical causes for consumers rejecting textiles. Enhanced durability would allow customers to use clothes for longer periods while also supporting circular business models such as reuse, rental and repair, take-back services, and second-hand retail, providing citizens with cost-saving alternatives (Ecos, 2021). EU voluntary schemes "EU Ecolabel criteria for Textile Products" and the "EU Green Public Procurement (GPP) criteria for textiles products and services" currently encompass environmental standards for textiles products. They include precise criteria for high-quality and long-lasting products, constraints on toxic chemicals, and guidelines for environmentally friendly textile fiber (JRC, 2020; Official Journal of the European Union, 2014). Additionally, by defining guidelines for safe and sustainable by design chemicals and materials, the commission intends to assist industry in substituting as many as possible and minimizing chemical compounds that are undesirable in textile products placed on the EU market, such as carcinogenic, mutagenic, or toxic to reproduction. This is consistent with the actions outlined in the "EU Strategic Framework for Health and Safety at Work 2021–2027" to improve the safety of employees exposed to hazardous and toxic substances (European Commission, 2021).

3.2 Setting an End to the Destruction of Unsold or Returned Textiles

It is a waste of both value and natural resources to dispose of unsold or returned textiles. As an alternative to this practice, the strategy provides a transparency responsibility that demand large businesses to publicly disclose the quantity of products they dispose of, including textiles, as well as their treatment afterward in regard to reuse, recycling, incineration, or landfilling. Moreover, the commission will investigate, in collaboration with industry, how modern technologies, such as digital technologies, might reduce the high percentage of return of clothing purchased online, motivate on-demand customized production, and thus enhance the effectiveness of manufacturing procedures while lowering the carbon footprint of online shopping.

3.3 Preventing Microplastics Pollution

Textiles comprised of synthetic fibers are a major source of inadvertent microplastic emission. The EU strategy intends to address every phase of the lifecycle which synthetic fibers are released into the environment through a set of preventive and reduction initiatives, including mandatory design criteria. Efforts will target production methods, prewashing at industrial production plants, labeling, and encouraging the use of new products. Other alternatives involve the development of milder detergents, maintenance and washing instructions, end-of-life textile waste treatment, and legislation for enhanced wastewater, which can reduce the volume released from laundry by up to 80%.

3.4 Introducing Data Requirements As Well As a Digital Product Passport

Simple, organized, and readily available data on the sustainability details of products enables both companies and customers to come to more educated choices and encourages inter-actor communication. This kind of information also increases awareness and credibility of environmentally friendly companies and products. As a result, the strategy proposes the development of a Digital Product Passport for textiles as part of the new "Ecodesign for Sustainable Products Regulation." In addition, the commission intends to investigate the introduction of a digital label.

3.5 Extended Producer Responsibility and Boosting Reuse and Recycling of Textile Waste

Making producers take responsibility for the waste that they produce is critical for decoupling textile waste production from the expansion of the industry. EPR regulations have been found to be helpful in enhancing separate waste collection. EPR could encourage product design that supports circularity throughout the material life cycle and addresses product end-of-life. Consumer purchase habits are difficult to change until organizations offer new circular business models including product-as-a-service theories, take-back solutions, second-hand collections, and repair facilities. Since fast fashion is associated with the increasing usage of synthetic fibers derived from fossil fuels, changing to more sustainable models will decrease both clothing companies' reliance on fossil fuels and their consequences on environmental degradation.

Within the framework of the new strategy, a new philosophy is being developed: "driving fast fashion out of fashion." Enterprises that have developed their economic models by offering a growing variety of fashion lines and micro collections

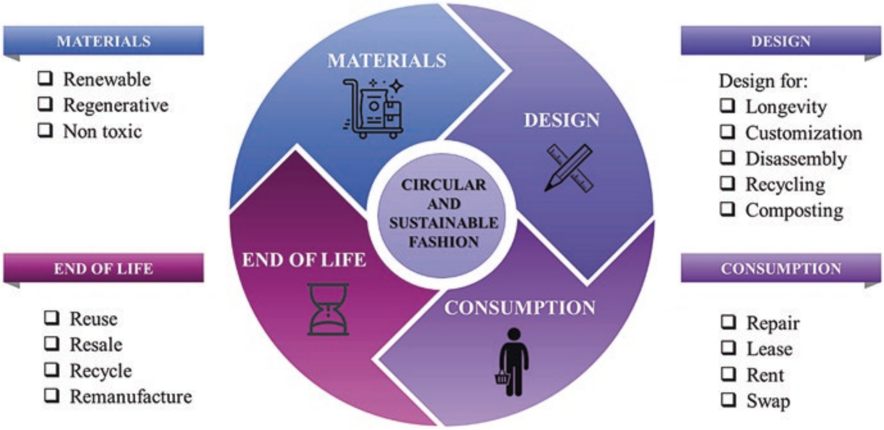

Fig. 4 Circular fashion according to EU strategy for sustainable and circular textiles. (Figure created by the authors)

Fig. 5 A general overview of the main stages involved in fashion industry in a linear model. (Figure created by the authors)

to market at an increasing rate are strongly advised to embrace circularity concepts, minimize the number of collections per year, take responsibility, and act to reduce their environmental footprint (Fig. 4). Consumer purchase habits are difficult to change until organizations offer new circular business models including product-as-a-service theories, take-back solutions, second-hand collections, and repair facilities. Since fast fashion is associated with the increasing usage of synthetic fibers derived from fossil fuels, changing to more sustainable models will decrease both clothing companies' reliance on fossil fuels and their consequences on environmental degradation.

4 Circular Economy Practices and the Fashion Industry

The fashion industry is a multi-complex industry that includes the design, production, marketing, and retail of clothing, footwear, accessories, and other fashion-related products (De Ponte et al., 2023). The industry includes many production and management processes such as the production of textiles from raw materials, the design and production of products (e.g., clothes), transportation, sales, and others wherein a linear model they are linked to many environmental challenges and impacts (Šajn, 2019). These processes can vary depending on the company, product, and market (Fig. 5) involving many stages, in which each stage may include a complex network of suppliers, manufacturers, retailers, and consumers. Generally, the main stages involved in fashion industry are as follows: (i) the production of raw materials such as cotton, silk, wool, and polyester. These materials have a different environmental footprint which the industry is making efforts to minimize. For example, cotton requires high amount of water, land, fertilizers, and pesticides which result in various environmental impacts. The industry is trying to minimize these impacts with bio-cotton (Furferi et al., 2022; Koszewska, 2018; Liu et al., 2019; Ütebay et al., 2019). In the case of polyester, it has the disadvantage of being non-biodegradable but has lower water footprint than cotton. Its use though is associated with the release of microplastics, which is one of the most important environmental issues that the industry has to face. The research community is trying to face this problem with bio-based polyester (Deckers et al., 2023; Furferi et al., 2022; Harmsen et al., 2021; Ribul et al., 2021; Šajn, 2019).

The next stage is the processing and garment production which includes the preparation of fabrics and the design process, which involves creating sketches, patterns, and prototypes of new fashion products. Following design process sourcing and production takes part where the collection of proper material such as type of textiles is decided and production methods are followed. This stage may include fabric and trim sourcing, pattern making, cutting, sewing, and finishing. These processes require high amounts of energy, water, and chemicals such as paints, which may be classified as hazardous to health or the environment. Next, after the products are produced, they are marketed and promoted to consumers through advertising, social media, and other channels. This stage may also involve fashion shows and other events to showcase the products. Afterward, the products are sold and distributed through various retail channels, including e-commerce websites, and other online marketplaces. Nevertheless, this stage is marked by high CO_2 footprint due to transportation routes and the production of significant amounts of packaging. Once the products have reached the end of their useful life (end-of-life), they may be disposed of, recycled, or donated. It appears that the majority of clothing is still discarded, burned in incinerators, or dumped in landfills (Guillot, 2022; Šajn, 2019).

CE is an approach to economic and industrial activity that aims to keep resources in use for as long as possible, through reuse, recycling, and regeneration (Kirchherr et al., 2017). In the fashion industry, CE principles can be applied to reduce waste, conserve resources, and minimize environmental impact (Moorhouse, 2020; Papamichael et al., 2023c). The transformation though to a circular model depends on economic, environmental, and social aspects which the industry has to pay attention to. For this purpose, various business models are adopted where the shift to more sustainable business practices is reported to largely be driven by the scaling of circular business models (CBMs) (Dragomir & Dumitru, 2022; Hultberg & Pal, 2021; Sandberg & Hultberg, 2021). In the fashion industry business models, the case of fast fashion which includes the production of high product volumes at cheap prices and furthermore higher environmental impacts needs immediate actions in order to switch to circular models (Bailey et al., 2022; Yang et al., 2017). Furthermore, models for evaluating the sustainability of fashion supply chain in terms of its economic and environmental aspects are also investigated in the literature (Bottani et al., 2019).

Various strategies and actions are applied in the concept of circular economy to the fashion industry. As reported in Fig. 6, these actions may vary depending on the local industry, financial aspects, as well as some social aspects and more specifically producers and consumers' culture and generally influencing consumer behavior to favor more sustainable options. More specifically, various examples are reported in the literature in order to reduce waste, conserve resources, and minimize the environmental impact of the industry. As a first step, re-design approaches will contribute by designing products that are built to last longer, use sustainable materials, and are simple to repair, reuse, or recycle. For this, clothing designers can incorporate circular economy principles into their design process (Aus et al., 2021). Recycling and upcycling are main processes that the fashion industry incorporated in recent years. Clothing and textile waste can be recycled and transformed into new products. In textile recycling, used clothing is disassembled and transformed into new fibers that can be used to create new clothing or other products. Upcycling is the process of using waste materials to create new, more valuable products. It is reported that the amount of leftover fabric and textile waste produced during the making of a garment can range from 25 to 40%, depending on the size of the factory. According to experiments, 50% of that material can be reused to create new clothing, and for some leftovers, such as spreading loss and excess fabric, it can even be up to 80% (Aus et al., 2021). Regarding recycling, green chemistry is the new approach that is achieving to decrease chemicals used such as solvents and paints and uses green conversion technologies to treat textile waste. Chemical recycling, which breaks

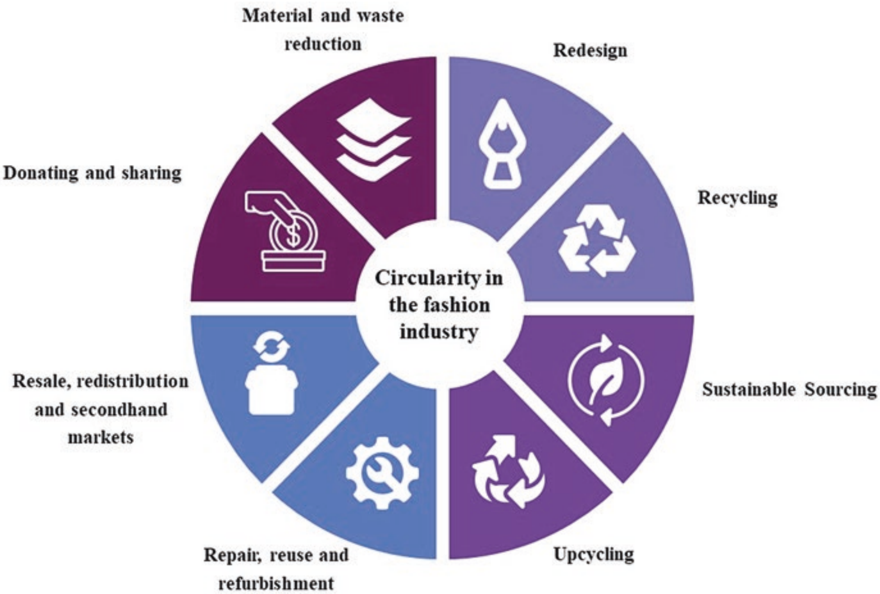

Fig. 6 Circularity in the fashion industry. (Figure created by the authors) (Data from Dragomir and Dumitru 2022)

down the materials into small parts (molecules–monomers) that were used to make any synthetic materials present (e.g., polyesters) can be applied for recycling purposes (Clark, 2022). Furthermore, the exploitation of valuable materials found in fashion industry waste is of high importance. Technologies such as pyrolysis, chemical extraction, and the production of new material from waste are reported. For example, the high content of cotton and PET in waste materials can be exploited for their transformation to new products (Clark, 2022). The different composition of textile waste presents both a problem and a chance. For example, cotton and polyester can be effectively separated due to their different chemical parameters, under particular processing conditions as shown in Eq. 1 (Clark, 2022; Haslinger et al., 2019).

$$\text{Cotton waste} \quad FeCl_3 \overset{130\ C}{\quad} \text{Glucose} \overset{190\ C}{\quad} \text{Porous Carbon} \quad FeCl_3 \tag{1}$$

Following the fashion industry value chain, rental and resale are two approaches that are applied to circular strategy. Platforms for clothing rental and resale allow customers to rent or buy used clothing, which lowers the demand for new products and increases the lifespan of existing ones. Furthermore, brands can collaborate with manufacturers and suppliers to establish closed-loop circular supply chains that reduce waste and encourage material recycling and reuse (Amed et al., 2022; Idiano D'Adamo et al., 2022a, b; PWC, 2018). One of the most important stages in the CE framework of fashion industry is the creation of new innovative materials. It is possible to create new, environmentally friendly materials and technologies that can be recycled or biodegraded at the end of their useful lives (Patti et al., 2021). For instance, some businesses are creating textiles using recycled plastic or agricultural waste (Sezgin & Yalcin-Enis, 2020; Siqueira et al., 2022).

Textile production involves various processes, which are dependent on the type of textile being produced and the production methods being used. An overall process flow production (Fig. 7) line may include the fiber production where natural fibers (e.g., cotton, wool, and silk) are harvested, while synthetic ones (e.g., polyester and nylon) chemically formed. The fibers are then spun into yarns either manually or through mechanical equipment. The yarn is then wound onto bobbins or cones which are woven or knitted together to create fabric. A pre-treatment step is followed for "cleaning" the materials from any impurities, which may involve washing, bleaching, or chemical treatment (wet processing). Furthermore, fabric is dyed or printed with various colors and designs either by hand or by using machinery. Afterward, the fabric is finished to give it the desired texture, feel, and appearance through brushing, coating, etc. The fabric is now finished and ready to be cut into patterns and sewn together to create the final product, such as clothing. The finished products are then distributed to retailers, wholesalers, or directly to consumers (Lin et al., 2022; Patti et al., 2021; Shuvo, 2020).

Significant environmental impacts exist from the textile industry which may involve (i) water and chemical pollution, (ii) high energy consumption, (iii) waste and wastewater generation, and (iv) deforestation. The textile industry is one of the

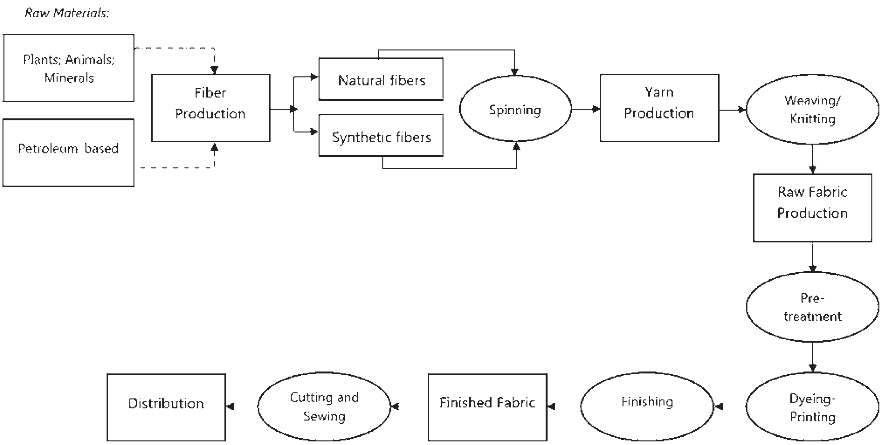

Fig. 7 A general overview of the processes involved in the textile industry. (Figure created by the authors) (Data from Patti et al. 2021 and Shuvo 2020)

largest industrial water consumers in the world, and furthermore produces high amounts of wastewater, which are contaminated with dyes, chemicals, and other pollutants. Regarding energy consumption, the textile industry is one of the most energy-intensive industries in the world. The production of textiles requires a lot of energy for processing, spinning, weaving, and finishing. This energy consumption contributes to greenhouse gas emissions, which are a major contributor to climate change (Šajn, 2019). A great amount of waste is generated through the textile industry, which may include fabric scraps and packaging materials. These materials can end up in landfills, where it can take years to decompose, or it can be incinerated, which can release harmful pollutants into the air. Lastly, the textile industry is a major consumer of natural resources, including wood and cotton (PWC, 2018). The production of these materials often requires the clearance of natural habitats, which can have a devastating impact on biodiversity and ecosystems. It is important for the industry to adopt sustainable practices and reduce its environmental footprint as for example the use of eco-friendly dyeing of textiles (Amutha et al., 2020; Che & Yang, 2022; Lara et al., 2022; Pervez et al., 2023).

One of the most critical stages in the textile industry that can be linked to the CE is fabric production. This is because fabric production requires significant amounts of energy, water, and raw materials and generates a large amount of waste and pollution. For example, Shuvo (Shuvo, 2020) reports high volumes of water demands for cotton cultivation (up to 550–950 L/m^2) and for its further processing (29 tn/kg of water per product kilogram) (Shuvo, 2020). The transition to a circular economy model, the textile industry needs to focus on reducing the environmental impact of fabric production by implementing sustainable practices such as using recycled fibers, reducing water consumption and pollution, and adopting cleaner production methods. Additionally, the circular economy approach would involve extending the lifespan of fabrics through strategies such as reuse, repair, and recycling, thereby reducing the amount of waste generated by the industry. Furferi et al. (2022) proposed a set of guidelines to guide textile industries to adopt circular economy processes. Chen et al., (2021) proposed that the industry has to focus on specific stages in order to achieve circular economy transition. These stages are as follows: (i) materials, (ii) production, (iii) usage, and (iv) after usage of clothes. More specifically, regarding (i), raw materials efforts should be focused for increasing of their recyclability. This could be achieved by using big data material informatics to recognize new materials. Also, regarding small parts such as plastic fibers and filament, which are untraceable fiber plastics released in the environment, efforts should be made for their replacement with biodegradable materials. (ii) Printing and the use of naturally derived dyes big batch dyeing processes can be used to replace high-energy, high-water usage, and high pollution processes like wet processing during dyeing. (iii) Through brand commitment and policy, fast fashion can be discouraged in favor of more high-quality, long-lasting clothing that is suitable for long-term use. (iv) The use of Radio Frequency Identification (RFID) tags can help sorting of fibers and fabrics before recycling (Chen et al., 2021). Schumacher and Forster (2022) indicate the need for overall collaboration, and data and information exchange to achieve circular economy targets. They also propose specific data needs to facilitate a circular economy for textiles.

Furthermore, several other new technologies are used for circularity in the fashion industry production line. Some of these include 3D printing which allows to produce garments and accessories with minimal waste, as it only uses the necessary amount of materials to create the item. It also enables on-demand production, reducing the need for large-scale production runs and excess inventory (Pasricha & Greeninger, 2018). RFID tags and block-chain technology can be used to track garments and accessories throughout the supply chain, providing transparency and traceability. This can help to reduce waste and improve sustainability by enabling better inventory management and reducing the risk of overproduction (Agrawal et al., 2021; Chen et al., 2021).

5 Monitoring Circularity and Sustainability of the Fashion Industry

Textile products have a significant environmental impact at every stage of their life cycle. As more clothes are manufactured, used, and disposed than ever before, the textile sector's existing linear, take-make-dispose approach puts a tremendous stress on planet's resources, environment, and climate (Abdelmeguid et al., 2022; Dissanayake & Weerasinghe, 2022; Koszewska, 2018). Even though these challenges have been extensively researched, methods for addressing them have received significantly less attention. Despite the fact that several practices have been proposed, these are still generally scattered and not interpreted through an overarching approach, inhibiting understanding of how circular supply chains should be handled and integrated (Saccani et al., 2023). Furthermore, a new holistic model for monitoring both circularity and sustainability in textile sector is imperative. This new approach should include key performance indicators (KPIs) as well as Life Cycle Assessment (LCA) and Quality Protocols (i.e., ISO) for quantifying the environmental impacts, to provide efficiency actions, assess the level of success in achieving the circular economy's objectives, as well as all legislative requirements (Luján-Ornelas et al., 2020; Papamichael et al., 2022; Zorpas et al., 2021).

5.1 Standards, Protocols, and Certifications

The textile industry is a significant economic sector on a global scale, and so are the technical standards, which frequently serve as the international language of the entire supply. Despite the fact that numerous voluntary self-regulations have proven unsuccessful in transitioning to a circular model, standards offer the ability to give instruments for the textile sector to embrace circular economy concepts (Luján-Ornelas et al., 2020; Textile_Exchange, 2023). Standards can facilitate circular design by preparing for durability, reuse, repair, and promoting recyclability at the end of life, along with an overall decrease in the environmental impacts (OECD, 2020). While standards play a vital role in supporting forthcoming regulatory needs, they are currently now insufficient or non-existent on crucial concerns that might greatly contribute to sustainability and circularity. New standards are needed to promote accurate evaluations of textile performance and materiality, along with providing trustworthy data and assessment methods that encourage the reuse, repair, and recycling of textiles. It seems that there is an urgent need to define what "circular" entails for the sector, as well as establish and standardize circular actions. This process should allow for the evaluation of direct consequences such as durability, prolonged life cycle, use of materials, and minimized waste production (Schumacher & Forster, 2022).

Regardless of existing standards' weaknesses, several international certifications, schemes, and similar initiatives have emerged to evaluate the level of adoption of circular economy and sustainability in textile sector. The most important are as follows: (i) labels, namely, the EU Ecolabel, Nordic Swan, Blue Angel; (ii) certifications schemes, such as the Global Organic Textile Standard, Textile Exchange, Cradle-to-Cradle, (iii) number of initiatives, remarkably the ones from WRAP which look at Design for Longevity and their Clothing Longevity Protocol, as well as the Jeans Redesign Guidelines; (iv) additional actions on the topic from the Nordic Council of Ministers, and the Ellen MacArthur Foundation (Ecos, 2021; Luján-Ornelas et al., 2020).

5.1.1 Labels

Since 2009, the European Commission has promoted the use of sustainable practices in the textile sector through the EU Ecolabel, a voluntary eco-labeling program (European Commission, n.d.). Textile products having the EU Ecolabel are defined by more sustainable fiber production, a longer product life, lower emissions from the manufacturing process, and restrictions on the use of harmful substances (Clancy et al., 2015; Furferi et al., 2022). The EU Ecolabel defines nine "fitness for use requirements" related to resources efficiency, particularly durability. Textiles with the ecolabel must meet those requirements and could therefore be more durable than non-labeled textile products. The Nordic Council of Ministers launched the Nordic Swan Ecolabel in 1989 as a voluntary eco-labeling scheme for the Scandinavian nations of Denmark, Finland, Iceland, Norway, and Sweden (The Nordic Swan Ecolabel, 2023). The purpose was to act as an effective tool to assist organizations develop more sustainable products and services, allowing consumers to choose the most environmentally friendly goods. The Nordic Swan eco-label for textiles is recognized for its rigor—the requirements are extremely stringent on the usage of chemicals (Nordic Council of Ministers, 2017). Its newest version emphasizes how textiles could contribute to the circular economy. This means a greater emphasis on product longevity, take-back methods, re-design, and fiber composition. However, even in Nordic nations, the share of eco-labeled textiles in overall textile turnover is still quite low (Nordic Council of Ministers, 2018). The Blue Angel criteria for textile consider every step of the production process and reflect all processes that are related to the environment and health. The Blue Angel mainly serves as an ecolabel, but customers are increasingly evaluating working conditions in manufacturing. In addition to the traditional environmental criteria, social aspects of textile production are considered (Blue Angels, 2021).

5.1.2 Certifications Schemes

The Global Organic Textile Standard (GOTS) is the world's top organic textile production standard, integrating ecological and social factors. GOTS provide a trustworthy assurance to the consumer from raw material harvesting to environmentally and socially responsible manufacture and labeling (Global Organic Textile Standard, 2021). The standard prohibits the use of chemicals, which are hazardous to health, and regulates the water and energy consumption (European Environment Agency, 2022; Luján-Ornelas et al., 2020). Cradle-to-Cradle is a nature-inspired design concept that emerged in the 1990s. It refers to a manufacturing process in which products are developed for closed-loop systems in which every output ingredient is harmless and beneficial—either to decompose naturally (referred to as a biological nutrient) or to be completely recycled into high-quality resources to be reused in subsequent product generations (referred to as a technical nutrient) (Isaac, 2018). The Cradle-to-Cradle Certified Product Standard takes a comprehensive approach to evaluating a product's design, manufacturing procedures, and usage and reuse potential. It guides designers and producers through a process of continuous improvement (Henninger et al., 2019).

5.1.3 Other Initiatives

In 2013, WRAP Design for Longevity was introduced (WRAP, 2013). It includes resource-efficient business approaches, apparel life-cycle design, fiber and fabric choices, customer behavior, reuse, and recycling. It is divided into four sections: size and fit, textile quality, styles, colors, and care. The publication provides best practices and recommended options for every clothes category, including appropriate fiber and fabric selection, design and production, care and repair, and reuse and disposal. The WRAP Clothing Longevity Protocol, published in 2014, gives guidance for testing and performance requirements (WRAP, 2014). The Jeans Redesign guidelines motivate prominent brands, mills, and producers to reinvent the jeans production process. They are a template for group action to scale circular practices founded on the concepts of a circular economy. The guidelines serve as an initial basis for enterprises to design and manufacture products that adhere to the concepts of a circular economy. Designing jeans that are more durable, can be remade, and are produced from safe, recycled, or renewable resources. They are a "minimum bar" that will be evaluated and modified on a regular basis to guarantee they continue to propel the sector forward. The Jeans Redesign guidelines by Ellen MacArthur Foundation motivate prominent brands, mills, and producers to reinvent the jeans production process (Ellen MacArthur Foundation, 2021a).

Despite the fact that several instruments have been developed to embrace circular economy and a sustainability in the textile sector, their approach does not focus on every one of the textile strategy's objectives related with durability, recyclability reusability, and repairability (Table 1) (Ecos, 2021).

Standards remain a long way from enabling a circular textile industry successfully. However, it is worth noting that, although insufficient, considerable area already has been covered. Protocols have been introduced to ensure the safety, quality, and efficiency of products and services while taking all three pillars of sustainability and circular economy goals into account (Loizia et al., 2021; Papamichael et al., 2023b). According to the International Organization for Standardization (ISO), common protocols developed for textile sector include (i) ISO 5077 for determination of dimensional change in washing and drying, (ii) the ENISO 13934 series on tensile properties of fabrics, (iii) EN-ISO 12945 for the determination of fabric propensity to surface fuzzing and to pilling, (iv) EN-ISO 12947 for determination of the abrasion resistance of fabrics, and (v) EN-ISO 105 test for color fastness (ISO, n.d.).

Table 1 Coverage of material efficiency aspects per instrument applied to textile products (Ecos, 2021)

Name of Instrument		Coverage of material efficiency aspects			
		Durability	Reusability	Repairability	Recyclability
	Eu Ecolabel	✓	✗	✗	✗
	Nordic Swan	✓	✗	✗	✗
	Blue Angel	✓	✗	✗	✗
	WRAP	✓	✓	✓	✓
	Nordic Council of Ministers	✓	✓	✓	✓
	Global Organic Textile Standard v6.0	✗	✗	✗	✓
	A new textiles economy: Redesigning fashion's future	✓	✓	✗	✓
	Cradle-to-Cradle	✗	✗	✗	✓
	The Jeans Redesign Guidelines	✓	✗	✗	✓

5.2 *Key Performance Indicators (KPIs)*

Circularity KPIs categorized according to different characteristics that encompass the level of circular economy adoption, the circular economy loops, the effectiveness, and the general acceptance of circularity (Rincón-Moreno et al., 2021). KPIs are computational sets that attempt to measure, simplify, and transmit information that is difficult to observe unequivocally (Papamichael et al., 2023b). They can assess the progress and optimization of a product or a service against a specific goal (Vardopoulos et al., 2020). Most of circularity KPIs have received criticism for failing in representing the greater context of the circular economy. This highlights a limitation in comprehensively assessing data coin circular economy approaches. As an outcome, the methodologies and criteria created to assess the level of circularity for products, services, or organizations fail to comply with a commonly accepted set of principles (Saidani et al., 2019). Establishing circular economy KPIs does not come without challenges. Despite their underappreciation, the usage of KPIs along with goals will be crucial. Admittedly, “what you can’t measure, you can’t manage.” When it comes to KPIs development, stakeholders tend to communicate in “many languages.” With the goal to successfully encourage the transition to a circular economy, indicators must be constantly relevant, generally recognized, and easy to use (Corona et al., 2019; D’Adamo et al., 2022a, b). The same holds for KPIs in the textile sector since there is not a common set of indicators for textile recycling technology and assessing the tangible performance of the circular economy textiles initiatives (Jia et al., 2020). However, occasional attempts have been made to develop indicators targeted at evaluating specific aspects of fashion circularity.

Galatti and Baruque-Ramos (2022) in their study identified 40 KPIs that measure social innovation in the context of the Brazilian textile and fashion sector related with employment, relations between employers and employees, workplace health and safety, educational and training opportunities, diversity and equal chances, and equitable income distribution. In another study carried out by Dragomir and Dumitru (2022) try to gather information on practical circularity solutions and indicators developed by largest companies in the fast fashion industry. They also highlight the fact that the indicators used, associated with a certain aspect and that there are very few indicators associated with the design stage. Among the most significant KPIs developed by the six big global players (H&M, Inditex, Gap, OVS, PVH, VFS) are as follows: (i) “number of stores with recycling systems for main types waste”; (ii) “number of employees who have received training on circularity design”; (iii) “quantity of fabric saved in creating new materials”; (iv) “proportion of recycled materials in the packaging used”; (v) “the proportion of facilities with water-efficient equipment”; (vi) “the number of supplier declarations in the traceability management system”; (vii) “the quantity of garments produced using recycled materials”; and (viii) “the avoidance of restricted chemicals in finished goods.” Rossi et al. (2020) developed a set of indicators focusing on the three pillars of sustainability used by circular business models (i.e., textile sector) to capture the advancements generated by the circular economy that standard metrics fail to evaluate. These indicators seek to quantify reduction of raw materials; renewability (i.e., renewable energy, renewable raw materials); recyclability (i.e., recycled materials, recyclability potential); reduction of toxic substances; reuse (i.e., in manufacturing process); product longevity; financial results (i.e., cost reduction, revenue generation, profitability); job creation; client mindset. Furthermore, another four indicators related with fashion circularity to assess the circularity of fiber inputs and include the following: (i) The Ellen Macarthur Foundation Material Circularity Indicator (Ellen MacArthur Foundation, 2019); (ii) The World Business Council for Sustainable Development %age circularity indicator (WBCSD, 2020); (iii) The Circular Materials Guidelines feedstock requirements (Fashion Positive, 2020); and (iv) The Cradle-to-Cradle Certified™ Product Standard Material Reutilization Score (Cradle-to-Cradle Products Innovation Institute, 2020).

5.3 Life Cycle Assessment (LCA)

LCA is a globally accepted and commonly used approach for analyzing a range of environmental impacts throughout the product and service life cycle. In brief, an LCA covers for all environmentally relevant flows of materials and energy within system boundaries, from cradle to grave, and uses description methods to "translate" these flows into environmental stresses defined by various categories of impact such as climate change, eutrophication, acidification, contamination, and water depletion (Corona et al., 2019; Peters et al., 2018). In this method, LCA presents an overview of the studied product's environmental performance (Shou & Domenech, 2022; Stylianou et al., 2023). The information collected can be used to make choices, such as prioritizing efforts to enhance environmental performance (Wiedemann et al., 2022).

Numerous LCA studies have been carried out to assess the environmental impact of textiles during their whole lifecycle (Corona et al., 2019; Rossi et al., 2020; Shou & Domenech, 2022). According to Quantis (2018), the procedures of dyeing and finishing, yarn preparation, and textile manufacturing have the greatest effect on the production stage. Dyeing and finishing consume an extensive amount of energy and chemicals, and they contribute to water pollution. On the other hand, according to the Global Fashion Agenda, (2021), due to the cultivation practices that rely significantly on agrochemicals and water, textile manufacture has a major effect on freshwater consumption. Leather is an essential material in textile sector and fashion accessories, with larger impacts per kilogram of material than cotton and synthetic fibers (Global Fashion Agenda & The Boston Consulting Group, 2017). Based on LCA research, the leather industry leads to acidification, eutrophication, climate change, and water shortages. Quantis (2018) assessed leather shoes to synthetic and textile shoes and concluded that, whereas leather shoes account for 25% of total footwear manufacturing, they contribute for 30–80% of environmental impacts.

6 Circular Business Models Development

6.1 Crafting a Circular Business Model

The fashion sector has taken major advances toward circularity and sustainability (Niinimäki et al., 2020). Eliminating any stereotypes about circular thinking, such as re-using clothing through second-hand markets, the environmental and social effects of second-hand clothing, as well as the added benefits of price reduction, are critical elements in the development of viable business models that provide essential benefits to consumers (Borg et al., 2020; Idiano D'Adamo et al., 2022a, b; Kasavan et al., 2021). Price reduction in the fashion sector in terms of circularity development must be a significant component of the creation of circular business models. According to Zorpas et al. (2021), there is a substantial association between income level and waste generation, which translates to a correlation between income level and fashion waste output. The relationship extends to a more ethical dimension of fashion production, such as occupational hazards arising from the proximity of residential areas to a textile industry, which is correlated with the standard of income as there is a higher level of danger for low- and middle-income countries (LMIC), space for LMICs as mentioned in Sect. 1.

According to Abdulgadir and Abdulgadir (2020), five strategies must be implemented to strengthen the supply chain (Fig. 8): (i) sustainable manufacturing, (ii) green material preparation, (iii) green distribution, (iv) consumer ethics, and (v) re-shoring against offshore. The authors suggested that to fulfill the companies' competitive objectives, a change from labor-intensive to capital-intensive suppliers must occur to develop strong branding, trust, collaboration, transparency, and traceability. This will be regarded valuable since it will allow societal acceptability through the introduction and collaboration with strong capital providers, as well as technological innovation (i.e., raw materials from organic sources and biodegradable plastic) in terms of green materials and process efficiency. At the same time, according to Dissanayake and Weerasinghe (2022), there are four basic concepts when dealing with circular fashion: (i) resource efficiency, (ii) circular design, (iii) product lifespan extension, and (iv) end of life of fashion items. These issues are addressed by introducing alternative raw material inputs (such as recycled polyethylene terephthalate, or RPET, plant-based materials, and waste), introducing design longevity and customization, repairing and renting to extend product lifetime, and

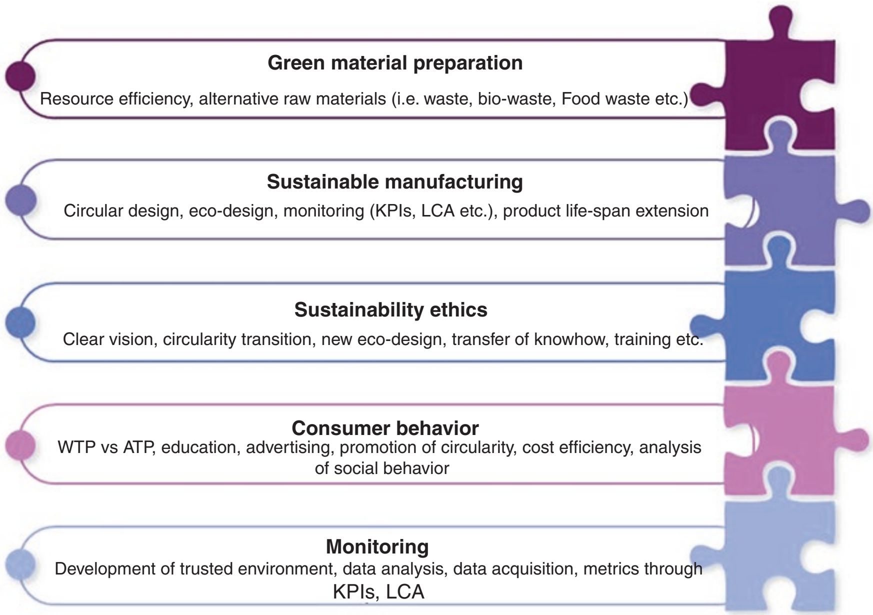

Fig. 8 Strategies to be implemented for circular fashion. (Figure created by the authors)

"R" strategies for end-of-life treatment such as recycling, refurbishing, and remanufacturing (Ellen MacArthur Foundation, 2021b; Gupta et al., 2019; Mahdi et al., 2021).

Furthermore, as evidenced by several premium high fashion firms, greater flexibility is required to help in the reduction of demand risk. Hugo Boss and Benetton are forsaking worldwide supply networks linked with low-cost manufacture (e.g., Bangladesh and Vietnam) in favor of investigating local manufacturing or enterprises closer to their own premises (Arribas-Ibar et al., 2022). This offers various advantages, both environmental (i.e., supply transportation) and providing greater access and control over production (McMaster et al., 2020). Simultaneously, improving the carbon footprint of the fashion industry by replacing fossil fuel power with alternative energy sources (i.e., renewable energy) has been proposed as a business model for the fashion industry's energy consumption, production, and use (Peters et al., 2021).

According to the above, holistic circular business model for circular fashion has been created that mainly includes seven main common elements (Papamichael et al., 2022, 2023a, c): (i) new eco design development for increasing product's lifecycle; (ii) the development of trusted environment by monitoring the performance throughout the production line (i.e., KPIs, LCA, monitoring, and quality protocols); (iii) improve clothing characteristics (i.e., durability); (iv) use of alternative raw materials (i.e., waste) instead of conventional ones (i.e., cotton); (v) use the "R" strategies of circular economy (i.e., reuse, reduce, recycle, remanufacture, refurbish, rent, and repair); (vi) develop an inclusive vision for sustainable development in the fashion industry; and (vii) advertising, training, and promoting circular fashion to both consumers and employees of different parts of the supply chain (Antoniou & Zorpas, 2019; D'Adamo & Lupi, 2021; Kazamias & Zorpas, 2021; Manshoven et al., 2019; Papamichael et al., 2022, 2023a, c; Symeonides et al., 2019; Voukkali et al., 2021; Voukkali & Zorpas, 2022). More specifically, it is vital for circular business models to include "R" strategies for development such as the following: *Refuse* (waste generation); *Reduce* (waste volume); *Reaccept* (new waste-derived items); *Rethink* your purchasing and disposal practices, *Reuse* (excellent quality clothing to extend its life); *Rent* (in the case of weeding, e.g., rent garments rather of purchasing); *Repair* clothes that may be reused, rented, or donated; *Recycle* (recyclable clothing); *Refurbish* (modernizing old clothing); *Remanufacture* (using used parts of discarded clothing in a new product with the same function); *Repurpose* (using discarded products in a new one with the same function); *Recover* (recovering materials from textile and other waste for the production of raw materials to be used in industry) (Papamichael et al., 2022; Zorpas, 2020). Even if such strategies seem closely related and to some even identical, their uniqueness in their actual implementation could create a spiral of processes which can entail new understanding and innovation from consumers and the industry for the development of a targeted Circular Economy business plan (De Ponte et al., 2023; Papamichael et al., 2023a) (Fig. 9).

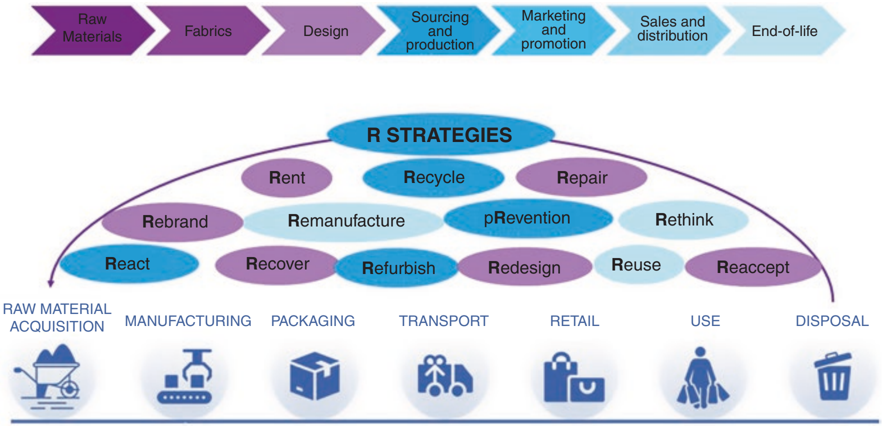

Fig. 9 R strategies of circular fashion to convert linear production line to circular. (Figure produced by the authors)

6.2 Optimization and Barriers of Textile Circular Business Models

In relation to the technologies used for circularity in the fashion industry production line, some of the optimization points include the improvement of production process efficiency, which includes waste reduction and resources optimization. To achieve the application of new circular economy processes, the technologies should be able to be implemented across the industry and in different regions of the world and additionally and should be cost-effective in order to be adopted easily. Furthermore, efforts should be focused on consumers' acceptance. This can be strengthened by creating products with a pleasing appearance, functional, and affordable, while also being sustainable and environmentally friendly (Ellen McArthur Foundation, 2017; Gazzola et al., 2020; de Hugo et al., 2021; PWC, 2018). The need for saving funds and resources is also linked to maximizing resource consumption, reducing energy waste, and reducing waste, which will influence the environment both inside and outside of a circular company (Gazzola et al., 2020).

There are several barriers to the adoption of circular economy technologies in the fashion industry (Abbate et al., 2023; Jia et al., 2020; Luoma et al., 2022). First, financial barriers are one of the most important obstacles faced from companies. The implementation of circular economy technologies can be expensive, which can be a barrier for smaller businesses or those with limited resources. Also, the lack of infrastructure, such as recycling facilities or waterless dyeing equipment, can hinder the adoption of circular economy technologies. The adoption of circular economy technologies may require specialized knowledge and skills, which may not be readily available in the fashion industry. Consumers may not yet fully understand or appreciate the benefits of circular economy technologies or may not be willing to pay a premium for sustainably produced garments. Some fashion industry stakeholders may be resistant to change and may be hesitant to adopt new technologies or processes. Also, there may be regulatory challenges related to the adoption of circular economy technologies, such as certification requirements, which can add complexity and cost to the implementation process. The supply chain in the fashion industry can be complicated because there are many parties involved in the production process. It can be difficult to coordinate the adoption of circular economy technologies throughout the supply chain.

Furthermore, mismanagement, insufficient legislation control, lack of digitalization, skilled workforce, funding, low performance, material and energy use, waste management, resource quality, governmental support, market demand, resistance to change of mindset, management support, and short-term visions are all associated with the fashion industry‘s supply chain, according to Kumar et al. (2021). According to their findings, the most significant barrier to implementing circular techniques is a shortage of skilled labor. Tura et al. (2019) classified such limitations and obstacles into seven categories: (i) environmental, (ii) economic, (iii) social, (iv) institutional, (v) technical, (vi) supply chain, and (vii) organizational. These categorizations enable decision-makers to focus on the major issues and assess the actual challenges of each unique facility (Abdelmeguid et al., 2022; Gray et al., 2022).

Abbate et al. (2023) report that the main barriers associated with circular economy in the textile, apparel, and fashion industries are "(i) Restricted technology which makes separating materials difficult, (ii) high research and development costs, (iii) the supply chain complexity (which includes many stakeholders involved in the manufacture), (iv) Undefined performance metrics, (v) Weak alignment with the current strategy, (vii) Lack of internal skills and competences, (viii) Lack of customer interest" (Abbate et al., 2023). Hugo et al. (2021) report that one main barrier is fast fashion consumer culture. Despite the fact that the world is becoming more aware of social and environmental issues, awareness has not yet reached large populations regarding the effects of fast fashion (de Hugo et al., 2021). Lack of human, technological, and financial resources has been cited as a major barrier to the adoption of the circular economy in the textile sector (Luoma et al., 2022). The need for increasing consumer acceptance is critical. Digital technologies are fostering new methods of exchanging and sharing goods and services. Digitization is widely acknowledged as a catalyst for innovation in many industries. In other consumer goods markets, like consumer technology, used goods and resale have significantly grown, thanks in large part to online platforms (Charnley et al., 2022; Chauhan et al., 2022).

6.3 Customer Attitude and Behavior

As mentioned throughout the chapter, overconsumption of textiles and by extend raw material depletion can be easily attributed to consumer behavior and characteristics like compulsive purchasing patterns, disposal practices and mindset, linked with fast fashion trends. Waste management and the fashion industry are strictly linked with consumer behavior as they are key players of the environmental impact of the supply chain (Bansal, 2020; Borg et al., 2020). Taking into account consumption patterns and habits will provide useful information on the level of understanding of the citizens on circular fashion but also on their willingness to pay for circular products (i.e., clothes made from waste) but also their ability to pay (i.e., for labeled or non-labeled circular products). Luxury fashion can encourage sustainability and quality, as well as exclusivity to customers of various economic statures, thereby providing a heritage for the brand of fostering sustainability and circularity.

During the last decade, the quantity of research on ecologically responsible consumer behavior and environmental views has grown. Consumers have grown more reactive, demonstrating more knowledge as well as a readiness to change behaviors and choose alternative goods. Despite this, customer sentiments are frequently viewed as contentious or illogical, and it is difficult to find specific grounds for negative opinions. In general, consumer environmental awareness and concerns rarely translate into their purchasing patterns. There is a wide range of green behavior where, in general, green consumers are interested in ecological lifestyles and environmental consciousness. Therefore, they carefully select their products and volunteer in many different environmental events. But social constructs evolve around the influence of social norms in members of society. Therefore, interpersonal communication is vital in building rules for consensus and affirmation of behavior, to establish new social standards for sustainable fashion purchasing (Vehmas et al., 2018).

Lack of consumer awareness, engagement, and social responsibility is a critical aspect for circular fashion because eco-conscious purchasing is required to aid in the development of a new mindset; knowledge exchange and education of both consumers and staff are required to make this transition possible (Khan et al., 2022; Papamichael et al., 2022; Wang et al., 2022). A great debate and challenge concerning customer attitude is their willingness to pay (WTP) vs their ability to pay (ATP) for circular and green products. As sustainable claimed products are becoming more and more popular in the fashion industry and market, they also have gained increasing attention on behalf of the consumers. Still, there is a distinct difference between what customers are willing to pay for clothes/shoes/accessories made from waste and what they can pay for labeled or non-labeled circular products (Papamichael et al., 2022; Zhang et al., 2021). In general, higher income level means greater WTP and ATP for green products due to the general access of higher income statues to environmental education, social attitude (i.e., adjustment of circular advertising effect), cultural background (i.e., Europeans tend to care more about environmental issues), religious background (Muslims are not at large concerned with sustainability while Buddhists prioritize social equity), and ability to prioritizing fashion circularity (i.e., primary human needs like food, shelter, and safety have been established).

By understanding customer behavior and preferences, fashion companies can create products and services that align with sustainable consumer values. This includes designing garments that are durable, repairable, and recyclable, as well as offering rental services, clothing swaps, and other circular business models. Moreover, customer behavior also drives demand for sustainable fashion, creating an incentive for companies to adopt circular business practices. As more consumers prioritize sustainability and demand eco-friendly fashion options, companies will have to adapt to meet these preferences, potentially leading to a more significant shift toward a circular fashion industry. Overall, customer behavior is essential in driving the transition toward a circular fashion industry. By educating consumers on the benefits of sustainable fashion and creating products and services that align with their values, companies can encourage more sustainable consumption habits and work toward a more sustainable future.

7 Case Studies

There are many successful case studies of circular economy practices in the fashion industry. The Ellen MacArthur Foundation has published several case studies on circular economy practices in the fashion industry (Ellen McArthur Foundation, 2017, 2023; Kowszyk & Maher, 2018). According to Ellen McArthur Foundation (2023), "the vision of a new global textiles system relies on three focus areas: (i) New business models that increase clothing use, (ii) Safe and renewable inputs (iii) Solutions so used clothes are turned into new." The strategy is focusing on designing products which will minimize waste produced and pollution linked to it, create a circulate use of materials and products, and finally regenerate nature (Ellen McArthur Foundation, 2017).

7.1 H&M

The Swedish fashion retailer H&M has implemented several circular economy initiatives, including its garment collection program, which encourages customers to bring in old clothing for recycling. H&M also uses recycled and sustainably sourced materials in its clothing and has set a goal to become 100% circular and climate positive by 2030. In 2022, the company introduced the "Circulator" which is new design tool that can be used internally as well as from other companies and designers in order to be able to design products according to circularity (Ellen McArthur Foundation, 2022; H&M Group, 2023). In the same context, "Looop" was developed by the H&M Foundation (2020) in Sweden and the Hong Kong Textile and Clothing Research Institute (H&M: Magazine, 2020). Within 5 hours, Looop transforms discarded clothes regularly provided by customers into new clothing items. This initiative is very similar to other repair services like "Clothes Doctor" which offers simple and convenient clothe repair as well as other variety of services. Clothes Doctor was founded in response to traditional clothing repair services that it found unappealing and disempowering. Through their services, customers are educated and empowered by newfound knowledge regarding clothing care and sustainability while benefited with convenient user experience fit in a busy lifestyle (Ellen MacArthur Foundation, 2021b).

7.2 ERDOS Cashmere Care Center

ERDOS cashmere care center, located in Beijing, constitutes a cleaning, maintenance, and repair service to ERDOS Group members. Anyone can join and earn credits to be "cashed" in the form of such services. By reducing water and detergent consumption, centralized and specialized care services can help the environment. Many cashmere garments that had been worn for more than 20 or even 30 years were sent to be looked after (Ellen MacArthur Foundation, 2021c).

7.3 Patagonia

The outdoor clothing company Patagonia has a long-standing commitment to sustainability and circularity. Patagonia encourages customers to repair their clothing rather than replacing it and offers a repair service for its products. The company also uses recycled and organic materials in its clothing and has set a goal to be carbon neutral by 2025 (Perkins et al., 2023).

7.4 Levi Strauss & Co.

The denim company Levi Strauss & Co. has implemented several circular economy initiatives. Their strategy includes producing products with future use passing from "end of life" to "end of use" application for products design. For example, their efforts involve the "Water Less" technology, which reduces the amount of water used in denim production. The company also offers a recycling program for old clothing and has set a goal to use 100% sustainable cotton by 2025–2026 (Levi Strauss & Co, 2021). This is very similar to the company Circular Systems which has developed a technology called "Texloop," which uses a closed-loop system to recycle textile waste into new fibers. Texloop is being used by several fashion brands. Furthermore, they developed "Agraloop" with which they are able to transform crop waste into scalable high-value natural bio-fibers (Circular Systems, 2023).

7.5 Mud Jeans

Mud Jeans, a Dutch company, offers a circular business model, where customers can lease jeans rather than buying them. When the jeans are returned, they are repaired, washed, and resold or recycled into new products. The company uses technologies in order to minimize its environmental footprint such as laser and ozone are used instead of product "washing" in order to minimize water consumption. Also, the dye used "indigo dye" is Cradle-2-Cradle certified (Mud Jeans, 2023). Similarly, a Japanese company "JEPLAN" uses chemical recycling to turn used polyester clothing into new polyester fiber. Their strategy "Closing the Loop on Polyester" uses chemical recycling to turn used polyester clothing into new polyester fibers where the recycling process uses 100% raw materials derived from waste fibers (JEPLAN, 2022).

7.6 Adidas

Adidas, a sportswear company, has put into practice a number of circular economy initiatives, such as using recycled materials in its footwear and clothing and creating a closed-loop manufacturing process. The breakthrough by Adidas "FUTURECRAFT.LOOP" will create performance footwear that is completely recyclable. The new product is a 100% recyclable running shoe that can be sent back to Adidas, disassembled, and used to make new running shoes (Adidas, 2022). Nike, following Global Fashion Agenda, created circularity where products are designed under specific principles such as material choices, cyclability, waste avoidance, disassembly, green chemistry, refurbishment, versatility, durability, and circular packaging (NIKE, 2022).

7.7 "By Rotation"

In terms of customer behavior and attitude, "By Rotation," a peer-to-peer fashion rental platform was launched in 2019, which pushed users to rent what they need and donate what they do not. The mobile app simulates social media habits by giving the options to like, comment, and share its products among users. It now has over 150,000 users and allows renters to set the price of each item per day as well as the rental period. By increasing the number of users per item, By Rotation effectively increases clothing use. It may also eliminate the requirement for fresh clothes creation if customers decide to rent rather than buy something they will not wear again. If five individuals share one occasion dress instead of each purchasing their own, resource consumption and environmental consequences are decreased. The peer-to-peer networking app allows users to trade idle items with one another. The firm does not acquire merchandise and does not collect

Table 2 Successful circular economy practices in the fashion industry

Case study	Company	Circular economy practice or product	Reference
1	H&M Group	Circular products, circular supply chains, circular customer journeys	Ellen McArthur Foundation (2022) and H&M Group (2023)
2	Patagonia	Reduce, reuse, repair, recycle and re-imagine	Perkins et al. (2023)
3	Levi Strauss & Co.	Water-less technology	Levi Strauss & Co. (2021)
4	NIKE	Circularity strategy	NIKE (2022)
5	Adidas	Closed-loop manufacturing process, recycled materials; FUTURECRAFT. LOOP	Adidas (2022)
6	Circular Systems	Texloop; Agraloop	Circular Systems (2023)
7	Mud Jeans	Lease, repair, upcycle	Mud Jeans (2023)
8	JEPLAN	Chemical recycling for polyester fibers	JEPLAN (2022)

subscription fees in its efforts to develop a diversified and style-conscious community (Ellen MacArthur Foundation, 2021d).

7.8 Ralph Lauren

Ralph Lauren is said to be one of the first premium firms to embrace circular thinking. Because of the "The Lauren Look" rental subscription service, the firm has been able to profit from the influx of clients with smaller budgets, as well as address the issue of overproduction that the company was having. Customers can rent apparel that, in normal circumstances, would be purchased and worn only a few times. With membership fees starting at $125, the value of this rental industry is expected to reach $4.4 billion by 2028 (Ellen MacArthur Foundation, 2021e; Papamichael et al., 2022).

These are just a few examples of successful circular economy practices in the fashion industry (Table 2). Many more companies are implementing circular economy initiatives to reduce waste, conserve resources, and promote sustainability (#CEstakeholderEU, 2019; Kowszyk & Maher, 2018).

8 Conclusions

The analysis of the fashion industry's manufacturing line within the context of circularity might be difficult. The creation of distinct business models at each stage of production is both important and critical, since data collection assists in the identification of resource capacities in order to engage in feasible circular practices. Simultaneously, a comprehensive presentation of all business models in one approach offers a greater knowledge of the industry's environmental effect since one may optimize the phases of the production line based on their own profile. Furthermore, such techniques encourage participation from various parties involved in each stage of the production chain (i.e., R&D, engineers, marketing, shop owners, consumers, ateliers), as well as external players (i.e., customers, decision makers, and local authorities). As a result, the usage of such a business model provides a standard approach to which interested parties can go for direction rather than a rigid rule. Hence, economic and social elements and indicators must be included in such models to guarantee that all three sustainability pillars—environment, economy, and society—are covered.

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Catalytic Methods for Sustainable Textile Dyeing

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1 Introduction

Dyes are coloring substances applied over the fabrics providing any desired or fashionable color and making the product visually appealing and aesthetic to the user. Dyeing is classified as one of the finishing steps of the fabric industry. It binds with the fibers chemically, and depending on the nature of fiber and dyes, their fixation mechanism over textiles is different (Kirk-Othmer, 2004; Bafana et al., 2011). Common fibers of fabrics include both natural and synthetic fibers, and their chemical structures vary significantly. Natural fibers include cellulose and cellulosic materials such as cotton, hemp, wool, silk, and leather obtained from plants and animals. Synthetic fibers involve polyester, polyamide, polyacrylamides, and polyolefins (Grishanov, 2011). Dyes, on the other hand, have different natures depending on their chemical constituents (Benkhaya et al., 2022). They are known as acid dyes, basic dyes, dispersed dyes, direct dyes, reactive dyes, etc., which have different functionalities and natures of bonding with various textile fibers. Thus, the dye species are naturally fixated at a different rate on the surface of different fibers.

Many methods have been followed for dyeing fabrics, inter alia, physical, chemical, electrostatic, biological, catalytic fixation, etc. Physical fixation is done by treating

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the fabric in a dye solution with ultrasound, UV light, plasma or microwave radiation (Bahria & Erbil, 2016; Haji & Naebe, 2020; Sun et al., 2010). On the other hand, reactive dyes chemically react with the fiber materials and form covalent bonds with the fibers leading to stronger binding of the dyes over the textiles. Ionic dyes are incorporated over pre-treated electrostatically activated fibers. The ionic dyes easily adhere to the fabric surface with the help of electrostatic attraction.

The catalytic fixation of dye species can make industrial-scale dyeing of textiles faster, economically viable, environmentally benign, sustainable and produce better-finished products. Consequently, it has drawn significant attention in recent years. Reactive dyes have been fixed on fibers in the presence of catalysts such as micelles, salts, mordants, and crosslinkers (Tang et al., 2018; Singh et al., 2019; Ahmed, 2005; Zhang et al., 2022). These catalysts act as a bridge between the dye species and the fiber surface. One of the catalytic systems uses a reverse micellar approach to fix dye on the surface of the fiber. This process allows hydrophilic dyes to be dissolved in the nonaqueous system preventing water pollution as well as increasing the wet fastness of the dye (Bairabathina et al., 2022). On the other hand, natural dyes face difficulties such as poor wet fastness and exhaustion during fixating over the fabric. These difficulties are minimized by utilizing metal and metal salts during dyeing to improve the linkage between natural dyes and fiber. Natural fibers such as cellulose become negatively charged during aqueous dyeing and thus repel the negatively charged dye ions from incorporating over cellulose. This issue is solved by using salts such as NaCl and Na_2SO_4, which neutralize the surface charge of the fabric eventually assisting dyes to efficiently bind with the cellulose fiber (Sun et al., 2017) via covalent bonds. The pH of the dye bath influences the extent of bond formation between cellulose and dyes by increasing the negative charges over cellulose. Thus, alkali treatment is also used in fixating dyes over cellulose fabric (Paul et al., 2017). It is noted that certain dyes form very weak bonds with the fiber surface which results in a poor wet fastness of the dye. These dyes require an external agent that will act as a binder between the fiber surface and the dyes. Crosslinkers are an excellent binding agent that forms a bridge between the crosslinker dyes and fibers (Zhang et al., 2022).

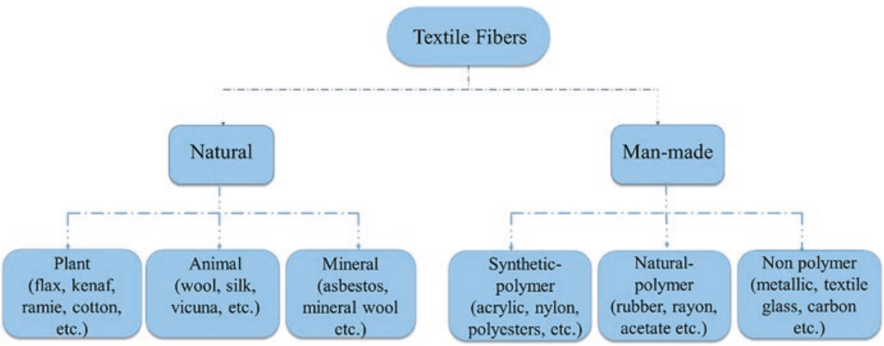
This chapter explores the prospect of utilizing the catalytic dye fixation methods as a sustainable manufacturing practice in the textile and fabric industries. It discusses the existing conventional dye fixation methods and probes into their credibility as sustainable production practices. The principles and mechanisms of different modern techniques for dye fixation over fabrics have been widely reviewed to gain insight into their efficiency, economic feasibility, and environmental friendliness. Furthermore, it assesses the various facets of catalytic fixation methods with a special emphasis on their efficiency, economic feasibility, and overall feasibility as an industrial-scale manufacturing technique. Finally, the future potential of catalytic fixation and related challenges are also highlighted.

2 Textiles and Dyes: Structures and Properties

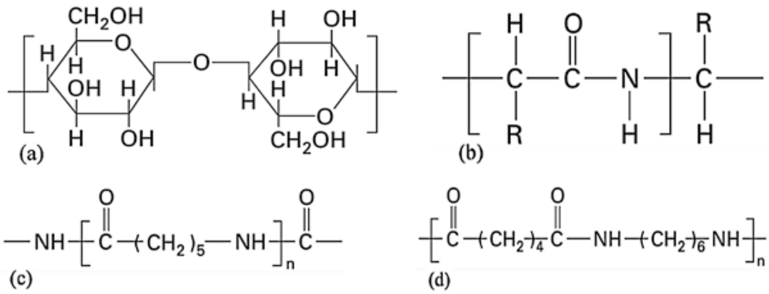
The term "textile" refers to any filament, fiber, or thread that can be woven into fabric or cloth. When compared with other materials, textiles stand out due to their exceptional strength, elasticity, pliability, durability, heat insulation, water absorption/repellency, lightweight, softness, water and chemical resistance, dyeability, etc. Textile fibers, as a textile raw material, are distinguished by their flexibility, fineness, and high length-to-thickness ratio. These fibers can be natural or synthetic (Scheme 1). Natural fibers come from either plants or animals. Cotton, wool, silk, and linen are examples of natural fibers. Synthetic fibers are developed through certain chemical processes. Similarly, polyester, nylon, and rayon are examples of synthetic fibers. Blended fibers are a complex blend of natural and synthetic fibers. All textile fibers, whether natural or synthetic, differ in characteristics and hence significantly vary in quality as end-use products.

Textile fibers differ in their structure and shape. Fiber materials are made up of various monomers, linkages, and functional groups. Their cross-sectional shapes and sizes, moisture absorption and swelling rates, thermal behavior, crystallinity, stress values, tensile properties, viscoelastic properties, and other bulk mechanical properties are all highly influenced by the chemical or physical structures of the fiber materials and thus these properties vary from fiber to fiber (Gupta, 2008). All these characteristics of fiber make it appropriate for spinning before being turned into fabric. Certain properties of fiber also have an impact on the dyeability of fiber materials. For example, cellulosic fiber is one kind of polymer made up of linkages between 1, 4-β-D-glucose units.

As can be seen from Scheme 2a, each repeating unit of cellulose contains six -OH groups which help the fiber to make hydrogen bonds and covalent bonds with suitable sides of appropriate dyes. Furthermore, the presence of ether groups in the monomer unit of such fabrics facilitates the bonding of ionic dyes to the fiber via



Scheme 1 Classification of textile fibers (Kozlowski & Mackiewicz-Talarczyk, 2020; David & Pailthorpe, 1999)



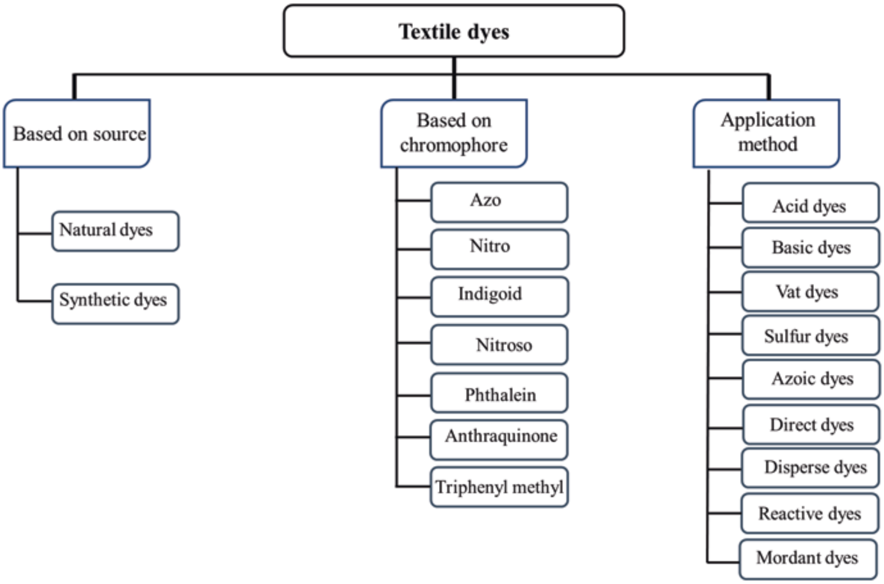
Scheme 2 Primary repeat units of (**a**) cotton or cellulosic fibers, (**b**) protein fibers (e.g., wool and silk), (**c**) polyamide (Nylon 6), and (**d**) PET fibers

ion–dipole interaction. Scheme 2b depicts the monomeric repeating group found in protein fibers. The side chains (-R) of monomers include varying quantities of amino acid groups, which are responsible for the various physical characteristics of protein fibers such as wool and silk. These groups are capable of becoming cationic under specific circumstances and forming bonds with anionic dyes like acid dyes. The fibers can also form hydrogen bonds with some dyes at their side chains.

Similarly, amino end groups or amide connections in the monomers of synthetic fibers like nylon allow the fibers to form ionic interactions with acidic dyes, covalent links with reactive dyes (Scheme 2c), also hydrogen or van der Waals bonds with dispersion pigments (Grishanov, 2011; Gupta, 2008; Hynes et al., 2020). Polyester (PET) fiber, on the other hand, is compact, crystalline, hydrophobic, and resistant to color absorption because of the presence of methylene (-CH_2-), carbonyl (>CO), and ester group (-COOR) in its monomeric structure (Scheme 2d). For this, traditional dyes, which form a strong ionic or covalent bond with wool, silk, or cotton, cannot be applied for dyeing PET. Dispersed dyes may dye PET using van der Waals forces, but the process demands high temperature and pressure (Ketema & Worku, 2020). Dyeing involves multiple phases such as the following:

- Diffusion of dye species and approach toward fiber.
- The adsorption of dye species to the surface of the fiber.
- The molecular migration of dyes from the surface of fiber to its inside.
- Creation of bonds between dye entity and substrate fiber, leading to a proper fixation.

It is remarkably noted that all dyes cannot be used on all sorts of fibers, and based on dye and fiber, fixation rates also vary (Hynes et al., 2020). Dyes that are applied to textile fabric are generally classified based on source, molecular structure, or application methodology (Scheme 3). The wettability of the fiber, its physical structure with suitable functional groups, adequate space among the groups, and their sufficient movements decide the compatibility between dyes and fiber.



Scheme 3 Classification of textile dyes (Hynes et al., 2020; El Harfi & El Harfi, 2017)

3 Simple Mechanism of Dye Fixation

Dye fixation is the process of attaching a dye molecule to a fiber so that it becomes a permanent part of the material. The fixation efficiency determines the color brightness of the dyed material and resistance to bleeding or fading. The mechanism of dye fixation depends on the type of dye, fabric, and the method of fixation (Fox, 1973). The fixing of dye molecules in the fiber structure mainly depends on intermolecular interactions of dye and fiber. Four different kinds of bonds can be developed between dye and fiber polymer molecules, namely, van der Waals forces, hydrogen bonds, ionic bonds, and covalent bonds (Grishanov, 2011). The rate of dye fixation on fabric differs from dye to dye and fabric to fabric as shown in Table 1 (Ammayappan et al., 2016; Patel, 2018; Scalbi et al., 2005).

As stated in the preceding section, dyes and fabrics are required to be compatible with each other. Compatibility between dyes and fibers is dependent on their functional groups, and these groups actually determine the nature of bonding between them. For example, reactive dyes contain some reactive functional groups, which enable them to form a covalent bond with fibers such as wool, cotton, cellulose, hemp, and silk (Lewis, 2014). As shown in Scheme 4a, a reactive dye, reactive black 5 (RB5) forms a covalent bond with its reactive side and the terminal $-NH_2$ (amino) group of wool fiber. The same fabric can also be dyed with acid dyes. However, in that situation, dye–fiber interactions will take place via van der Waals forces, ionic bonds, or hydrogen bonds (Table 1). The textile acid dyes ($R\text{-}SO_3Na$) are effective for protein fibers such as silk, collagen, wool, nylon, and modified acrylics. In the

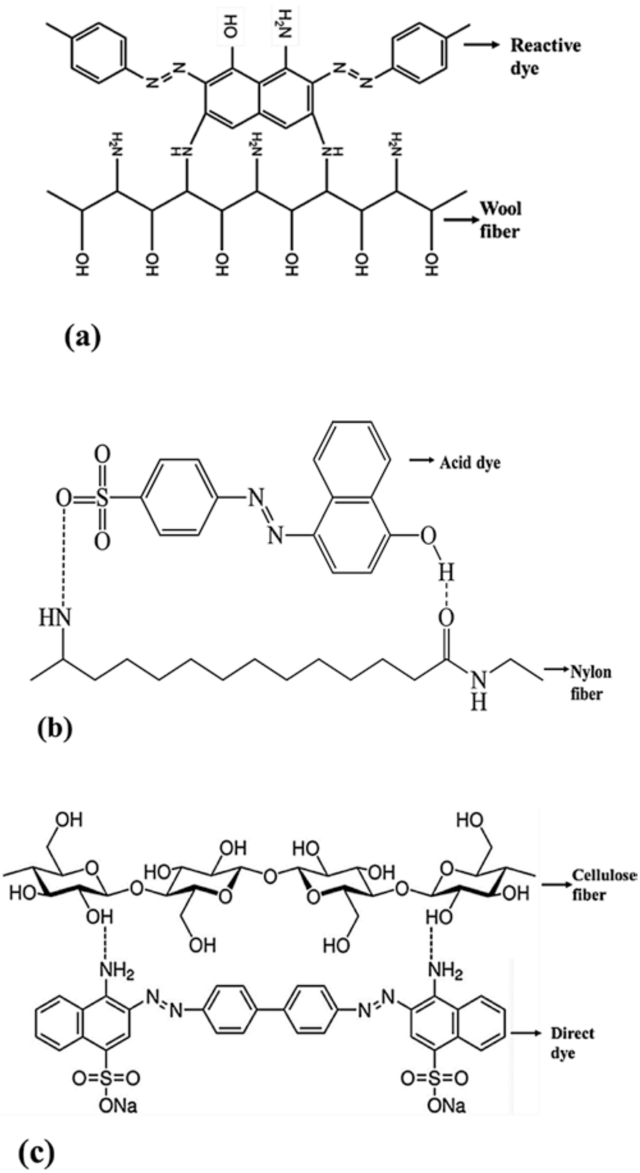
Table 1 Characteristics of fixation of different dyes on different fibers (Ammayappan et al., 2016; Patel, 2018; Scalbi et al., 2005)

Dye	Substrate	Functional groups	Interaction between dye and fiber	Fixation (%)
Basic	Modified nylon, polyester, polyacrylonitrile	Azo, azine, oxazine, xanthene	Hydrogen bonding, ionic bonding	95–100
Disperse	Acrylic, polyamide, polyester	Nitro, azo, styryl, benzodifuranone	Van der Waals forces	90–100
Acid	Wool, nylon, silk	Nitro, azine, xanthene, and triphenylmethane	Hydrogen bonding, ionic bonding, van der Waals forces	80–95
Vat	Wool, rayon, cotton	Indigoids and anthraquinone	Hydrogen bonding, van der Waals forces	80–95
Direct	Rayon, nylon, cotton	Azo, oxazine, stilbene	Hydrogen bonding, van der Waals forces	70–95
Sulfur	Rayon, cotton	Intermediate aromatic compounds	Hydrogen bonding, van der Waals forces	60–90
Reactive	Nylon, silk, wool, cotton	Azo, oxazine, formazan	Covalent bonding, hydrogen bonding	50–90

acidic dye bath, amino and carboxyl groups of nylon fiber are transformed into positively charged NH_3^+ and negatively charged carboxylate (COO^-) ions. Possible molecular interactions between acid orange 7 (AO7) dye and nylon 6 fabric are illustrated in Scheme 4b. Here ionic interaction takes place between amino groups of fiber and anionic groups of dye. In addition, hydrogen bonding occurs between the COO^- of fiber and the -OH side of the dye. The dye is thus bonded to the fabric by electrostatic attraction as well as its affinity for the fiber.

Scheme 4c demonstrates molecular interaction between cellulosic fabrics with a reactive dye, direct red 28. Direct dyes are molecules that bind to fabric molecules on their own, without the need for other chemicals. They have an affinity for a wide variety of fibers such as cotton, viscose silk, jute, and linen. They do not form any long-lasting chemical bonds with the fibers but are connected to them through very weak hydrogen bonding. However, for efficient fixation of dyes with the fibers, only dyes and fabrics are not enough. Sometimes dyes have poor fixation, which can be remedied with the use of other substances. Additionally, some fabrics require chemical modification before dyeing for better fixation. Salt, surfactants, alkali, mordant, and crosslinking agents are such types of substances used during dyeing for effective fixation. These substances even increase the fixation by acting as catalysts. The process of fixing dyes to fabric using a catalyst is referred to as dye fixation by catalysis. This catalyst acts as a facilitator or mediator, accelerating the chemical reaction between the dye and the fabric and allowing for more efficient dye fixation.

Evaluation of fixation efficiency of dyes is determined by analyzing the amount of dye in the dye bath before and after dyeing that can be assessed, for example, using UV–visible absorption spectroscopy. The UV–visible spectrum is used to compute the percent depletion and percent fixation. Color strength (K/S)



Scheme 4 Interactions between (**a**) RB5 with wool fabric, (**b**) AO7 with nylon fabric, and (**c**) direct red 28 with cellulosic fabric

measurements appear to change linearly with fixation rates in the majority of cases. Consequently, values of K/S obtained from the Kubelka-Munk (K-M) function are used to evaluate fixation in the maximum literature. The fixation is also influenced by some dyeing conditions such as temperature, pH value, dyeing time, and liquor concentration (Sun et al., 2017; Zhang, 2014).

4 Dye Fixation

Dye fixation is a critical stage in the dyeing process because it guarantees that the dye molecules are permanently attached to the fabric or substance, making it resistant to fading and washing. The conventional method of dye fixation includes both physical and chemical processes. For decades, conventional dye fixation procedures, such as UV, ultrasound, microwave, plasma, salt and alkali treatment, have been utilized to attain this purpose. However, these methods have various drawbacks that may be overcome by different processes. Some conventional dye fixing methods are mentioned in the following subsection.

4.1 Salt Treatment

Salt has numerous effects on dye fixing and textile dyeing. It acts as an electrolyte and serves as an excellent catalyst for dyestuff migration, adsorption, and fixation to cellulose fiber. Different cellulosic fabrics such as cotton, viscose, and linen contain different reactive groups. While dyeing in aqueous media, these reactive groups become negatively charged, resulting in experiencing repulsion from the dye anion. This phenomenon leads to ineffective dye fixation over the cellulosic fabric with anionic dyes. In the presence of salt, dye molecules get aggregated and dye adsorption is enhanced on the surface of the fabric (see Scheme 5). Salts in this case neutralize the negative charges on the fabric surface which helps to reduce the repelling forces between the dye and the fabric (Wolela, 2021).

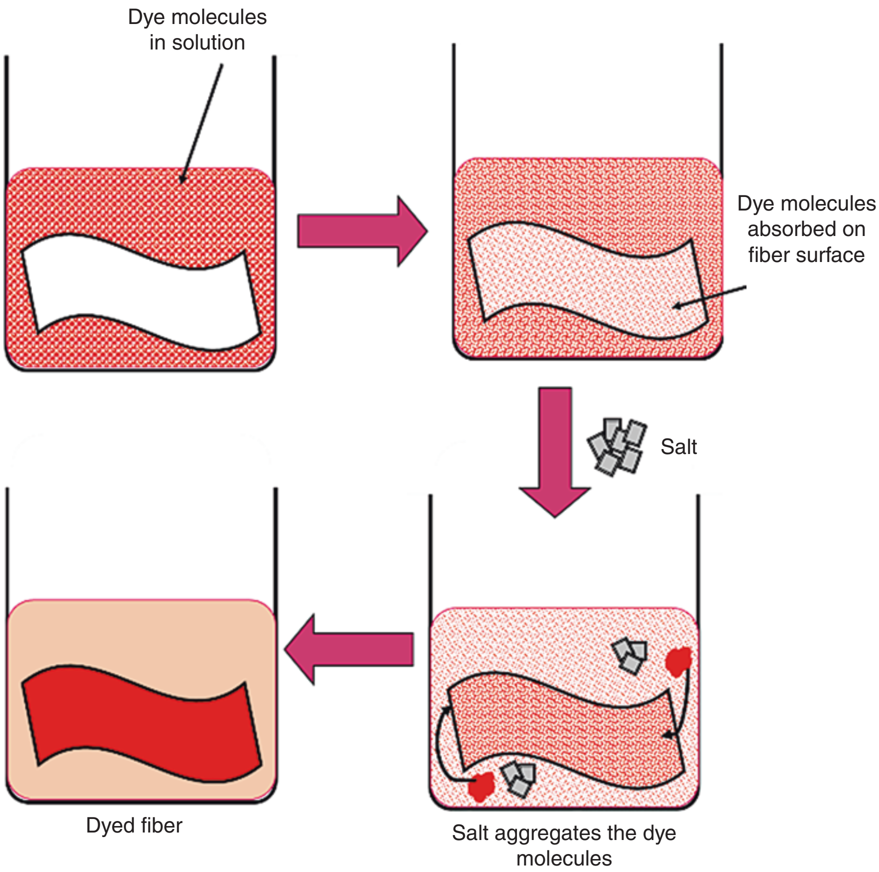
In textile dyeing, several inorganic salts such as Na_2SO_4, NaCl, $ZnSO_4$, $Al_2(SO_4)_3$, NH_4Cl, and $CuSO_4$ are commonly used. The dyeing mechanism of reactive dyes that generally contain sulfonic acid (-SO_3H) in the presence of such inorganic salts on cellulose fiber (Cell-OH) can also be understood through the following reactions (Eqs. 1–6) (Lewis, 2014):

$$\text{Cell} - OH \rightarrow \text{Cell} - \text{O}^- + \text{H}^+ \tag{1}$$

$$\text{Reactive dye} - \text{SO}_3Na + \text{H}_2\text{O} \rightarrow \text{Reactive dye} - \text{SO}_3^{\ -} + Na^+ \tag{2}$$

$$\text{NaCl} \rightarrow Na^+ + Cl^- \left(\text{Common salt}\right) \tag{3}$$

$$\text{or } Na_2\text{SO}_4 \rightarrow 2Na^+ + \text{SO}_4^{2-} \left(\text{Glauber's salt}\right) \tag{4}$$



Scheme 5 Schematic representation of fabric dyeing in the presence of salt

$$\left(\mathrm{Cell}-\mathrm{O}^{-}+\mathrm{H}^{+}\right)+\left(Na^{+}+Cl^{-}\right)\rightarrow \mathrm{Cell}-ONa \tag{5}$$

$$\mathrm{Cell}-ONa+\mathrm{SO}_3^{-}-\mathrm{Reactive\,dye}\rightarrow \mathrm{Cell}-\mathrm{O}-\mathrm{Reactive\,dye} \tag{6}$$

Aside from neutralizing the negative charge on cotton fibers, the principal effect of electrolytes on such colorants is to increase the degree of agglomeration of dye molecules in solution through the common-ion effect. Recent studies have found that the dyeing efficiency or color strength in the presence of various salts changes with their type and concentration (Wolela, 2021).

The fixation of reactive colors on cotton fiber depends on the strength of covalent bonds between dye particles and the –OH group of cotton fiber. This type of linkage occurs in the presence of salts in a high pH (>10.5) medium. However, after use, salts must be discarded with excess water, which increases both the cost and environmental pollution (Arivithamani & Dev, 2018). Various techniques have been

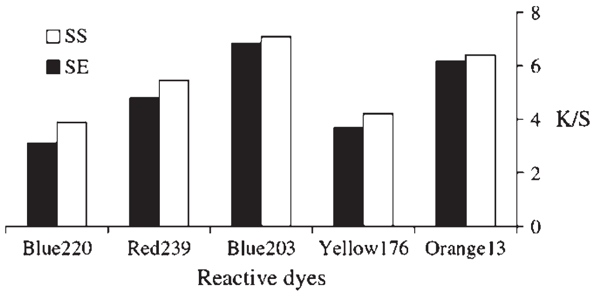


Fig. 1 Effect of organic salt on dye fixation (Ahmed, 2005)

developed to reduce salt consumption while increasing dye fixation. In some literature, biodegradable organic salts have been used in place of nonbiodegradable inorganic salts. Almost similar results have been observed, and in some cases, improved dye fixation has also been reported (Prabu & Sundrarajan, 2002).

Figure 1 represents the results of the fixation of various reactive dyes using sodium edate (SE) as salt to dye on cotton fibers. Exhaustion behavior and reactive dye fixation of this organic electrolyte are compared with sodium sulfate (SS) and sodium carbonate (SC). From the K/S values, it is clear that the SE method has similar results with all reactive dyes compared with other salts used (Ahmed, 2005).

4.2 Alkali Treatment

In an actual dye bath environment, reactive dye is commonly fixed in a high-pH media with a significant concentration of supportive electrolytes, such as sodium sulfate. As can be seen from the following reactions, the surface of the cellulosic fiber develops a negative charge at the aqueous solution/cotton contact as a result of the dissociation of accessible cellulose hydroxy (Cell-OH) groups. Cotton also includes carboxylate groups formed by the oxidation of end-chain aldehydes, which contribute to the negative charge mentioned above. The alkalinity of the aqueous medium has a noticeable impact on how much Cell-OH dissociates as expressed in Eqs. 7 and 8 (Bhuiyan et al., 2012; Lewis & Vo, 2007):

$$\text{Cell}\quad OH\quad \text{H}_3\text{O}\qquad \text{Cell}\quad \text{O}\quad \text{H}_2\text{O} \tag{7}$$

$$\text{Cell}\quad OH\quad \text{M}\ OH\qquad \text{Cell}\quad \text{O}\ \cdots \text{M}\quad OH_2 \tag{8}$$

The purpose of alkali is actually to trigger the release of H^+ from some of the –OH groups in the cellulose. Consequently, the dye can react with the cellulate ion (Cell-O^-). The concentration of alkali, treatment temperature, applied tension, duration of residence, source of cellulose, physical state of cellulose (fibril, fiber, yarn,

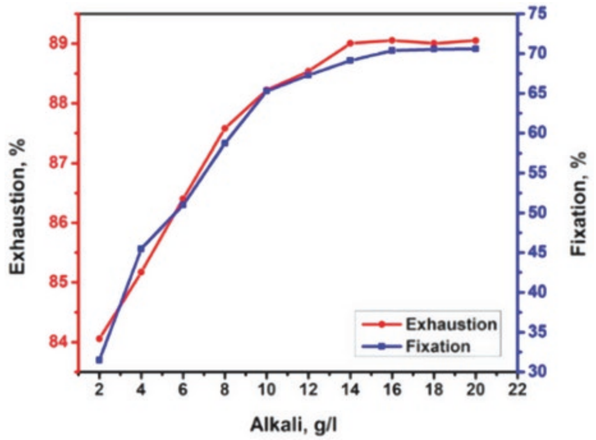


Fig. 2 Influence of alkali concentration on exhaustion and fixation of cotton woven fabric with reactive dye (Hossain et al., 2020)

or fabric), and degree of polymerization all have an effect on the characteristics and degree of change after treatment.

Alkali soda ash is commonly used to increase pH and fixation for deep shade on fabric but higher fixation has been obtained with mixed alkali (soda ash and caustic soda) instead of soda ash or caustic soda alone (Bhuiyan et al., 2012). The effect of mixed alkali (sodium ash and sodium hydroxide) on the fixation of deep shades (8, 7.6, and 7.2%) of two different reactive dyes has been studied. At an optimum ratio of caustic soda and soda ash in mixed alkali, strong fixation and decreased hydrolysis of dye molecules have been achieved.

The influence of alkali (soda) on exhaustion percentage, fixation percentage, and K/S while dyeing cotton plain woven fabric with reactive dye has been investigated in different studies. It has been observed that the exhaustion and fixation values increase as the amount of alkali increases (Fig. 2) (Hossain et al., 2020). Thus, as the alkali content increases, the dye binds more strongly to the fiber.

The alkali concentration also affects the K/S values and color fastness properties. In one observation, single jersey cotton knitted fabrics have been dyed with some reactive dyes where, except for alkali concentration, all other parameters were kept fixed. Alkali concentrations have been varied from 6 to 10 g/L. The better color strength has been obtained with 8 g/L alkali (Paul et al., 2017). Lyocell fabrics have been pre-treated with varying concentrations of NaOH and then dyed with nine different types of reactive dyes. It has been revealed that NaOH pretreatment improves the rate of fixation with increasing alkali concentration (Goswami et al., 2009).

4.3 Ultrasound Treatment

Ultrasound has an important role in textile dyeing. The frequency range covered by ultrasound in the sound spectrum is from 20 kHz to 10 MHz, which is further classified into power (20 kHz to 2 MHz) and diagnostic (5–10 MHz) ultrasound (Kamel et al., 2003; Merdan et al., 2004). It is employed in the fixation of various types of dyes on different fabrics due to its operating mechanism. In liquid media, if ultrasound waves are transmitted, they cause formation and frequent collapsion of bubbles or cavitations. When ultrasonic waves are used during dyeing, these cavitation ruptures occur near solid cloth surfaces which release trapped gases from liquid dye baths as micro-jets. These micro-jets cause dye molecules to be incorporated into intra-yarn and inter-yarn pores. Numerous studies have been conducted on the use of ultrasound for dyeing various kinds of natural or synthetic materials, including cotton, nylon, lycra, polyester, and wool. Implementation of ultrasound while dyeing textile fabric resulted in good color strength and wash-fastness capabilities in almost all applications. Moreover, it requires less time and lower temperature for dyeing of the fabric. Better dye penetration or good covalent fixation of dye particles with the fabric surface occurs upon applying ultrasound technology resulting in superior fastness qualities (Atav, 2013).

4.4 Ultraviolet Treatment

Ultraviolet radiation ($\lambda = 100 - 400$ nm) is well known for its detrimental effects on organic molecules, such as the breakdown of their chemical bonds. It has a substantial impact on the dye uptake of many textile fabrics. UV radiation causes photo modification of the textile fibers. It increases the depth of shade in dyeing, indicating a higher amount of dye or pigment fixation on fabric. It has also been reported that dye fixation occurs more quickly under normal conditions when UV is applied (Sun et al., 2010). The effect of UV irradiation on commonly used fabrics, such as wool, polyester, and cotton as well as dyes such as reactive and disperse has been widely documented in the literature for a very early time. For example, exposing wool fabric to UV for dye penetration on fabric has been well known since the beginning of the 1960s. When compared with unexposed samples, UV-irradiated fabrics while dyeing displayed a number of positive impacts, including improved color strength, greater levels of dye uptake, even dyeing, and deeper shades. However, short-term UV irradiation produces chemical changes only on the surface of the fabric but does not affect the bulk of the fabric (Millington, 1998, 2006; Iqbal et al., 2008).

4.5 Plasma Treatment

In addition to solid, liquid, and gaseous states, the fourth state of matter is referred to as plasma. Upon applying more energy to gas, it gets ionized and forms a plasma state. Depending on the gas employed, the plasma environment contains free electrons, radicals, ions, and a variety of other excited particles. Plasma technology is a viable alternative to wet treatments in the textile industry because different types of plasmas have specific useful effects such as surface cleaning, activation, etching, and depositing of materials on the surfaces of different fabrics (Haji & Naebe, 2020; Atav, 2013). Plasma technology is environment-friendly for increasing the absorption capabilities of the textile. Plasma only reacts with the fabric surface, not with the internal structure of the fibers like traditional surface treatments. It can be applied for dyeing both the natural and synthetic yarns. Significant effects of plasma treatment on requiring less time for dyeing and energy usage are also extensively reported in addition to enhancing dye uptake or dye fixation rates. It can also be considered as a potential substitute for mordants in dye fixation, reducing reliance on harmful metallic chemicals (Haji & Naebe, 2020; Atav, 2013).

4.6 Microwave Treatment

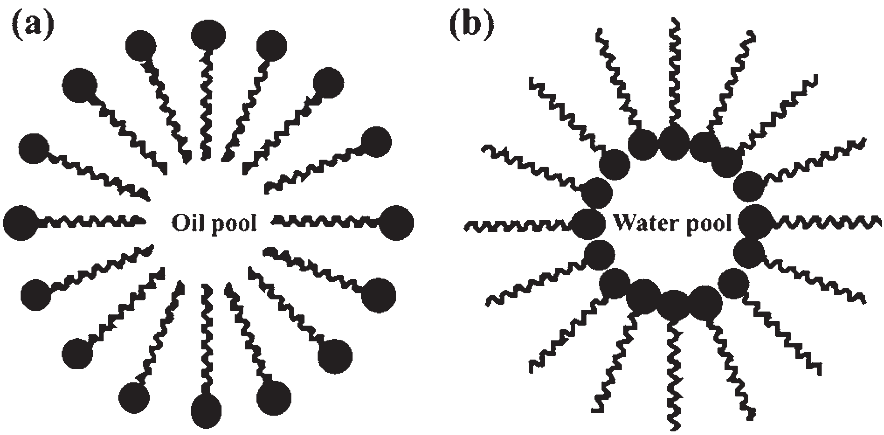
Heat is required in textile manufacturing for different operations, such as dye fixation, heat setting, or drying the product. Microwave (MW) technology has been applied to textile dyeing as an energy-efficient source of heat for dye fixation. MWs are radio waves having wavelengths ranging from 1 m to 1 mm, or with frequencies ranging from 300 MHz (0.3 GHz) to 300 GHz (Kozlowski & Mackiewicz-Talarczyk, 2020). Microwave radiation has been used as a heating method for almost five decades. The basic mechanism of microwave heating includes an oscillation of polar molecules or ions that are oscillated under the influence of an electric or magnetic field. Particles attempt to align themselves or move in phase with the field when it is oscillating in their presence. However, opposing forces (inter-particle contact and electric resistance) limit the velocity of these particles, which results in random motion and heat production. In different literature, using microwave heating enhanced dye fixation on different fabrics was reported. When compared with conventional dye fixing processes, MW heating even reduces dyeing time by nearly half. It has been reported that, for fixing certain reactive dyes on wool, it required only 30–60 s for fixation. MW irradiation generates heat and causes a change in the morphology and structure of the wool surface which increases dyeability and reduces dye fixing time (Atav, 2013).

5 Catalytic Dye Fixations

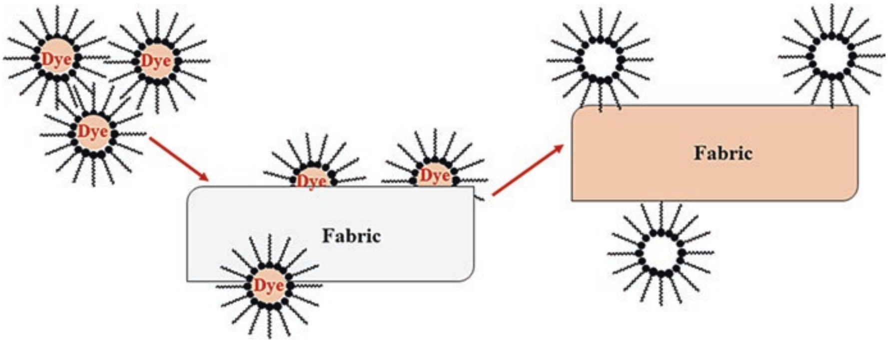
Catalytic dye fixation methods use catalytic agents, which are compounds that accelerate a chemical reaction without being consumed in the process, to fix or set dyes onto fabrics or materials. These methods have various advantages over traditional dye fixation methods, including lower water and energy use, fewer processing times, and better color fastness. The dye fixation methods employed are determined by a number of criteria, including the type of dye used, the type of cloth or material being dyed, and the required amount of color fastness. Some dyes require specific fixation procedures to be successfully set, whereas others can be fixed using a variety of methods. Several catalytic dye fixing methods are covered in this section.

5.1 Reverse Micellar System

Micelle formation occurs owing to the amphiphilic nature of the surfactant molecules. Surfactant molecules are made up of both hydrophilic (water-loving) and hydrophobic (water-hating) components. They have a tendency to group together when introduced into a polar solvent (often water) in order to reduce their exposure to the solvent. The hydrophobic tails of the surfactant molecules start to interact with one another as the concentration of surfactant molecules in the solution rises, resulting in the formation of tiny clusters as shown in Scheme 6a. As more surfactant molecules are introduced to the solution, these clusters keep expanding. The clusters grow large enough to form micelles when the concentration of surfactant molecules reaches a particular value known as critical micelle concentration (CMC). The hydrophobic tails of the surfactant molecules are directed toward the center of the micelle, while the hydrophilic heads remain in contact with the solvent.



Scheme 6 Schematic diagram of (**a**) micelle and (**b**) reverse micelle



Scheme 7 A schematic diagram of dye fixation by the reverse micellar system

A reverse micelle, on the other hand, is a kind of colloid in which surfactant molecules form frequently spherical shapes surrounding a polar core presented in Scheme 6b. Reverse micelles form in nonpolar solvents such as hydrocarbons or chlorinated solvents, as opposed to regular micelles, which form in polar solvents. A reverse micelle has a hydrophilic head that faces the polar core and a hydrophobic tail that faces the nonpolar solvent around it. Water or other polar molecules that would typically not dissolve in a nonpolar solvent can be found in the polar core of a reverse micelle. The mechanism of formation of a reverse micelle is similar to a regular micelle. The size and shape of the micelle/reverse micelle are determined by factors such as the size and shape of the surfactant molecule, the nature of the solvent, and the concentration of the surfactant in the solvent (Bairabathina et al., 2022).

Reverse micellar systems have been utilized to fix dye in textiles, particularly hydrophobic materials, at a greater rate while maintaining color uniformity and depth. A schematic diagram of dye fixation by reverse micellar systems is shown in Scheme 7. During this process, the dye is dissolved in the polar solvent and is surrounded by the hydrophilic core of the reverse micelles. When the textile fibers are immersed in the solution, the dye may then diffuse out of the hydrophilic core and attach to the surface of the fibers. Moreover, a micellar system can help solubilize hydrophobic dyes and facilitate their dispersion in the dye bath, which can enhance the color uniformity and depth of the resulting fabric. The usage of various cationic, anionic, zwitterionic, and nonionic surfactants as well as efficient dyeing by reverse micelle generation system has been extensively researched for various textile dyeing operations for natural fabrics like wool, and cotton is mostly used as summarized in Table 2.

The effects of reverse micelles on dye fixation on the surface of various fibers, including cotton, wool and silk, have been studied using a variety of dyes, such as direct, reactive, and dispersive dyes. The results have shown that the dye fixation rate is higher in reverse micellar-based systems than in the conventional water-based approach (Sawada et al., 2002). Cotton fiber has been dyed with different reactive dyes in both aqueous medium and reverse micellar systems consisting of heptane and octane with polyethylene glycol (PEG)-type nonionic surfactants

Table 2 Fixation of dyes on different fibers in reverse micellar systems

Reverse micellar system	Surfactant	Fabric	Dye	References
Cationic	DTAC, SB	Cotton	2-Arylazo-1-naphthol	Oakes and Gratton (2003)
Nonionic	AOT	Cotton	RR 2	Sawada and Ueda (2003a)
Cationic	DC3-12; DC6-12	Polyester	1,4-DAA; DV 1	Choi et al. (2001)
Nonionic	AEO-9	Cotton	RB 19	Cai et al. (2015)
Nonionic	DMAESS	Cotton	RY; RR; RB	Xie et al. (2011)
Nonionic	PT	Cotton	LR; LB; LY	Wang et al. (2016)
Nonionic	CTAB; SDS; TX-100	Cotton	NS; Y	Miran et al. (2015)
Nonionic	Chitosan	Wool	RR 184	Yen (2001)
Anionic	PFPE	Wool	AR 52	Jun et al. (2004)

1,4-DAA 1,4-diaminoanthraquinone, *AEO-9* fatty alcohol polyoxyethylene ether, *AOT* sodium bis-2 ethylhexylsulfosuccinate, *AR 52* acid red 52, *CTAB* cetyltrimethyl-ammonium bromide, *DC3-12* propanediyl-a,o-bis(dimethyldodecylammonium bromide), *DC6-12* hexanediyl-a,o-bis(dimethyldodecyl-ammonium bromide), *DMAESS* dibutyl maleic acid ester sodium sulfate, *DTAC* dodecyl trimethylammonium chloride, *LB* Levafix CA blue, *LR* Levafix CA red, *LY* Levafix CA yellow, *NS* Navy Sc, *PFPE* perfluoro 2,5,8,11-tetramethyl-3,6,9,12-tetraoxapentadecanoic acid ammonium salt, *PT* poly (oxyethylene glycol) tridecyl ether, *RB 19* reactive blue, *RR 184* reactive red 1, *RR 2* CI reactive red 2, *RY* reactive yellow, *SDS* sodium dodecyl sulfate, *SB* *N*-dodecyl-*N*, *N*-dimethyl-3-ammonio-1-propanesulfonate, *TX-100* Triton, *Y* yellow

Table 3 Color yield of different dyes fixed in aqueous and micellar media (Wang et al., 2016)

		K/S value	
Color	Concentration of dye (%)	Water	PEG-based reverse micelle (heptane)
Red	0.1	21.14	51.12
	2.5	115.78	241.40
	6.0	254.84	407.51
Yellow	0.1	20.78	32.77
	2.5	99.50	139.76
	6.0	197.74	280.81
Blue	0.1	29.26	38.00
	2.5	154.15	177.44
	6.0	300.56	335.78

(Wang et al., 2016). Table 3 compares the color yield of different dyes over cotton fiber in aqueous and nonaqueous micellar systems. Significant increases in dye fixation rates have been observed in the reverse micellar system. The dissolved water of a surfactant-based dye bath has lower polarity in the interior of the reverse micelle than bulk water. In the interior of the nonaqueous reverse micellar medium, it solubilizes a small amount of water forming a stable aqueous microenvironment, known as a water pool. The dye remains highly concentrated in the water pools of the micellar bath. These all cause the reactive dye molecules to become less ionized in

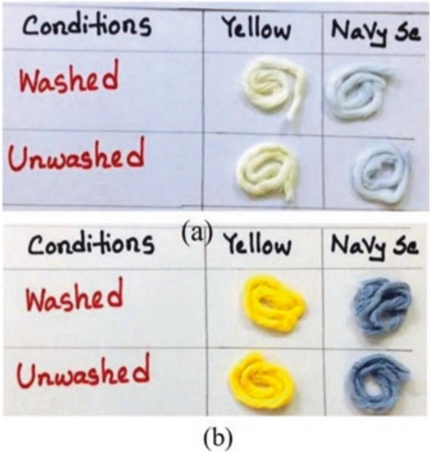


Fig. 3 Images of cotton after adsorption of dyes in (**a**) absence and (**b**) presence of cationic surfactant (Miran et al., 2015)

the micellar core for which the repulsion between the dye and the fiber surface reduces. Also, the adsorption capacity of dye increases on the surface of the fiber.

Cotton fiber has been dyed with two bi-functional reactive dyes (yellow and navy Sc) in the absence and presence of different ionic and nonionic surfactants (Miran et al., 2015). It has been found that micellar solutions of cationic surfactant have significant effects on cotton fabric. Images of the dyed yarn shown in Fig. 3 have been taken before and after multiple washing. It has been observed that, in the absence of a micellar solution, dyes have not been adsorbed even after 24 h (Fig. 3a), whereas it took only 15 min for dyeing and giving very deep shade in the presence of cationic surfactant with the same reactive dyes (Fig. 3b). From the extraordinary retention behavior of these dyes on cotton in a cationic surfactant medium, it can be claimed that cationic surfactant acts as a catalyst.

Conventional aqueous dyeing and nonaqueous reverse micelle systems of nonionic surfactant have been investigated for dyeing of wool fiber with reactive dye. When compared with traditional aqueous dyeing, reverse micellar dyeing for wool requires less temperature (about 10 degrees) and does not require salt or pH adjustment. The K/S obtained from both processes can be compared to evaluate the effective fixation of dyes on wool fiber. It has been observed that the K/S in reverse micellar approach is superior to that of traditional aqueous dyeing. The dyeing and fixing processes have been thus enhanced in the reverse micelle solution (Kan, 2018).

Reverse micellar system has been utilized to fix C.I. reactive red 2 dye onto the silk fiber using sodium bis-2-ethylhexylsulfosuccinate surfactant (Sawada & Ueda, 2003b). The effects of reactive dyeing on silk and wool in a reverse micellar system in both aqueous and supercritical carbon dioxide (SC-CO_2) medium are shown in Fig. 4. To determine the effectiveness of this approach, the color depth of dyed silk cloth before and after fixing has been evaluated. As illustrated in Fig. 4a, it can be observed that reactive dye has a significant ability to adsorb on silk. Additionally, the fixation ratio of reactive dye on silk reaches a sufficient level (80–90%) in the presence of the reverse micellar system.

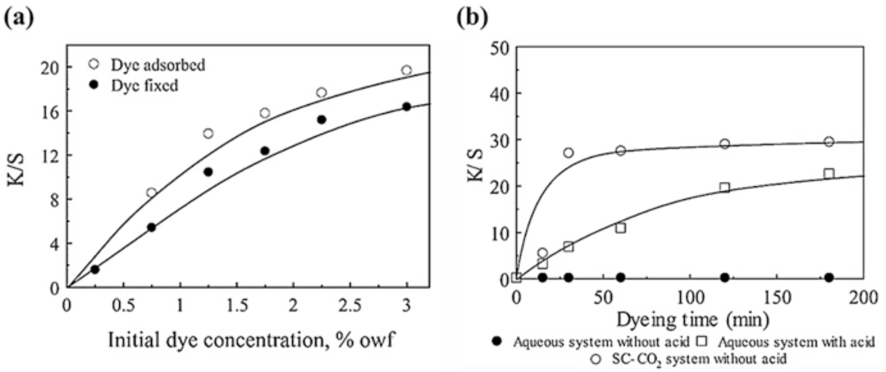


Fig. 4 Color strength (K/S) against dye concentration representing adsorption and fixation of reactive dye on (**a**) silk in the reverse micellar system (Sawada & Ueda, 2003b) and (**b**) color depth change against dyeing time on wool in aqueous, acidic aqueous, and nonaqueous SC–CO_2 in the reverse micellar system (Jun et al., 2004)

For dyeing wool and cotton fabric in the presence of a reverse micellar system, in some studies, supercritical CO_2 (SC–CO_2) was used as a substitute for conventional aqueous or nonaqueous dyeing techniques (Sawada & Ueda, 2003a; Choi et al., 2001; Jun et al., 2004). Figure 4b depicts the dyeability of acid dye over the wool fabric by the reverse micellar system in both aqueous and SC-CO_2 media. The rate of dyeing was compared for both conventional aqueous and reverse micellar systems in SC–CO_2. The dyeing rate or rate of bonding between wool and dye in a reverse micellar system with SC-CO_2 is noticeably faster than aqueous system. It has been considered that acid dye would not be soluble in bulk CO_2 media, but the dye dissolves in the water pool of the PFPE surfactant reverse micelle in SC–CO_2. As a result, there remains apparently a high concentration in the water pool for which more dye may therefore be absorbed at the same time than the aqueous medium. The addition of an acidic solution to an aqueous medium increases the dyeability of the used dye on wool compared with the aqueous system without acid. However, the rate is still lower than the surfactant used reverse micelle in the SC–CO_2 medium. Such results have been obtained because, in aqueous medium, acidic condition increases the electrostatic attraction between dye and wool fiber. On the other hand, in the water pool of the PFPE surfactant reverse micelle in SC–CO_2, CO_2 is dissolved into the water pool and subsequent ionization of carbonic acid occurs. It makes the system acidic in spite of using additional acidic substances (Niemeyer & Bright, 1998).

5.2 Use of Mordants

During dyeing different fabrics with natural dyes, it faces some fixation complexities due to its poor exhaustion and fastness. To overcome these problems, different binders are used which can improve the linkage between fabric and adsorbed dyes by giving better dye fixation. Such binders are called mordants. Usually, mordants include polyvalent metal ions and their salts. The primary action of mordant is to form a coordination complex with the dye molecules. This complex is thus attached to the surface of the fiber material. Apart from metallic salts, some natural compounds containing metal ions, or other complex forming agents are also used to improve dye uptake and fixation. Some of the important mordants used are tannic acid, alum, chrome alum, sodium chloride, aluminum, chromium, copper, iron, iodine, potassium, sodium, and tin. Table 4 lists the most common mordanting conditions that are compiled from various studies (Elsahida et al., 2019; Baig et al., 2019; İşmal & Yıldırım, 2019; Saxena & Raja, 2014).

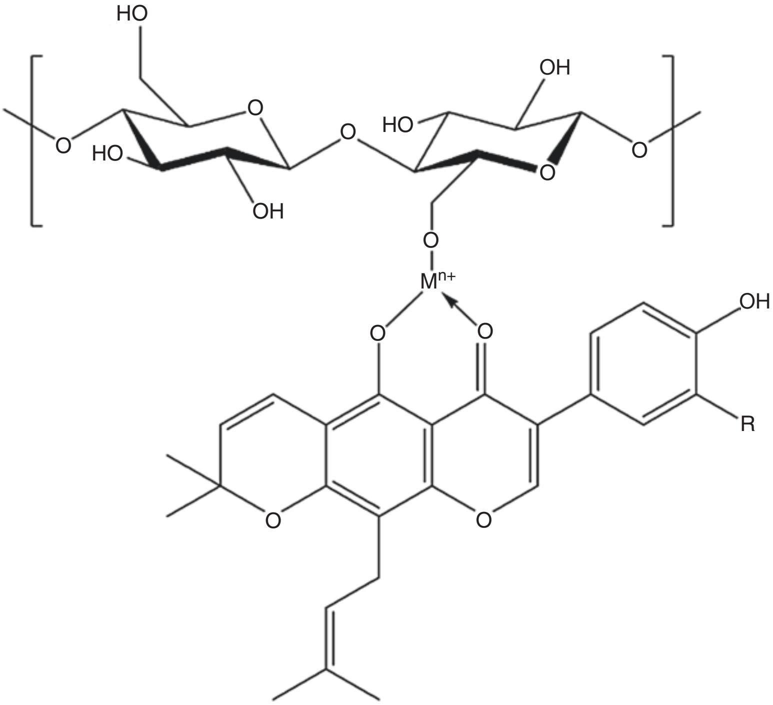
Mordants improve the fixing of natural colorant on the fiber by forming a protective layer around the dye molecules which have limited substantive capabilities for the fiber. Mordants are implemented to improve the dye fixation capability of the natural dyes. To improve the color fastness of the dyed fiber, natural dyes primarily involve the use of metal ion mordants which are capable of providing a chemical link between the polymer chain of textile fibers and the adsorbed dye as typically illustrated in Scheme 8 (Sawada & Ueda, 2003b; Niemeyer & Bright, 1998; Elsahida et al., 2019; Baig et al., 2019; İşmal & Yıldırım, 2019; Saxena & Raja, 2014).

This complex between dye and fabric mordant can be made in three distinct ways as pre-mordanting (applying the mordant first, then dyeing), meta-mordanting (applying the dye and mordant at the same time), or post-mordanting (adding the mordant after dyeing the material). Which mordanting techniques yield the deepest shades, as well as improved wash and light fastness, depends on the type of dye, fabric, or mordant used during dyeing (Jabar et al., 2020; Hosen et al., 2021). The concentration of mordant is also important for achieving a darker shade of dye (Ismal, 2016). In addition to extraction and dyeing methods, temperature during dyeing, time of dyeing, and pH of the dye bath all have a substantial impact on the results of natural dyeing. Mordants help bind the dye to the fiber while also changing the pH of the medium to improve dyeing properties.

As a natural dye, *Bridelia ferruginea Benth* has been used for dyeing cellulosic fiber in the presence of Ca^{2+} and alum mordant (Jabar et al., 2020). The fabrics dyed with *Bridelia ferruginea Benth* dye in the presence of any form of mordant produce

Table 4 The most common mordanting conditions (İşmal & Yıldırım, 2019)

Condition	Value
Concentration	0.5–30 g/L
Temperature	30–100 °C
Time	30–60 min
pH	3–10



Scheme 8 Bonding of Osage orange dye (natural dye) to cellulose by means of a metal ion (M^{n+}) mordant

a more intense shade of hue than nonmordanted fibers. This may be due to the capacity of metal salt to improve the color of natural dye in cellulosic fabric. Among all mordanted dyed cotton fibers, pre-mordanted dyed fibers give the darkest shade compared with post- and meta-mordanted fibers. In addition, $CaCl_2$-mordanted dyed fabrics provide a darker color compared with alum-dyed fabrics. This could occur because Ca^{2+} reacts more strongly than Al^{3+} with -OH of cellulosic fiber. Furthermore, compared with alum mordant, the higher reactivity of Ca^{2+} encourages faster migration of dye molecules into the cellulose matrix (Jabar et al., 2020).

Significant effects of different metallic salt mordants have been observed during the dyeing of wool fiber with natural dye. Using modest amounts of various metallic salt mordants, woolen yarn has been found to become easily colored with a natural coloring solution derived from walnut bark as illustrated in Fig. 5 (Bukhari et al., 2017). In this study, the effects of $Al_2(SO_4)_3$, $FeSO_4$, and $SnCl_2$ mordants on dye fixation over woolen yarns have been examined. Samples colored with $Al_2(SO_4)_3$ displayed unusual and striking light and brilliant brown hues, whereas those dyed with $SnCl_2$ showed reddish brown shades and the fabric dyed with $FeSO_4$ showed dark brown tones (Bukhari et al., 2017).

However, metallic mordants are thought to be environmentally hazardous. Due to residual toxic metal ions in wastewater and the effluent disposal problem,

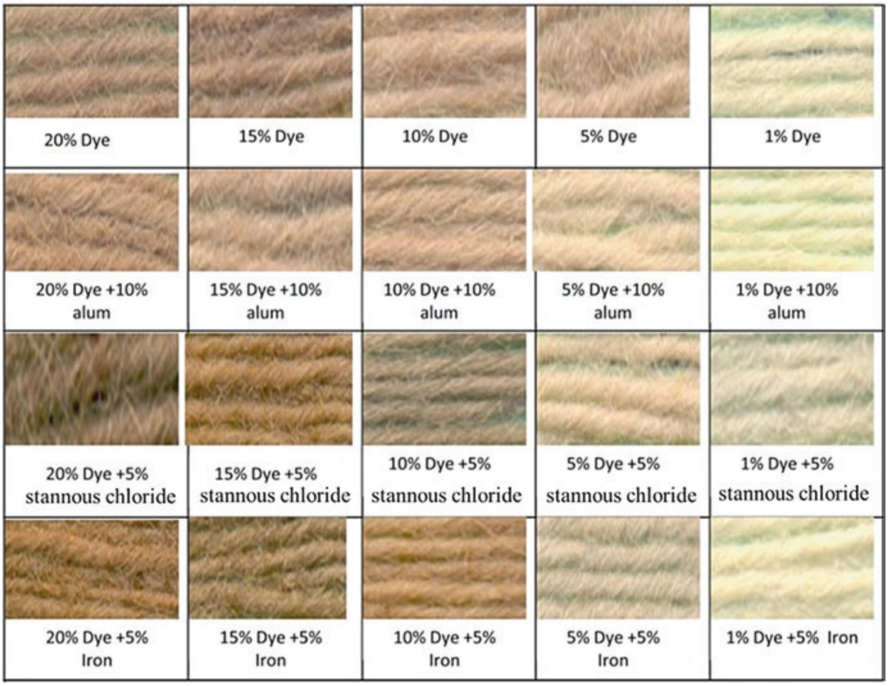


Fig. 5 Shades of different dyed samples using mordants (Bukhari et al., 2017)

environmental concerns have led to criticism of the use of conventional metal salts in textile natural dyeing. The replacement of metal mordants with bio-mordants is an intriguing and popular topic among some researchers. Bio-mordants, like metallic mordants, can alter color yield and fastness or be ineffective on color darkness and fastness values depending on their type and concentration. The bio-mordants derived from *Citrus limon* and *Colocasia esculenta* bulk have been used to investigate the fastness properties of dyed cotton fabric (Hosen et al., 2021). The bio-mordant treated sample has exhibited twice as high K/S as the metal-mordanted sample at about K/S = 8.6 and 4.0, respectively. Using the same dyeing conditions, they have shown that *Citrus limon* and *Colocasia esculenta* mordant even gave deeper color shade visually than the conventional metal salts (Hosen et al., 2021).

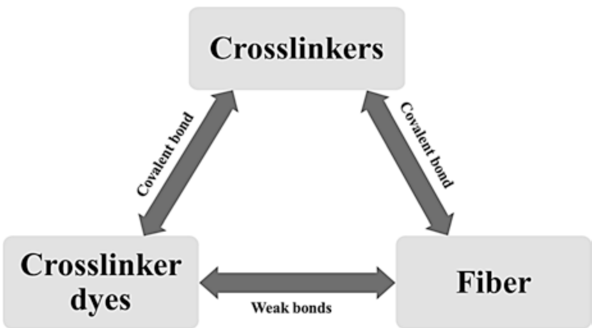
5.3 Crosslinking Agents

Some kinds of chemical bonding between dyes and fibers are necessary for the effective coloring of the fabric. Some dyes are unable to make strong bonds with fibers, so third reagents are occasionally required to form strong bonds between dye molecules and fabric fibers. Crosslinking agents or crosslinkers are such types of compounds that can provide covalent dye-fiber linkages and hence improve the fixation of coloring particles on fabric (Zhang et al., 2000, 2022; Lützel, 1966). Moreover, the dyes that are fixed with the fibers with the help of crosslinkers are referred to as crosslinking dyes. Various reactive dyes act as crosslinking dyes, for example, basazol, indosol, and aminoalkyl. Crosslinking agents serve as a bridge during dyeing to join the dyes with the fibers via covalent connections (Zhang et al., 2000, 2022; Lützel, 1966) as illustrated in Scheme 9.

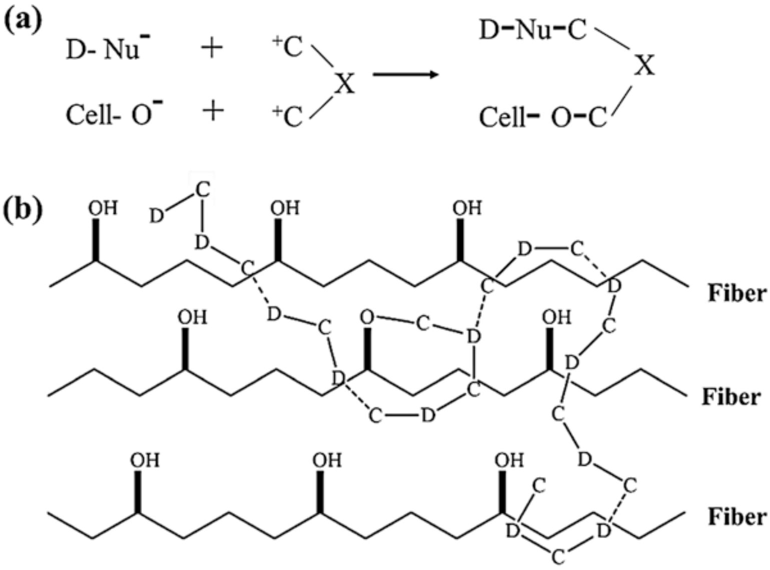
Crosslinking agents contain a minimum of two reactive groups. In alkaline conditions, these reactive groups form stable chemical binding with both the fabric and the dye. Crosslinking dyes, on the other hand, must have appropriate nucleophilic functional groups such as -OH, $-NH_2$, -NH-, $-SO_2NH_2$, and -SH, to bond with the fibers via reactive groups of crosslinkers (Lewis & Ho, 1995). However, due to the presence of different functional groups in the monomeric groups, fibers can act as nucleophilic reactants as illustrated in Scheme 10. Where dye and fiber cannot bond with each other directly, crosslinking agents with their reactive sides help to fix the dye molecules on the fabric surface.

The factors affecting the effective dye fixation include the type of crosslinking agents, temperature, dye concentration, and pH (Tang et al., 2006). In the presence of a crosslinking agent, silk and cotton fabrics have been colored using synthetic polymeric dye. For these type of materials, a very high percentage of fixation has been obtained to be silk of ≥99% and cotton of 99%. The application of a crosslinking agent allows the reactive groups of dye to crosslink with fiber. Hence, the polymeric dye has been observed to result in superior fixation.

Silk fabric exhibits a much better dye binding or fixation nature in the presence of crosslinkers for the same dye and dyeing conditions (Zhang et al., 2000). Silk fibers contain $-NH_2$ and -SH groups, which have reactivity similar to the $-NH_2$ groups of crosslinking dyes and are more reactive than -OH groups of cotton. As a result, the crosslinking dyes can establish covalent connections with silk more easily than cotton. Microscopic analysis of the cross sections of the dyed silk and cotton fibers can be seen in Fig. 6. It has been revealed that silk fiber is more strongly



Scheme 9 Representative scheme of the relation between crosslinker, dye, and fiber



Scheme 10 Schematic (**a**) reactions and (**b**) structural arrangement of covalent crosslinking among dyes, crosslinkers, and fibers. (Nu = a nucleophilic grouping; X = a polyfunctional crosslinking agent)

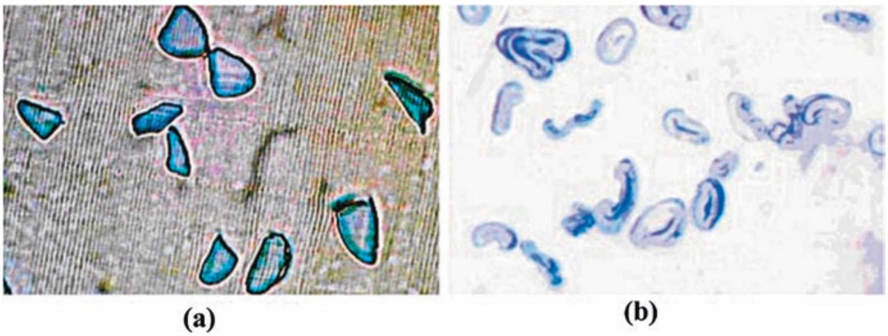


Fig. 6 Microscopic view of the cross sections of the silk (**a**) and cotton (**b**) dyed with the same dye in the presence of crosslinkers (Zhang et al., 2000)

bonded than cotton fiber with deeper dyeing on the same dyeing conditions as cotton fiber (Zhang et al., 2000).

The dye exhaustion and covalent fixation of amino-ethyl anionic dyes on cotton fabrics have been studied. The crosslinking agent, 1, 3, 5-triacroylamino-hexahydro-*s*-triazine (Fixing Agent P-FAP), has been employed (Lewis & Ho, 1995). Figure 7 depicts the percent exhaustion and fixation of amino-ethyl anionic dyes on unmodified nylon with varying pH of the dye bath. The fixation of the amino-ethyl anionic dye on FAP-treated nylon is, however, much better than the other two substrates and

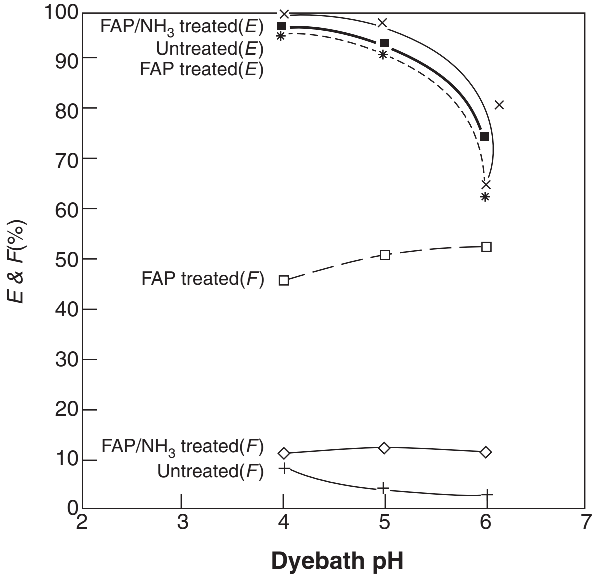


Fig. 7 Exhaustion (E) and fixation (F) of anionic dye on crosslinker FAP-treated, untreated nylon, and FAP/NH_3 fabric (Lewis & Ho, 1995)

percent fixation increases proportionally with the pH of the dye bath (Lewis & Ho, 1995). The fixation values of this dye on untreated and FAP/NH_3-treated nylon have been found low and showed little pH dependency. On the other hand, in terms of exhaustion, all of these had nearly identical findings; however, the untreated sample showed the least fixation. This might be because of the removal of absorbed dye from the fabric during the fixation test in the stripping media. The lack of a covalent bonding between the dye and the FAP untreated sample is responsible for such occurrence. In the case of untreated and FAP/NH_3 treated samples, both showed almost similar values of dye fixation. This minor residual fixation of the FAP/NH_3-treated sample could be generated by an activated C=C bond residue which was formed from FAP-treated fabrics (Lewis & Ho, 1995).

6 Future Prospects

Physical and chemical treatments, such as UV, microwave, plasma, salts, and alkali, are utilized in conventional dyeing methods. These basically neutralize charges between dye and fiber and improve the binding. Salts and alkalis are mostly used in reactive dyeing processes. However, most of these substances cause environmental pollution and physical treatment is costly. In addition to that, these chemicals are required to be discharged through excess water. Catalytic dye fixation methods are a viable alternative to traditional processes, with the potential to increase the efficiency, sustainability, and quality of the dyeing process. However, these approaches require additional research and development to improve their effectiveness and economic viability.

Different crosslinking agents, surfactants, mordants, enzymatic dye fixation, etc., are some of the most commonly used catalytic media. These eliminate the need for harsh chemicals. These techniques can also be used with particular kinds of dyes and fabrics, which cuts down on waste and boosts effectiveness. Using the reverse micellar system to color fabric in supercritical fluid in the presence of surfactants is a better choice than using traditional water-based processes. It also enhances the dye fixation rate compared with conventional dyeing. Furthermore, reverse micelle could be formed more efficiently by using co-surfactants to properly stabilize the micelle formation. For example, bio-mordant derived from natural plants instead of traditional mordants is an excellent choice of catalyst for dye fixation. Similarly, organic salts also gave similar fixation results. However, there are not many studies about enzymes, organic salts, or bio-mordants. Such organic chemicals should be made and used as catalysts to fix dyes on fabric more frequently.

Enzymatic dye fixation methods offer a promising opportunity for the textile industry to reduce the environmental impact of conventional dyeing processes. Compared with traditional dyeing methods that use large amounts of water, energy, and chemicals, it leads to potential hazards for the environment and human health. On the other hand, enzymatic dye fixation methods use enzymes to fix dyes onto fabrics, eliminating the need for harmful chemicals. Subsequently, this process significantly reduces water and energy consumption and would be highly selective and can be utilized for specific types of dyeing with an improved efficiency that would reduce the generation of wastes. Finally, enzymes can be easily integrated into existing dyeing processes, making it easier for textile manufacturers to adopt these methods in large-scale applications.

7 Conclusions

The central focus of this chapter is to get insight into the catalytic fixation of the dyes over the textile fabric highlighting its promising features as sustainable textile production practices. To efficiently fix dye over the surface of textile materials, it is basically necessary to examine various techniques of dye fixation over the fabric matrix. Physical, chemical, biological, and electrostatic fixation techniques have been briefly discussed. The interaction between dyes and fabric determines the extent of dye fixation over the fabric. In the current context, three techniques have proved to be very promising including the reverse micellar approach, application of mordants, and utilization of crosslinker agents.

Dyeing with reactive dyes is conducted in alkaline conditions. Strong alkaline environments induce partial dissociation of the H^+ from the cellulose matrix resulting in the formation of anion. This anion strongly interacts with the dye molecules to bind it by electrostatic interaction. One of the conventional methods of fixating reactive dyes with the fabric is using salts to improve the efficiency of the reactive dyes. Salts are ionic compounds composed of positive and negative ions which are strongly held by electrostatic interaction between the ions. For various fabrics such as cotton, viscose, polyester, and silk, while dyeing in the aqueous medium, the fiber surface is partially hydrolyzed in a strong alkaline condition. This increases the negative surface charge on the fabric, causing it to repel other fibers. Moreover, the reactive dyes in the aqueous solution partially hydrolyze and the hydrolyzed form of the dye has reduced fixation efficiency. Salts provide an essential linkage between reactive dyes and the fiber by neutralizing this negative surface charge. Subsequently, the repulsion between the dye anions is also reduced to facilitate better adhesion between the dye and the fabric.

Although these methods are somewhat efficient, excess salts and alkali from the dye bath are released into the environment which contributes to pollution and increases the cost of manufacturing deeming it unsustainable at the industrial scale. On the other hand, physical processes such as ultraviolet, plasma, and microwave are highly expensive.

The reverse micellar system could prove to be promising as a sustainable method of dye fixation due to its efficiency, use of nonhazardous chemicals, and lower amount of effluent released into the environment. This approach of dyeing involves using various surfactants that form reverse micelle in the dye bath. Generally, dyes that are not compatible with the fabric or have weak interaction with the fabric surface show very poor color shade and wet fastness of the dye. Conventionally, the aqueous solution is used to dye these fabrics which results in a poor fixation of dye. It encourages the use of nonpolar solvent as a medium and favors the binding between polymer and dye, unlike aqueous solution. The reverse micelle contains a hydrophilic core which easily solubilizes the dye with a high concentration. This system makes the dye stabilize in the nonpolar solvent which is efficiently incorporated over the fabric due to stronger fiber–solvent interaction. Moreover, the usage of a lower amount of water in dyeing enables controlling environmental pollution to a significant extent. Finally, the dyeing medium can be repeatedly used by adjusting the amount of the components of the reverse micellar dye bath.

Another dye fixation method that is sustainable on an industrial scale is the use of mordants. It exhibits excellent binding behavior with natural dyes that are environmentally friendly but are weakly bonded with various textile garments. Mordants are similar to salts; however, the function of mordants in fixing dyes is different from salt. Salts help reactive dyes by minimizing the repulsion between the dye anions and the negatively charged fabric surface, whereas mordants are complexing agents forming a coordination complex with the dye molecule that then binds with the fiber surface. This provides better efficiency in dye fixation, color fastness, and faster processing while consuming less water and energy. Polyvalent metal ions form coordination compounds with the natural dye which also form a bond with the polymer leading to stronger color shade, wet fastness, and more color stability. Moreover, the recent application of bio-mordants could prove to be promising as green and environmentally sustainable dye fixation technique.

The crosslinker agents are used to fixate crosslinker dye molecules with the fabric. These dyes possess weak interaction with the fabric surface resulting in inefficient dyeing on an industrial scale. Crosslinker agents increase the interaction between these dyes and textiles improving the efficiency, thus reducing excess release of dyes and highly caustic solution into the environment. Crosslinkers are alike mordants in action; however, the mechanism of binding with the dye and fiber is different. Crosslinkers contain at least two different reactive groups: one strongly interacts with the dye molecules and the other binds with the fabric surface. Crosslinker agents act as a bridge between the dye molecule and fabric by covalent bond formation. Hence, crosslinker agents can act as a potentially sustainable method for dye fixation over textiles.

Catalytic fixation processes for dye fixation exhibit features that contribute to the overall sustainability of the dyeing process. These processes prevent the release of excess salt or alkali, utilize lower water and energy, require less time to process, and provide better color fastness. Moreover, all types of dyes and textiles could be fixated by these processes, and the use of biocompatible fixing agents makes catalytic fixation very attractive as a sustainable manufacturing practice. Finally, recent progress and future prospects as well as critical challenges are discussed. The reverse micellar approach as a catalytic fixation technique is much more efficient considering its immense potential in dye fixation as well as its being environmentally friendly. Mordants and crosslinkers mostly include the introduction of harmful chemical and metal ions into the environment which can lead to potential pollution in the environment.

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Date Palm Leaf Mat: A Sustainable Textile Craft

Sankar Roy Maulik and Tithi Mitra

1 Introduction

Textiles and clothes have become essential to daily life and constitute a large segment of the global economy. They play a significant role in expressing human individuality. These sectors employ millions of people globally and contribute to economic prosperity. The textile and garment industries have traditionally been based on a linear "take-make-waste" model. The rapid fashion movement results from increased clothing demand and rising production within the linear textile system have significant environmental and social consequences (Wojciechowska, 2021). Sustainability can be addressed by a development that meets the needs of the present without compromising the ability of future generations to meet their own needs. Nowadays, it is a buzzword in every manufacturing process, including textiles. Sustainability primarily focuses on eco-friendly products with minimum environmental impact. The three pillars of sustainability are the economy, society, and the environment. It can only be achieved through strict process control using an eco-friendly route, raw materials, chemicals, etc. Materials play a crucial role in making textiles sustainable. There has been a move toward more sustainable practice, but there is still some way to go. Sustainable development is one of the most difficult challenges mankind has ever faced, and to support meaningful and effective transformation, a comprehensive and holistic approach is required. However, in recent years, the industry has "woken up" to the sustainability issues it faces, and many organizations have began to change their business strategies in a more responsible direction. The term "circular economy" refers to an industrial economic structure that reduces waste and pollution by making the most of already accessible

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resources. The circular economy is increasingly recognized as a better alternative to the dominant linear economic model. The circular economy is the solution to increasing the sustainability of the textile industry. However, its implementation necessitates a more significant systematic shift, with multiple actors interacting in a complex environment. The circular economy philosophy is evolving into an influential driving force behind sustainability. The circular economy intends to continuously keep products, components, and materials at their highest value. It is a long-term method in which today's products are tomorrow's materials. For this reason, initiatives moving toward a more circular and sustainable system are gaining momentum. One of the ways is the concept of a circular economy involving environment-friendly production based on eco-design, reuse, and repair, as well as textile collection and recycling. A new textile economy relies on four principles: eliminating substances of concern and reducing plastic release, increased clothing utilization, improved fibers and textiles recycling, and effective use of resources. However, changing from a linear economic system to a circular one is challenging. Textile waste can be used as raw materials for creating value-added products. Before creating and purchasing a product, it is crucial to understand the material and its life cycle. A product's lifecycle may be split into three stages: production, consumption, and destruction; to reduce the environmental impact of the product, various techniques are employed within these three stages.

The mat produced from date palm leaf locally known as "*Talai*" is 100% sustainable and has traditionally been used for sleeping and seating arrangements. The article mainly emphasized the collection of raw materials, followed by various processes involved in making these mats. The production process requires significantly less volume of water, and practically, there is no use of hazardous chemicals for finishing and dyeing purposes, which makes them environmentally friendly and sustainable. These mats may be an alternative to plastic and polypropylene mats mainly available in the market. The authors have attempted to popularize this traditional textile technique through this documentation, and customers' preference for more sustainable materials has introduced a variety of diverse items and accessories manufactured from date palm leaf without diminishing the spirit of the craft. Documentation of this traditional textile craft is essential to keep its heritage alive forever so that it might reach every human being, thus expanding the artisans' opportunities for livelihood.

2 Craft and Textiles

Craft is a skill that creates every output without using modern machinery; thus, crafts are known as handicrafts. Craft protects our heritage and is deeply rooted in the culture. Practicing craft is a generational legacy. It reflects the evolution of the struggle of mankind for survival, and it is essential to remember the traditions; if not, then the foundation of human civilization will destroy. Art and craft are different from each other. Art is a form of self-expression and is very much linked to individual perception, which is not necessarily something that can be taught. In art, the medium of expressing the vision may remain the same, but the expression will vary from man to man. At the same time, the craft can be taught to someone, and it may continue from generation to generation and has a special kind of function and quality. Craft practice has been viewed as a more sustainable alternative to mass manufacturing because it stimulates the development of high-quality goods and has slow consumption rates (Roy Maulik, 2017).

India is a diverse country that emerges through its people and culture. The people and culture of every state in India are different in terms of language, attire, and food. A rich crafts tradition abounds in India, and the culture and handicrafts reflect India's glory or beauty. India's rich crafts and culture have evolved since ancient times, and that richness continues. Crafts determine the employability of the artisans involved in this profession and reflect our country's form, color, and diversity. The artisans' skillful hands and their love for that work create the beauty of crafts. A craftsman is not just a maker of something; he or she is an inventor, a creator, and one who solves problems in our daily lives.

Documenting a traditional craft process is essential to preserve our tradition. Many crafts are gradually being discontinued for various reasons, some of which every family formerly employed in a village, but now only one or two families are doing that craft. Some crafts are no longer in practice at all.

3 Talai—A Traditional Textile Craft

India is such a country where every state is full of unique crafts. Birbhum district in West Bengal is also famous for various crafts, namely, Kantha stitch, the leather craft of Santiniketan, and Batik. However, other crafts are not very familiar to most people. In the Sattore village of the Birbhum district in West Bengal, female artisans produce beautifully crafted handmade date palm leaf mats. Locally, these mats are known as *Talai*, made by interlacing date palm leaves. *Talai* is not a very familiar craft among ordinary people.

Talai is a craft made by the female artisans of the Muslim community, is important to the village people, and is associated with their culture and rituals. The date palm leaf *Talai* is made during the winter and monsoon seasons. The women artisans spend their leisure time making *Talai* after completing the household activities. The female artisan's spouse brought the necessary raw materials and arranged various tools and equipment for making *Talai*. This traditional craft's color and design aspects have changed a little due to the ever-changing taste of the new generation and customers. Fig. 1 shows a date palm leaf mat, i.e., *Talai*.

Fig. 1 Date palm leaf mat, i.e., *Talai*

Fig. 2 Date palm tree

3.1 Date Palm Tree

As shown in Fig. 2, the date palm tree is considered one of the significant and ancient crops. It is found along the roadsides of many places in the Birbhum district of West Bengal. Each part of the tree is used in many ways. The tree trunk is used in the villages to make mud house poles and other purposes, whereas the villagers use the leaves as fuel and in fences. The fruit is also delicious and has many unique health benefits. Date palm juice, locally known as *Khejurer Rosh* is very popular, and this juice is converted into jaggery, with which the emotions of the Bengalis are involved. *Talai* is made out of date palm leaves by artisans.

3.2 Suitable Weather for Weaving

The artisans do not weave *Talai* in the summer because the leaves dry out, stiffen, and break down while bending in a hot and dried atmosphere. During the rainy season, there is much moisture in the air, which allows the leaves to bend readily and makes it easier to weave *Talai*. Apart from the rainy season, *Talai* is weaved in the mornings of winter; craftsmen use the dew to soften the leaves, which facilitates weaving.

4 Raw Materials

The primary raw material for this craft is date palm leaves, as shown in Fig. 3. The leaves are typically obtained from Bihar; however, the village has abundant date palm trees. For various reasons, the craftspeople choose to purchase them from other sources. According to the artisans, the collection of leaves is a time-consuming and tedious process. As a result, people choose to buy the leaves rather than collect them. Few artisans revealed they do not have trees; otherwise, they prefer to collect individually rather than buy from a third party. The female artisans buy the dye powder as indicated in Fig. 4 from local village stores, which costs Rs.25 per packet.

Fig. 3 Date palm leaves

Fig. 4 Dyestuff used

Fig. 5 *Boti* (Traditional vegetable cutter used by Bengali women)

5 Tools and Equipment

The village people use indigenous tools and equipment to produce this mat. Figures 5, 6, 7 and 8 depict various tools and equipment the artisan uses.

6 Collection of Leaves

Figure 9 shows various stages of collecting date palm leaves for making mats. At first, the branches are collected from the trees, followed by plucking the individual leaves and separating them one by one according to their length. After separating the leaves, they should be spread in direct sunlight for drying. Usually, from a

Fig. 6 Cutter

Fig. 7 Plastic rope

branch, three to four leaves of different sizes are found. According to the length of the leaves, it has been divided into four categories: *Char Pata,* the smallest leaf, *Choy Pata*, *Aath Pata*, and *Dosh Pata,* the largest one, in ascending order. *Choy Pata* and *Aath Pata* are readily available, but *Dosh Pata* (the largest leaf) is not commonly found. The price of the leaves depends on their sizes. *Char Pata* is the cheapest of all. The cost varies from Rs. 10/− to Rs. 25/− per kg. During summer, the leaves are cut from the trees and dried in the sun.

7 Preparatory Processes

Making *Talai* is not that easy; it involves a lot of detailed work and patience. As mentioned earlier, the first step involves collecting and drying the leaf, followed by dyeing. The tips of the date palm leaves are very sharp; at first, artisans cut off the

Fig. 8 *Nora* i.e. Stone

Fig. 9 Steps of collecting date palm leaves: (**a**) cutting branches from a tree, (**b**) collecting the branches, (**c**) carrying those branches, and (**d**) leaves are plucked from the stalks

Fig. 10 The sharp tips are being cut off with the help of *Boti*

sharp tips with the help of *Boti* (Fig. 10). Then they have torn the leaf from the middle. There is a thick spine, colloquially termed as *Shir*, in the middle of the leaves; it is taken out from leaves and kept for later use. Then each leaf is split one by one in equal width with the help of a needle, as shown in Fig. 11. In the case of

Fig. 11 The leaves are split into two parts from the middle

colored design, the width of each leaf strip has to be the same; otherwise, the design will not be visible properly. Extremely fine leaf strips are used to develop delicate and intricate designs.

8 Dyeing Process

A water-filled vessel is placed over the flame, and the dyestuff is added to the boiling water. The artisans measure the amount of water and dyestuff based on their experience. When the dye begins to boil, the previously dried leaves are immersed in the bath, stirring the mixture for 5–10 min. Then they placed the leaves in a sieve to drain the excess water. After that, they spread the leaves under a shed in their house for drying and fixation of the color. It takes about 3–4 days for the leaves to dry properly. The stepwise process of dyeing is explained in Figs. 12, 13, 14, 15, 16, 17, 18, 19, 20 and 21.

9 Woven Sheet (*Pati*)

The individual extended woven sheet of date palm leaves is known as *Pati*, as shown in Fig. 22. As the leaves are shorter, the width of the *Pati* remains shorter, but the length of the *Pati* can be woven as long as desired, which also depends on the design and end product. At first, the *Patis* are woven one by one, and at the end, all the *Patis* are stitched together to form a large sheet known as *Talai*, as shown in Fig. 23. Colored design *Talai* is also woven similarly, but the placement of colored leaves is the primary key to a good design; artisans patiently calculate each step and then place the colored leaves according to their design. If even one leaf is placed incorrectly, the design of the whole weaving will be damaged.

Fig. 12 Vessel is ready for dyeing

Fig. 13 Heating process

Fig. 14 Measurement of the dye

Fig. 15 The dye is added in boiling water

Fig. 16 The previously dried leaves are dipped in the dye solution

Fig. 17 Stirring of the leaves

Fig. 18 Transferring the leaves to a sieve

Fig. 19 Draining of excess water

Fig. 20 Spreading the leaves under the shed

Fig. 21 Dyed leaves

Fig. 22 *Pati*

Fig. 23 A set of *Pati* known as *Talai*

10 The Process of Making *Pati*

The structure of *Pati* is made by interlacing the strips of leaves. The interlacement pattern may vary according to the design. Some common interlacement patterns are 1/1, 2/1, 3/1, and vice versa. The *Pati* is woven in a diagonal direction, as depicted in Fig. 24; a minimum of seven leaves are initially required for weaving the base. A few leaves should be cut into two thin strips, but the ends have to stick together; these leaves are used at the beginning of weaving to prevent unraveling (Fig. 25).

Once the base is woven, the leaves stretched from both sides are folded toward the weave; as shown in Figs. 26 and 27, the weaving is continued similarly. As the leaves are shorter from both sides, new leaves are incorporated in the middle to maintain the continuity of weaving.

Fig. 24 *Pati* weaving

Fig. 25 Cutting of leaves into two thin strips

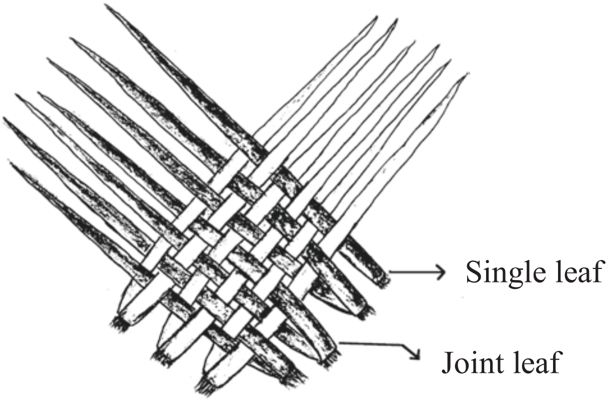

Fig. 26 Base weaving by interlacing the date palm leaves in 1/1 order

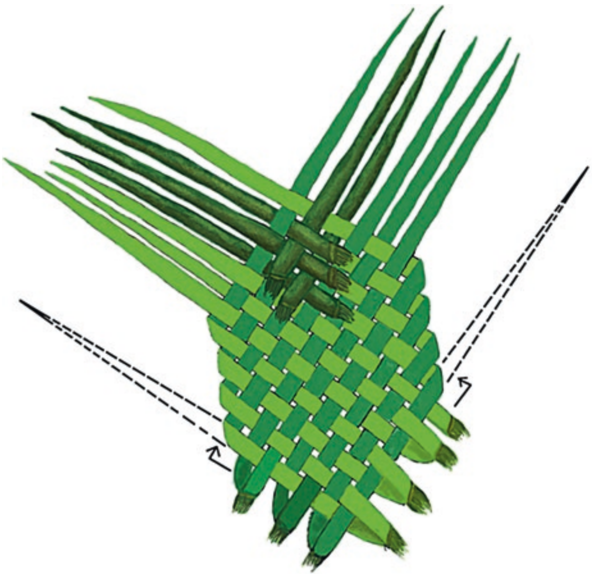

Fig. 27 The interlacing process

10.1 Joining the Pati

At first, two *Patis* are placed side by side, and then a stone or something heavy is placed on top of them so that the *Patis* do not roll up. Traditionally, the spines or *Shir* of the date palm leaves are used to stitch the *Patis*. However, now it has many alternatives that are very cheap and readily available in the market. Most artisans use polyethylene tape for sewing because it does not tear easily. After purchasing these tapes, they are cut to a specific length which helps in sewing. The *Patis* are stitched in a zig-zag manner, and the thin tape is inserted through the edges of one *Pati* to another. In this way, all the *Patis* are joined individually. Figure 28 shows the process of joining individual *Pati*. Figure 29 shows an artisan producing a mat.

11 *Talai*—A Custom

Nothing is as special as the unique and sacred relationship between a mother and her daughter. They share an unconditional love for each other. The happiest and saddest moment for a mother is her daughter's marriage. The pain of separation from the daughter after keeping her in her arms for so long cannot be explained in words.

Fig. 28 The process of joining *Pati*

Fig. 29 Artisan is involved in making *Talai*

Marriage is a spiritual bond; after the birth of a daughter, her mother starts preparing for her marriage, and one such preparation is the making of *Talai* (Fig. 30). For everyone, a gift is precious, and every parent wants to give their daughter some gifts to help her start a new journey. *Talai* and Kantha are the two most important gifts they give their daughters during the wedding.

Fig. 30 The use of *Talai* in a marriage ceremony

The craftspeople and their families have a deep connection with the craft *Talai*. This craft is used from the beginning to the end of their lives. When someone comes from outside, they spread the *Talai* on the floor to let them sit (Fig. 31). It is used as a sleeping mattress and as a sitting arrangement in events like a marriage ceremony. It is also used in many household activities. They sometimes use the *Talai* as a decorative item, like a wall hanging (Fig. 32). They use the *Talai* as their prayer mat because they believe it is very auspicious. The *Talai*, used for prayer, must be white and plain. This craft is also someone's companion in the last journey of life. When someone dies, their body is laid on *Talai*, which falls into their culture. The *Talai* used for this purpose has no color or design; it is entirely white. Moreover, they do not use this *Talai* for any other purposes; after using it, they clean and keep it carefully to use for the same purpose.

Fig. 31 Use of *Talai* in household activity

Fig. 32 *Talai* as a decorative wall hanging

12 Motifs

The designs or the motifs are drawn from various sources, and the *Talai* is termed according to the source of inspiration, e.g., Chocolate *Pati*, *Rajbari Gate Pati*, *Padma Pati, Surya Pati*, *Jahaj Pati*, *Ghati Pati*, and *Botam Pati*. Figures 33, 34 and 35 depict some motifs used in *Talai*.

Fig. 33 *Ghati Pati,* motifs are inspired by a pot which is colloquially termed *Ghati*

Fig. 34 *Rajbari Gate Pati*, the design inspiration is a palace gate

Fig. 35 *Botam Pati*, the design inspiration is buttons

13 Storing of *Talai*

The storing processes of *Talai* are depicted in Figs. 36, 37, 38 and 39.

Fig. 36 Rolling of the *Talai*

Fig. 37 Tying using a rope

Fig. 38 Storing in the rack

Fig. 39 Stored *Talai*

14 Marketing Channel

The artisans sell their handcrafted items in two ways. Craftsmen typically do not go outside to sell their products. Customers come to their homes and place an advance order; the craftspeople produce *Talai* for that specific customer. The second method is indirect selling through middlemen, in which a third party purchases *Talai* from artisans and sells it to shops. Every Friday, a *Talai Haat* (Market) is held in Ghuskara of Bardhaman district, 25.7 km from Bolpur-Santiniketan (Fig. 40). Some people buy *Talai* from artisans and also sell it at this market (Fig. 41).

15 Diversification of the Craft

The use of date palm leaf mats, i.e., *Talai*, has increasingly declined due to the introduction of widely available machine-made items. To promote this craft to the people, one can leverage its essence to produce new products that offer uniqueness to consumers, such as decorative items and accessories. The female artisans are selling those diversified items in the local market. Figures 42, 43 and 44 depict some diversified items produced from date palm leaves. The artisans had transformed the traditional item into a contemporary product range.

16 Conclusion

Talai is an ancient craft manufactured in several places in Bengal and primarily used for sitting and resting. Female artisans continue to practice this trade because it connects them to their cultural heritage. These female artisans rarely leave their homes, so they spend their free time making *Talai* to supplement their income.

Fig. 40 *Talai Haat* at Ghuskara, Bardhaman

Fig. 41 A customer buying *Talai* from a retailer at *Talai Haat in* Ghuskara

Fig. 42 The date palm leaf *Tote* bag

Fig. 43 Diversification of traditional *Talai*

Making *Talai* involves indigenous tools, equipment, and locally available raw materials with minimum water use and other hazardous chemicals. Thus, the date palm leaf mat produced by the artisans is 100% sustainable. As a result, the product is eco-friendly. It may be an alternative to plastic and polypropylene mats as modern society is becoming more aware of green consumerism and the need for eco-friendly products. The materials used to manufacture this textile craft do not adversely affect the health of workers or consumers during production or usage, and such materials are obtained through renewable, recycled, or both methods.

Fig. 44 The date palm leaf *Tote* bag

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Sustainable Performance Assessment of Textile and Apparel Industry in a Circular Context

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1 Introduction

The textile industry responds to the demand for clothing which is one of the basic human needs (Hansen & Schaltegger, 2013). The industry is one of the most economically substantial industries in terms of employment generation, trade, investment, and revenue (Keane & te Velde, 2008). Garment manufacturing is regarded as the world's third-biggest industry with USD 700 billion a year after the automobile and electronics sectors (Francis, 2014). Therefore, it has great impacts on the social and environmental aspects as well as the economy (Amini & Bienstock, 2014). However, these effects of the textile industry do not always have positive properties. The textile industry is one of the main causes of global pollution by consuming resources besides its role in employment generation (Desore & Narula, 2018). The textile industry consumes fuel, water, and electricity, with corresponding greenhouse gas emissions and wastewater (Hasanbeigi & Price, 2015).

The world's culture of "throwaway and replace," increase in population, and the demand for new production units have put tremendous pressure on resources (McCollough, 2012). The reality of the linear economy model is to produce and consume according to the idea of "take-make-use-dispose" of the resources (Berberoglu et al., 2023). A significant amount of waste is continuously produced by throwaway consumption (Ballie & Woods, 2015).

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Circular economy (CE) focuses on restructuring behaviors regarding the production and consumption of products to provide long-term usage of materials as possible instead of scrapping materials after a single use of the product (Di Maio & Rem, 2015). The principles of CE aim to eliminate pollution and waste by restructuring materials being in use (Haupt et al., 2017). Considering the textile sector, the mentioned wastes and pollutions are among the main problems (Xu et al., 2019) such as water waste (dos Santos et al., 2007), noise (Noweir & Jamil, 2003), gas (Rakib et al., 2017), and pre-consumer and post-consumer waste (Domina & Koch, 1997). Consumers of almost all apparel categories keep their clothes about half of the time compared with 15 years ago (Remy et al., 2016). In their report about the new textile economy based on CE principles, the Ellen MacArthur Foundation (2017) reported that deficiency of recycling and underutilization of clothes cause more than USD 500 billion of value loss on an annual basis as well as countless negative effects. The emerging textile industry model encompasses four key objectives: minimizing the use of harmful substances and microfiber release, maximizing clothing usage, enhancing recycling processes and resource efficiency, and shifting toward renewable materials as inputs. Thus, it seems that today's textile system causes wastes, pollutions, and related economic problems, and therefore, it is substantial to apply CE principles.

Performance assessment means measuring how well people or systems work on the basis of predefined indicators (Issa et al., 2015). Parameters and measures are determined, and desired performance measures are obtained by using a method to assess the performance. Sagnak and Kazancoglu (2016) indicated that it is essential to measure, monitor, and evaluate the environmental performance of a company continuously. Therefore, assessing the effective usage level of CE in the apparel industry is a necessity.

Within this perspective, past studies about CE, textile industry, and performance assessment were reviewed. The past studies include the binary combinations of CE, performance assessment, and textile industry subjects. However, no study integrated those three subjects; therefore, a significant gap was found for triple combination, which is the assessment of the CE performance in the textile industry. In other words, a review of the literature identified a gap in assessing CE performance in the textile industry. To fill this gap, this chapter has the motivation to propose a framework that can be applied to assess the performance of the textile industry. The contribution of this study is to highlight the gaps related to performance assessment in the textile industry within a circular environment and propose a novel framework to provide a roadmap. For this purpose, first, a criteria set has been identified to set the indicators that affect the performance of a company in the textile industry. Then, the fuzzy DEMATEL technique was chosen to identify the cause-and-effect connections among the criteria. Finally, the weightings of the criteria were found using the fuzzy Best-Worst method (BWM) to identify the roadmap for performance assessment.

Following the introduction, Sect. 2 presents the theoretical background for three subjects, CE, textile industry, and performance assessment, respectively. Then, in Sect. 3, binary combinations of past studies are presented. In Sect. 4, fuzzy

DEMATEL and fuzzy BWM methods are explained. Section 5 presents the proposed framework. In Sect. 6, the case study, findings, and implications are discussed. Finally, Sect. 7 summarizes the concluding notes, limitations, and possible future directions.

2 Theoretical Background

In this section, the specifications of CE, textile industry, and performance assessment subjects are summarized.

2.1 Circular Economy

Nowadays, the linear economy has a lot of challenges. As the demand for production is growing, some major challenges such as a lack of resources and a huge amount of waste are also growing. The adverse impacts of these challenges extend to social, environmental, and economic aspects globally, aligning with the triple-bottom-line principles of sustainability, which considers the interconnectedness of social, environmental, and economic factors. The perception of sustainability appeared originally in the Brundtland report (Keeble, 1988). To decrease the unfavorable environmental impacts of economic development, the Brundtland report was published to outline solutions to the issues that will be raised by industrialization and population expansion. A unified strategy that acknowledges the interdependence of these elements on a global scale was successfully established by the United Nations commission by integrating environmental concerns with social and economic issues.

Sustainability endeavors to satisfy the present needs while safeguarding the needs of the next generations, without compromising the triple bottom line principles, which encompasses social development, environmental protection, and economic growth. Environmental sustainability is to keep the rate in balance between natural resources and consumption of them by humans. Economic sustainability is to ensure the independence of financially needed resources. Social sustainability is to provide human rights and necessities accessible to all people to keep the community safe. To provide a sustainable situation, these three pillars should be accomplished.

CE is a sustainable system to eliminate the amount of waste and provide continuity of the current resources by creating closed-loop systems (Geissdoerfer et al., 2017; Ada et al., 2022). Furthermore, it aims to minimize waste amount, resource usage, pollution, and greenhouse gas emissions. This approach opposes the linear model of resource reduction of "take-make-dispose" (Ellen MacArthur Foundation, 2013). While CE focuses on reducing the impacts of a linear economy, it also aims to build long-term resilience, provide environmental and societal benefits, and create economic opportunities and businesses.

The Ellen MacArthur Foundation (2017) outlines four key components of CE. The first entails companies developing resources and capabilities in a circular design to enable recycling, reuse, and cascading of materials. The second involves adopting new business models that promote circularity. The third essential is acquiring the necessary skills for managing cascades and ensuring proper material return. Finally, market mechanisms, policy makers, educational institutions, and opinion leaders play a key role in driving the adoption of material reuse and more efficient resource utilization as common practices.

Recent studies have presented a framework to increase the circularity of a linear economy which is known as R-strategies. The strategies are based on 3R (reduce, reuse, recycle) (Brennan et al., 2015; Ghisellini et al., 2016; Yang et al., 2014; Sakai et al., 2011; Yong, 2007; King et al., 2006; Ada et al., 2021), 6R (reduce, reuse, recycle, recover, remanufacture, redesign) (Kuik et al., 2012; Sihvonen & Ritola, 2015; Ada et al., 2021), and 9R (refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, recover) (van Buren et al., 2016; Potting et al., 2017; Ada et al., 2021). Refuse is to abandon a product's function to make it redundant. Rethink is to make a product multifunctional to make it more intensive. Reduce is to increase efficiency while manufacturing or consume fewer natural resources. Reuse is to offer a product, which is still in a satisfactory state, to another customer. Repair is to solve the defects of the product and make it usable again. Refurbish is to restore a used product that makes it up to date. Remanufacture is the process of utilizing components from a previously discarded product to create a new one. Repurpose is like the remanufacture, but the parts are used for a different function. Recycle is to use materials so that they can be used again. Recover is to transform the materials into energy by incineration. The more these strategies are used, the more circular the economy gets.

2.2 Textile Industry

The textile industry has been critical for people since the beginning of history. It is one of the fundamental needs of Maslow's hierarchy of needs (Maslow, 1943). According to Kvavadze et al. (2009), the first textile products, wild flax fibers, go up to BC 27000 as the evidence of prehistoric linen production. Additionally, 30,000-year-old perforated bones and ivory sewing needles found during excavations at Kostenki, Russia, show that textile has a much longer history (University of Colorado at Boulder, 2002).

The primary motivations for individuals to wear clothing are related to factors such as protection, social status, and fashion. Climatic and geographical conditions made it more necessary. Those living in the cold climate preferred fur and thick clothes, while those living in the warm climate preferred thin clothes to protect them from the sun. Even in conditions unaffected by the weather, people wear clothes to protect against insects. The second purpose of using clothes after protection was to show status. Some outfits give information about people's professions, races, and religions. Vout (1996) indicated that, depending on the climatic conditions in the ancient Roman period, everyone preferred to wear a tunic, but the toga could only be worn by free people. Toga varieties and colors show the status in general and change according to your duty and status. According to the Dictionary of Fashion History (Cumming et al., 2010), standard dress code is still applied for many professions. Besides, fashion and trends determine clothes. Fashion is the clothes people wear to look beautiful and trendy. Fashion changes and advances every year; on the other hand, every decade has its own fashion trends.

Although textile was an old sector, it evolved in the 1790s with the invention of the sewing machine and the industrial revolution. A revolution in the textile industry was led by the sewing machine's invention (Gregory, 2006), and the limited production capacity went into mass production with this invention. According to the market research report about the textile industry (Grand View Research, 2020), the textile's worldwide market size was USD 961.5 billion in the prior year and 7% of the trade in the world occurs because of the textile industry. Many people are working in raw material supply and textile subsectors like dying. The fast fashion industry is causing a significant rise in both the spending on the textile industry and the production of waste.

The increase in landfill wastes is largely affected by fashion and the modern living way of the west (Chavan, 2014), and textile recycling is becoming more important for reducing waste. Textile recycling is also necessary because of the waste due to overproduction and diversified advantages in terms of the environment, socio-economy, and ecology (Leal Filho et al., 2019). Textile recycling is the collection of operations related to the reuse and reprocessing of old clothes, textile materials containing fiber, and production wastes (Patel & Pandey, 2015). Textile recycling involves recycling and reducing wastes both before and after consumption which are two starting materials (Chavan, 2014). Pre-consumer waste is the waste before consumption, also called post-industrial waste. It consists of the general term used for waste that increases or becomes unusable during production. Those materials are usually used for industries such as furniture, construction of homes, and automotive. The term post-consumer waste, the waste after consumption, is used for unwanted clothes. It can also be called a kind of textile scrap. After collecting the waste materials, the separation process is started. In the first step, textile waste is divided by a group with some criteria whether it will be reused or raw material. After this stage, there are five main groups of textile waste. These are export markets for second-hand clothes, converting textile into useful products, clothes for wiping and polishing, energy creation from landfill incineration, and diamonds (Hawley, 2006).

2.3 Performance Assessment

Performance assessment is measuring how well people or systems work according to predefined indicators (Bititci et al., 2012). First, parameters and measures are determined. After that, by using a method, the desired performance measures are acquired. It is used in a variety of fields. On the other hand, in industry settings, the focus is often on evaluating and measuring the effectiveness of systems or processes rather than individual outputs. The most used methods for industry are analytical and simulation methods (Sassanelli et al., 2019). The multicriteria decision-making (MCDM) techniques are the most popular analytical tools (Kazancoglu et al., 2018a, b; Huysman et al., 2017; Mardani et al., 2017; Angelis-Dimakis et al., 2016). There are also simulation methods used in previous studies (Gbededo et al., 2018). The analytical method involves creating a mathematical model that incorporates input parameters and output measures, which are then used to directly compute the performance of a system. On the other hand, simulation modeling aims to replicate an actual process or system through computer-based simulations, allowing for the study of its behavior and performance in a controlled environment (Sassanelli et al., 2019).

In recent times, there has been increased attention on sustainability among researchers and industrial corporations, which also involves assessing the performance of sustainability. Many methods used in this field rely on sets of indicators, and one commonly used approach is MCDM methods (Sassanelli et al., 2019; Shen et al., 2013). MCDM methods are designed to convert multiple indicator values into a single dimension, and they are applied in industries such as supply chain management, logistics, engineering, manufacturing, healthcare, and sustainable development (Karthee et al., 2018). Numerous studies have shown that MCDM methods are effective in addressing complex problems involving multiple criteria (Ishizaka & Resce, 2021; Kilic et al., 2015). However, in cases where there are conflicts among the criteria, finding a single optimal solution may not be possible. This is where a decision-making system is needed to help navigate the complexities and uncertainties of multicriteria problems. The AHP, ANP, TOPSIS, ELECTRE, DEA, BWM, GRA, PROMETHEE, COPRAS, DEMATEL, and VIKOR are some of the most common MCDM methods used by researchers (Ishizaka & Resce, 2021; Alao et al., 2020; Torbacki & Kijewska, 2019; Chen et al., 2019; Sawaf & Karaca, 2018; Suganthi, 2018; Gupta, 2018; Han & Trimi, 2018; Basso et al., 2018; Liu et al., 2018; Zarbakhshnia et al., 2018; Gardas et al., 2018; Li & Zhao, 2016; Kilic et al., 2015; Sakthivel et al., 2015; Bentes et al., 2012). As human judgments in decision-making often involve uncertain or linguistic language (Sagnak et al., 2021; Jajimoggala et al., 2010), fuzzy set theory that allows decision-makers to deal with linguistic assessments of data has been used (Wibowo & Grandhi, 2017; Li & Zhao, 2016). Fuzzy set theory enables the integration of mathematical operators and programming techniques for implementation within the fuzzy domain.

3 Literature Review for CE Performance Assessment of Textile Industry

In this section, the binary combinations of three subjects are presented.

3.1 CE in Textile Industry

Many academicians and experts are trying to maintain a sustainable circular system. Although energy and water have an important place in textile wastes, they are not suitable for reuse. For example, while growing 1 kilogram of cotton, an average of 8500 liters of water is consumed. There are a lot of studies aimed to reduce water usage and water footprint. dos Santos et al. (2007) tried to reduce water usage with the current technology of the decade. Alkaya and Demirer (2014) carried out a study on reducing water usage in woven fabric. Chico et al. (2013) mentioned the water footprint's significance on the water scarcity index for denim trousers (blue jeans) production. Angelis-Dimakis et al. (2016) worked on water usage systems in the textile industry in terms of eco-efficiency. Hasanbeigi and Price (2015) studied emerging technologies for the efficiency of water and reducing pollution within the textile industry. Joa et al. (2014) explained the usage of the Regionalized Cumulative Water Intensity (RCWI) technique in their study. The study of Maia et al. (2013) represents a sustainable lean system framework for energy and water reduction and environmental waste minimization. In the study of Ozturk and Cinperi (2018), techno-economical minimization techniques are utilized for the reduction of water waste.

Zabaniotou and Andreou (2010) worked on cotton ginning wastes. Ofluoglu and Atilgan (2016) used Five-R SSCM for utilizing textile wastes. Jacometti (2019) made a doctoral dissertation on textile waste within the fashion industry in the European Union. Briga-Sá et al. (2013) studied on carrying out of textile wastes on building insulation material. Cuc and Tripa (2018) provided utility solutions to figure out the product development processes such as rethinking, reusing, and upcycling the waste within the manufacturing phase for small- or medium-sized businesses. Fresner (1998) worked on the Austrian prepare-project to improve an assessment of the cleaner production in a textile plant. Raj et al. (2017) used sustainability's triple-bottom-line perspective on the garment industry in India. They had 51 participants who work for the Indian apparel production sector within the survey and evaluated lean production in terms of production of apparel, environmental sustainability, and waste management.

Boiten et al. (2017) tried to encourage waste collectors by touching upon the key drivers and opportunities for creating significant circular chains. They also mentioned the barriers of CE. Franco (2017) mentioned supply chain collaboration and the difficulties of CE integration within the textile industry. Moorhouse and Moorhouse (2017) focused on developing more sustainable industries. Moktadir et al. (2018) analyzed CE drivers in Bangladesh leather industry. Sandin and Peters (2018) dealt with the environmental effects of recycling and reusing materials. Moreover, Leal Filho et al. (2019) focused on the socio-economic parts of recycling and the CE concept in the textile industry. The study by Jia et al. (2020) evaluated the sustainable supply chain research. Köhler (2013) studied on eco-design for electronic textile waste.

According to the reviewed studies, 85% are about recycling and 41% are about reuse (27% of them cover both recycling and reuse). The most studied materials can be counted as cotton (76%) and polyester (63%). Table 1 shows the relevant studies about CE in the textile industry.

3.2 CE Performance Assessment

Iakovou et al. (2009) developed a "Multicriteria Matrix" for manufacturers to assess and select end-of-life alternatives. Santini et al. (2010) investigated the effects of pre-shredder treatment on reaching an 85% recyclability rate using the Design for Recycling software. Olugu and Wong (2012) created a fuzzy expert system to assess the management of closed-loop supply chains. Shen et al. (2013) examined green supply chain management and proposed a fuzzy MCDM approach for evaluating green suppliers. Jamali-Zghal et al. (2015) conducted an environmental performance assessment of metallurgical recycling using LCA. Issa et al. (2015) conducted a review analysis to classify and recognize indicators associated with the environmental performance of products. Pagotto and Halog (2016) utilized an input-output-oriented data envelopment model (I-O/DEA) and material flow analysis to assess the eco-efficiency performance of various sub-industries in the Australian agri-food systems and establish environmental and economic indicators.

Laso et al. (2016) evaluated the environmental performance of two waste management systems used in the anchovy canning business using the LCA approach. A decision-making framework was developed by Ng and Martinez Hernandez (2016) with the goal of facilitating multicriteria analysis and process design while taking energy, environmental, and economic considerations. For performance evaluation in sustainable supply chains, Motevali Haghighi et al. (2016) presented a hybrid technique integrating Data Envelopment Analysis and Balanced Score Card. Franklin-Johnson et al. (2016) suggested a brand-new indicator for measuring environmental performance that is connected to the CE. Pan et al. (2016) explained the five issues in evaluating the sustainability of industrial systems and adopted the classic EA method to deal with those issues. Huysman et al. (2017) developed indicators for various plastic waste treatment alternatives to assess CE performance. Grimaud et al. (2017) used Environmental Technology Verification guidelines to evaluate the economic, environmental, and social efficiency of processes. Martin et al. (2020) examined the environmental performance evaluation to see the effects of biofuel systems on related cases. Fregonara et al. (2017) used the LCA methodology for design activities used in new buildings or restoring existing buildings.

Table 1 Papers about CE in the textile/apparel industry

Author (Year)	Objectives	Methods
Fresner (1998)	Waste and emission minimization in an Australian textile mill	–
dos Santos et al. (2007)	Reviewing the technologies for decreasing wastewater amount in the textile industry	–
Zabaniotou and Andreou (2010)	Decreasing the greenhouse gas emissions in the textile industry by energy recovery	–
Briga-Sá et al. (2013)	Using textile-based wastes as an alternative resource	Case study
Chico et al. (2013)	Evaluating the water footprint of denim trousers	Water footprint assessment
Maia et al. (2013)	Reviewing some of the lean tools and initiatives that are totally aligned with sustainable development	–
Alkaya and Demirer (2014)	Applying different measures of sustainability and indicating benefits in terms of environmental and economic perspectives in a woven fabric	Environmental performance evaluation (EPE)
Joa et al. (2014)	Introducing a new indicator for performance assessment for the cotton industry	Regionalized Cumulative Water Intensity (RCWI)
Ofluoglu and Atilgan (2016)	Showing the benefits of Five-R technique in the clothing sector	Five-R
Hasanbeigi and Price (2015)	A review of emerging technologies' textile industry in terms of energy and water efficiency	Questionnaire
Angelis-Dimakis et al. (2016)	A framework was developed for measuring eco-efficiency in water usage systems within the textile sector	Life cycle assessment (LCA)
Boiten et al. (2017)	Identifying the key drivers and opportunities for waste collectors in the textile industry	Criteria-Quota- Individuals-Methodology (CQI)
Franco (2017)	A review on textile sector's micro-level CE challenges	Questionnaire
Moorhouse and Moorhouse (2017)	Examining the fashion industry under circularity	–
Raj et al. (2017)	Investigating the effects of production cost and practices in waste management on various environmental and economic impacts	Lean production
Ballie and Woods (2015)	Identifying the most appropriate sustainable design strategies for the fashion industry	Triple bottom line (TBL)
Cuc and Tripa (2018)	Opening a new research area that is suitable for SMEs within the textile industry	3R (Reuse, Recycling, Redesign)

(continued)

Table 1 (continued)

Author (Year)	Objectives	Methods
Moktadir et al. (2018)	Analyzing the drivers to CE and sustainable development in the leather industry	Graph theory and matrix approach (GTMA)
Ozturk and Cinperi (2018)	Reducing the water usage and the wastewater amount in a woolen textile mill	Analytic hierarchy process (AHP), weighted sum (WSM), and simple ranking methods (SRM)
Sandin and Peters (2018)	Evaluating the recycling and reuse effects on environment in the textile industry through a comprehensive review	Life cycle assessment (LCA)
Leal Filho et al. (2019)	A thorough examination of the social and economic advantages of textile recycling through a comprehensive review of existing literature	Review
Jacometti (2019)	Analyzing the available EU measures affecting sustainable development practices	–
Jia et al. (2020)	A systematic literature review on CE practices within the textile industry	Review

Wibowo and Grandhi (2017) proposed the MCDM approach to evaluate the performance of recoverable products. Favi et al. (2017) proposed an approach for comparing end-of-life scenarios based on EoL indices in product design to reduce landfill waste. Mardani et al. (2017) presented an overview of various models of Data Envelopment Analysis that can be used for evaluating energy efficiency. Using pre-existing frameworks and indicators, Petit et al. (2018) created new sustainable performance measurements for a food value chain. A thorough literature study was carried out by Gbededo et al. (2018) to examine sustainability methods from 2006 to 2015. For the purpose of determining CE indicators, Pauliuk (2018) suggested a general system definition based on MFA and MFCA. Laso et al. (2018) proposed an eco-efficiency evaluation method for the fish canning industry through LCA and LCC methodologies. Biganzoli et al. (2018) suggested the LCA methodology to evaluate the environmental effects of intermediate bulk container rotation numbers. Hadzic et al. (2018) investigated bio-waste scenarios using the LCA methodology. Kazancoglu et al. (2018a, b) identified a gap in the performance evaluation of the CE in GSCM. They also offered a novel, all-encompassing conceptual framework for GSCM performance assessment. Twenty-three Brazilian wood furniture enterprises were examined by Oliveira et al. (2018) to determine how well they operate in the CE. Expósito and Velasco (2018) used a novel DEA method to analyze the effectiveness of the recycling market in Spain. Table 2 shows the relevant studies about performance assessment for CE.

Table 2 Papers about performance assessment for CE

Author (Year)	Objectives	Methods
Iakovou et al. (2009)	"Multicriteria Matrix" is developed for manufacturers to distinguish the components according to their highest potential value	MCDM
Santini et al. (2010)	Design of recycling is used for end-of-life performance of products and the impact of pre-shredder treatment could have	Design for X (DfX)/ Guidelines (GL)
Olugu and Wong (2012)	An expert system is created to evaluate the closed-loop supply chains	MCDM
Shen et al. (2013)	Fuzzy MCDM is examined for a GSCM system	MCDM
Jamali-Zghal et al. (2015)	Uses the emergy approach and exergetic LCA to measure the environmental performance of metallurgical recycling	Life cycle assessment (LCA), Emergy approach (Em), Exergy approach (Ex)
Issa et al. (2015)	Identifies and systematizes existing environmental performance measures	Design for X (DfX)/ Guidelines (GL)
Pagotto and Halog (2016)	Evaluates the eco-efficiency performance of different sub-industries in the Australian agri-food systems	DEA Material flow analysis (MFA)
Angelis-Dimakis et al. (2016)	An LCA approach is used for presenting a framework to assess the eco-efficiency of water-use systems.	LCA
Laso et al. (2016)	Proposes the assessment of eco-efficiency for the fish canning industry	LCA, LCC
Ng and Martinez Hernandez (2016)	Energy, environment, and economy (3E) metrics are used to present a process design and decision-making framework for the selection of process design.	MCDM
Motevali Haghighi et al. (2016)	A framework to assess the performance of sustainable supply chains is proposed	BCA, DEA
Franklin-Johnson et al. (2016)	A novel indicator to evaluate the environmental performance connected to CE is presented	Material flow analysis (MFA)/material cost analysis (MCA)/material flow cost analysis (MFCA)
Pan et al. (2016)	EA method is applied to five issues for evaluating recycling and reuse benefits	Emergy approach (Em), Exergy approach (Ex)
Huysman et al. (2017)	CE performance for plastic waste was assessed	LCA Emergy approach (Em), Exergy approach (Ex)
Grimaud et al. (2017)	To ensure economic, environmental, and social efficiency, the paper uses Environmental Technology Verification guidelines to guide designers	LCA Design for X (DfX)/ Guidelines (GL), Material flow analysis (MFA)
Martin et al. (2020)	Assesses the environmental performance of the production of biofuel systems	LCA

(continued)

Table 2 (continued)

Author (Year)	Objectives	Methods
Fregonara et al. (2017)	LCA is used to propose a new methodology to support decisions in design activities in the building industry	LCA
Wibowo and Grandhi (2017)	An MCDM approach is applied to evaluate recoverable end-of-life products' performances	MCDM
Favi et al. (2017)	Design for end-of-life is used to help designers improve EoL performances	Design for X (DfX)/ Guidelines (GL)
Mardani et al. (2017)	Different models of DEA applied for the development of energy efficiency problems are reviewed	DEA
Petit et al. (2018)	Examines existing frameworks and indicators for value chain sustainability by building new sustainable performance metrics	LCA, MCDM
Gbededo et al. (2018)	A systematic literature review has been made for sustainable manufacturing approaches between 2006 and 2015	LCA
Pauliuk (2018)	General system definitions to derive CE indicators are proposed	LCA, material flow analysis (MFA)/material flow cost analysis (MFCA)
Laso et al. (2018)	Combines LCA and LCC methods and proposes the assessment of eco-efficiency for the fish canning industry	LCA, LCC
Biganzoli et al. (2018)	By using LCA, the environmental impacts of intermediate bulk containers are assessed	LCA
Hadzic et al. (2018)	LCA software EASETECH is used for the performance assessment of solid-waste management systems	LCA
Kazancoglu et al. (2018a, b)	Proposes a framework for GSCM performance assessment	MCDM
Oliveira et al. (2018)	23 companies in the wooden furniture industry were examined to assess the CE performance of the companies	Design for X (DfX)/ Guidelines (GL)
Expósito and Velasco (2018)	The DEA method is used to analyze the efficiency of solid-waste management in Spanish regions	DEA

3.3 Performance Assessment in Textile Industry

de Brito et al. (2008) analyzed the impact of sustainability on the fashion retail supply chain organizations' performance and organization itself. They reviewed the main challenges and stakeholders' views by dividing them into two groups, namely, the ones whose concern is economic survival and the others whose endeavor is extensive responsibility and improvement. They reported the view of fashion industry stakeholders according to an exploratory approach and specified the sustainable internal and external organization according to their views. They emphasized the necessity of a deeper examination of the conflict between modern supply chain principles and sustainability. They noticed that higher coordination is necessary for sustainable attempts and can support supply chain optimization. They concluded that a positive connection can be found between sustainability, coordination, and supply chain principles that refer to internal and external integration, and compatibility between them can be provided by a virtual circle initiated by companies. Kim and Ko (2010) proved that social media marketing of luxury brands is effective on the purchase behavior of customers. They proposed a strategy to enhance the performance of the brand by the determination of specific factors. The effects on customer relationships including sincerity and confidence, intention to purchase, and the mutual relationship among them are tested by multiple regression analysis to determine the performance. Turker and Altuntas (2014) focused on conceptually mapping how developing and developed companies in the fast fashion industry. They analyzed the reports of nine companies by content analysis based on five dimensions. The five main concepts provided by Seuring and Müller (2008) are avoiding risks, supplier selection criteria, contact with suppliers, development of suppliers, and supply chain performance. The findings of their study showed that companies prioritize auditing activities and implement additional monitoring measures, such as developing their own codes of conduct. These efforts are aimed at preventing production issues in developing countries. In other words, their study revealed that companies especially focused on integrating suppliers into their system for the purpose of adapting them to their sustainability approach. They proposed the main component of current sustainable supply chain management for risk avoidance.

Joa et al. (2014) proposed Cumulative Water Intensity (RCWI) for corporate water accounting in their study. They inferred that their concept for water performance assessment that considers environmental, economic, and social aspects is an appropriate method. Their study also showed that a company's indirect responsibility for the water usage of the company's suppliers affects its own water consumption performance. They concluded that a company has a significant effect on their purchasing amount as well as choosing suppliers in this regard. Alkaya and Demirer (2014) carried out a study on the reduction of water usage in woven fabric. They investigated the feasibility of different sustainable development measurements and indicated benefits in the economic and environmental manner in a woven fabric in Turkey. As a result of the applications for sustainable production, the total water usage of the company decreased by 40.2%. The company's total energy usage and carbon dioxide (CO_2) emissions were reduced by 17.1% and 13.5%, respectively, according to their study. Furthermore, the total consumption of salt decreased by 46.0%. The payback period for implementing these measures was determined to be approximately one and a half months. These findings suggest that the implementation of the five proposed sustainable production measures based on reuse and renovation could bring significant changes to the Turkish textile industry without requiring substantial technological investments.

Li et al. (2014) studied the effects of environmental and social responsibilities on the sustainability performances of the companies and their collaborators in the fast fashion supply chains. They found out that the core effect and corporation centrality should be enriched with an internal governance perspective, and stakeholders should collaborate to obtain sustainability from the external governance perspective. Shen and Li (2015) analyzed the impacts of reverse supply chains. They studied a supply chain in the fashion industry with two-echelon, one retailer, and one supplier under the return policy. Their interest is which effects undisposed products in an outsourcing textile supply chain have. They conducted a quantitative study by using the company's actual data and debated managerial insights based on the analysis. Pawęta and Mikołajczyk (2016) presented probable solutions to provide higher competitiveness in the Russian textile industry by the growth of innovative performance. Methods that can provide higher competitiveness for the Russian textile industry are changeover to flax and blended fibers rather than imported cotton types of raw materials, using better quality stains, purchasing new equipment to produce low-volume output instead of mass production, creating joint ventures with foreign companies to increase quality and employment. Angelis-Dimakis et al. (2016) examined eco-efficiency evaluation in water use systems in the textile industry. They used some eco-efficiency indicators that had been selected. The aim of their methodology is to simplify the use of modern technologies for minimizing the bad effects on the environment or maximizing economic performance as well as increasing eco-efficiency. Rakib et al. (2017) studied utilizing waste heat in the textile industry and quantified waste-heat utilization's potential for energy and cost saving with case studies. Prominent waste-heat sources were determined in their study. They found the measures feasible in terms of economy with a nominal payback period and practicable for the textile sector with ease. Pinheiro et al. (2019) determined the chances to enhance reverse logistics activities in the textile industry. They constructed a questionnaire based on the literature. They concluded that the readjustment of textile waste as a by-product in a new cycle is necessary in spite of the difficulty for the use of reverse logistics in the textile industry. Ali and Haseeb (2019) investigated effective supply chain activities of textile and apparel companies through radio frequency identification (RFID) and used a survey method for data collection. Ural (2019) studied the performance measurement of a solar air collector by the usage of textile fabric for absorption to provide a decent guide and practical information for the promotion of textile fabric usage in solar applications. Sahinkaya et al. (2019) investigated wastewater reuse in textiles and predicted reverse osmosis performance accurately. They conducted pilot-scale studies. Hayat et al. (2020) analyzed the effect of eco-labels on the economic and environmental performance of textile companies and concluded that eco-labels support sustainable growth in textile industry. Table 3 shows the studies about the performance measurement for textile and apparel industries.

Table 3 Papers about performance measurement in textile/apparel industry

Author (Year)	Objectives	Methods
de Brito et al. (2008)	Analyze the current effect and further impact of sustainability	Questionnaire
Kim and Ko (2010)	Explain how social marketing affects the CRM and purchase behavior of luxury textile brands	Questionnaire
Turker and Altuntas (2014)	Mapping the current condition of SSCM	Content analysis
Joa et al. (2014)	Propose a new method for corporate water accounting and test practical applicability in the cotton textile chain	Regionalized Cumulative Water Intensity (RCWI) Case study
Alkaya and Demirer (2014)	Examine the feasibility of different sustainable production measurements and indicate benefits in the economic and environmental manner in a woven fabric manufacturing plant	Environmental Performance Evaluation (EPE)
Li et al. (2014)	Examine the effects of institutional social responsibilities on the sustainability performances of firms and their collaborators in fast fashion supply chains	Case study
Shen and Li (2015)	Examine how the practice of returning unsold products impacts sustainability in the outsourcing fashion supply chain for retail	Mathematical modeling Numerical study
Pawęta and Mikołajczyk (2016)	Provide probable solutions to improve the innovation performance of the Russian textile industry	–
Angelis-Dimakis et al. (2016)	Present an approach for the eco-efficiency evaluation of water use systems	LCA
Rakib et al. (2017)	Quantify the potential of energy saving and cost reduction for the utilization of waste heat in the textile industry	Case study
Pinheiro et al. (2019)	Determine the chances to enhance reverse logistics activities in the apparel industry	Questionnaire Clustering ANOVA Cronbach's alpha
Ali and Haseeb (2019)	Examine the effective supply chain activities of textile and apparel companies through radio frequency identification (RFID)	Questionnaire
Ural (2019)	Assess performance of a solar air collector by using textile fabric for absorption to provide a guide and useful information for promotion of textile fabrics usage on solar applications	Test
Sahinkaya et al. (2019)	Evaluating wastewater reuse in textile and predict reverse osmosis performance	–
Hayat et al. (2020)	Analyze the eco-labels' effect on environmental and economic performance of textile companies	Regression model

4 Methodology

MCDM methods are highly efficient in resolving complicated decision-making issues in a range of industries, including engineering, logistics, and healthcare. The best selection from a range of possibilities is selected using these strategies based on various criteria or features. Zadeh (1965) developed the fuzzy set theory to lessen subjectivity and vagueness caused by the uncertainty involved in decision-making procedures. Continuous grades exist in fuzzy sets, a kind of object group. l, m, and u are triangular fuzzy numbers that are employed to evaluate choices.

In this chapter, the fuzzy DEMATEL and fuzzy BWM methods were used.

4.1 Fuzzy DEMATEL

Examining and simulating complex interactions between various choice criteria is typically done using the DEMATEL approach. The traditional DEMATEL technique does not account for uncertainties and decision ambiguity, even though they are prevalent in real-world CE situations. In this chapter, fuzzy sets are employed to manage uncertainties and ambiguity in decision-making, and DEMATEL is suggested to model the intricate interactions among choice criteria in CE. The proposed approach involves the following steps (Kazancoglu et al., 2018a, b; Tayaksi et al., 2020):

Step 1: Establish a set of decision criteria for the CE problem.
Step 2: Define the interrelationships among decision criteria using a fuzzy DEMATEL model.
Step 3: Calculate the fuzzy DEMATEL-based influence matrix.
Step 4: Determine the fuzzy DEMATEL-based direct and indirect influence of each decision criterion.
Step 5: Rank the decision criteria based on their fuzzy DEMATEL-based total influence.

4.2 Fuzzy BWM

AHP and the ANP are the two most often used techniques for weighing factors in decision-making. Rezaei (2015) introduced BWM, a more modern strategy. By contrast the most significant criterion with other criteria and the least significant criterion with other criteria, BWM calculates the weights of the various criteria. BWM was selected because it needed fewer comparisons than AHP or ANP did. Due to its fewer comparisons, BWM is a vector-based method that generates solutions more quickly and with less complexity. Furthermore, BWM employs a mathematical model, which makes it more reliable than other approaches. The weightings are determined using the BWM approach in five steps. BWM is additionally more reliable than other methods due to the usage of a mathematical model. The five steps involved in the BWM method for weighting decision criteria are as follows (Rezaei, 2015; Sagnak et al., 2021):

Step 1: Establish a set of criteria, shown as $\{c_1, c_2, \ldots, c_n\}$.
Step 2: Define two sets of criteria, one for the most important criterion and another for the least important criterion.
Step 3: Comparing the criterion that has the most importance rate with each of the remaining criteria.
Step 4: Comparing each criterion with the criterion that has the least importance.
Step 5: Determine the optimal fuzzy weights based on the comparisons made in the previous steps.

5 Proposed Framework

In this section, a framework for CE performance assessment in the textile industry was proposed. The criteria list includes 18 criteria. Table 4 shows the criteria set. The criteria were validated by three academics and two industrial experts.

Three academics are from the industrial engineering, business administration, and textile engineering departments. Two industrial experts are sustainability managers in two textile companies. These experts have experience more than 10 years. The criteria set was examined in detail. After validation, the fuzzy DEMATEL and fuzzy BWM methods were applied.

The proposed framework can be seen in Fig. 1.

6 Case Study, Findings, and Implications

The implementation of the study was conducted in five textile companies located in Izmir, Turkey. Twenty experts including sustainability managers, supply chain managers, and operations managers attended the data collection process.

The data collection process consists of pairwise comparisons. The criteria were compared pairwise for both fuzzy DEMATEL and fuzzy BWM applications. First,

Table 4 Criteria set

Criteria	References
Environmentally friendly transport (C1)	de Brito et al. (2008); Li et al. (2014); Kazancoglu et al. (2018a, b)
Health and Safety (C2)	de Brito et al. (2008); Turker and Altuntas (2014); Eastwood and Haapala (2015); Grimaud et al. (2017); Sagnak et al. (2021)
Social fairness and sustainable human resource management (C3)	de Brito et al. (2008); Turker and Altuntas (2014); Petit et al. (2018); Kazancoglu et al. (2018a, b)
Respect for national laws (C4)	Turker and Altuntas (2014); Wibowo and Grandhi (2017)
Working conditions (C5)	Turker and Altuntas (2014); Grimaud et al. (2017); Kazancoglu et al. (2018a, b)
Supplier commitment (C6)	Olugu and Wong (2012); Li et al. (2014)
Ethics (C7)	Li et al. (2014)
Greenhouse gas emissions (C8)	Li et al. (2014); Issa et al. (2015); Kazancoglu et al. (2018a, b); Sagnak et al. (2021)
Recycling (C9)	Olugu and Wong (2012); Shen et al. (2013); Li et al. (2014); Franklin-Johnson et al. (2016); Meksi and Moussa (2017); Kazancoglu et al. (2018a, b); Pinheiro et al. (2019)
Using natural resources responsibly (C10)	Li et al. (2014)
Creating employment (C11)	Li et al. (2014); Sagnak et al. (2021)
Empowering through education (C12)	Li et al. (2014); Sagnak et al. (2021)
Community engagement (C13)	Li et al. (2014); Grimaud et al. (2017); Kazancoglu et al. (2018a, b); Sagnak et al. (2021)
Cost (C14)	Olugu and Wong (2012); Grimaud et al. (2017); Meksi and Moussa (2017); Wibowo and Grandhi (2017); Kazancoglu et al. (2018a, b); Pinheiro et al. (2019); Hayat et al. (2020); Sagnak et al. (2021)
Performance of reverse logistics (C15)	Pinheiro et al. (2019); Sagnak et al. (2021)
Pollution prevention and control (C16)	Shen et al. (2013); Angelis-Dimakis et al. (2016); Sagnak et al. (2021)
Energy usage (C17)	Eastwood and Haapala (2015); Issa et al. (2015); Laso et al. (2016); Petit et al. (2018)
Waste generation (C18)	Issa et al. (2015); Petit et al. (2018); Kazancoglu et al. (2018a, b)

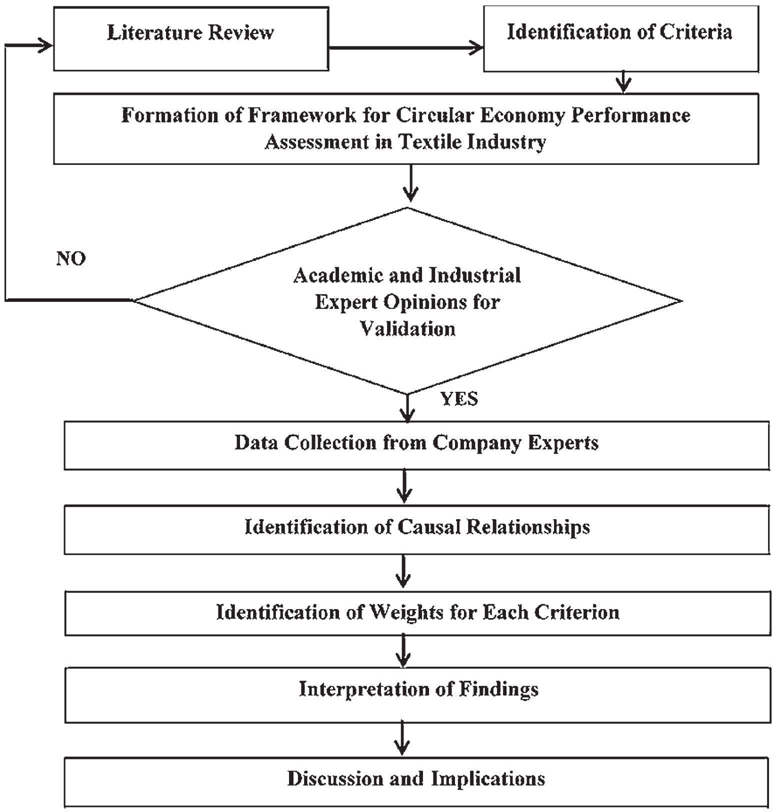

Fig. 1 The proposed framework

the causal relationships between the criteria were found. Table 5 shows the total relations matrix, T.

Accordingly, the cause-effect diagram was drawn to determine the cause group criteria, and the effect group criteria, respectively. Figure 2 shows the cause-effect diagram.

According to the cause-effect diagram, the cause group includes social fairness and sustainable human resource management (C3), respect for national laws (C4), working conditions (C5), supplier commitment (C6), cost (C14), and pollution prevention and control (C16). The effect group includes environmentally friendly transport (C1), health and safety (C2), greenhouse gas emissions (C8), recycling (C9), using natural resources responsibly (C10), creating employment (C11), performance of reverse logistics (C15), energy usage (C17), and waste generation (C18). Ethics (C7), empowering through education (C12), and community engagement (C13) are neither cause nor effect group criteria.

Table 5 Total relation matrix, T

T	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18
C1	0.126	0.164	0.088	0.105	0.097	0.086	0.122	0.177	0.122	0.183	0.071	0.071	0.068	0.170	0.176	0.178	0.181	0.182
C2	0.127	0.084	0.092	0.132	0.101	0.085	0.147	0.119	0.113	0.120	0.064	0.064	0.060	0.147	0.115	0.116	0.118	0.119
C3	0.129	0.114	0.075	0.099	0.147	0.128	0.153	0.120	0.114	0.121	0.120	0.120	0.076	0.112	0.117	0.118	0.120	0.121
C4	0.223	0.195	0.163	0.104	0.173	0.116	0.190	0.207	0.198	0.213	0.103	0.103	0.096	0.159	0.205	0.206	0.210	0.211
C5	0.136	0.158	0.106	0.142	0.085	0.092	0.158	0.126	0.120	0.127	0.121	0.121	0.117	0.118	0.123	0.124	0.126	0.127
C6	0.125	0.110	0.131	0.094	0.139	0.060	0.138	0.116	0.111	0.118	0.068	0.068	0.062	0.115	0.120	0.121	0.123	0.124
C7	0.176	0.159	0.138	0.141	0.146	0.092	0.093	0.167	0.159	0.121	0.073	0.073	0.068	0.111	0.116	0.117	0.119	0.120
C8	0.178	0.104	0.079	0.083	0.087	0.078	0.099	0.102	0.158	0.173	0.066	0.066	0.062	0.146	0.160	0.161	0.157	0.158
C9	0.181	0.117	0.081	0.086	0.090	0.079	0.102	0.162	0.097	0.168	0.067	0.067	0.064	0.156	0.162	0.163	0.166	0.167
C10	0.167	0.110	0.087	0.090	0.084	0.074	0.096	0.110	0.102	0.099	0.063	0.063	0.059	0.137	0.150	0.151	0.154	0.156
C11	0.072	0.064	0.065	0.055	0.077	0.061	0.074	0.067	0.064	0.068	0.031	0.046	0.043	0.063	0.066	0.066	0.068	0.068
C12	0.079	0.070	0.103	0.061	0.108	0.056	0.082	0.073	0.070	0.074	0.052	0.037	0.048	0.069	0.072	0.072	0.074	0.074
C13	0.084	0.078	0.108	0.068	0.063	0.055	0.069	0.072	0.068	0.073	0.049	0.049	0.030	0.068	0.071	0.071	0.073	0.073
C14	0.215	0.148	0.108	0.122	0.166	0.148	0.180	0.200	0.191	0.206	0.093	0.093	0.088	0.126	0.198	0.199	0.203	0.205
C15	0.184	0.111	0.086	0.089	0.094	0.116	0.123	0.158	0.150	0.177	0.069	0.069	0.065	0.151	0.107	0.166	0.169	0.170
C16	0.200	0.172	0.095	0.112	0.115	0.090	0.167	0.186	0.177	0.191	0.076	0.076	0.072	0.171	0.177	0.121	0.175	0.176
C17	0.105	0.090	0.063	0.076	0.068	0.060	0.076	0.097	0.093	0.108	0.052	0.052	0.050	0.092	0.097	0.098	0.074	0.138
C18	0.185	0.160	0.085	0.101	0.092	0.081	0.106	0.172	0.164	0.179	0.069	0.069	0.066	0.137	0.159	0.167	0.170	0.114

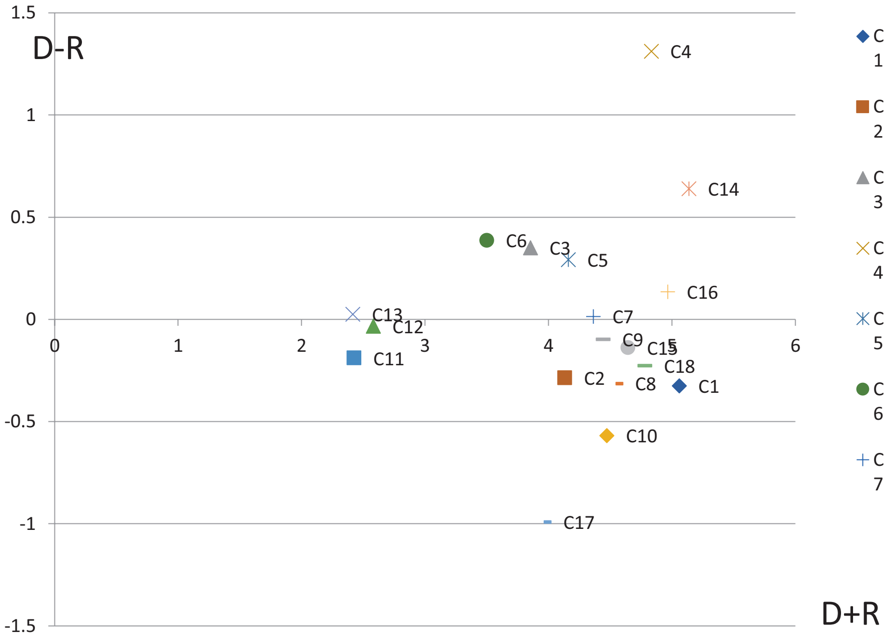

Fig. 2 Cause-effect diagram

The outcomes of the fuzzy DEMATEL analysis were used as the foundation for the causal group. Within this context, respect for national laws (C4) was found to be the most influencing factor, followed by cost (C14) and supplier commitment (C6), respectively.

The outcomes of the fuzzy DEMATEL analysis were used as the foundation for the effect group. Within this context, energy usage (C17) was found to be the most influenced factor, followed by using natural resources responsibly (C10) and environmentally friendly transport (C1), respectively.

The results of the fuzzy BWM results show us the importance level of the criteria and, therefore, help decision-makers and policymakers determine the roadmap for CE performance assessment of the textile company. Table 6 shows the fuzzy weights of relevant criteria.

Table 7 shows the defuzzified criteria weights.

Accordingly, cost (C14) is the most important criterion for CE performance assessment in the textile industry. Greenhouse gas emissions (C8), pollution prevention and control (C16), and health and safety (C2) are other important criteria. This means that, to have better CE performance, the textile companies should first emphasize these criteria.

Table 6 Fuzzy weights of criteria

Weights	L	M	U
C1	0.04045	0.062514	0.091687
C2	0.042978	0.068765	0.091687
C3	0.032745	0.042978	0.045844
C4	0.029898	0.038203	0.038203
C5	0.036192	0.052896	0.065491
C6	0.029898	0.04045	0.041676
C7	0.028652	0.038203	0.038203
C8	0.045844	0.076406	0.114609
C9	0.036192	0.052896	0.065491
C10	0.034383	0.049118	0.057304
C11	0.029898	0.04045	0.041676
C12	0.032745	0.045844	0.050937
C13	0.01744	0.018944	0.021911
C14	0.076406	0.152812	0.152812
C15	0.034383	0.049118	0.057304
C16	0.042978	0.068765	0.114609
C17	0.038203	0.057304	0.076406
C18	0.04045	0.062514	0.091687

Table 7 Final criteria weights

C1	0.064264
C2	0.068245
C3	0.041619
C4	0.036852
C5	0.052218
C6	0.038899
C7	0.03671
C8	0.077706
C9	0.052218
C10	0.047924
C11	0.038899
C12	0.04439
C13	0.018848
C14	0.138609
C15	0.047924
C16	0.072872
C17	0.057541
C18	0.064264

7 Conclusion

The main purpose of this study is to reveal the relevant literature about CE in terms of performance measurement in the textile and apparel industry. As a result of the research, no study integrating those three subjects was found; therefore, the contribution of this study is to highlight the gaps related to performance assessment in the textile industry within a circular environment and propose a framework to determine a roadmap.

In Sect. 2, CE, textile industry, and performance assessment subjects are summarized. Then, previous studies were investigated to determine the gap and identify the criteria set. The fuzzy DEMATEL technique was chosen to identify the cause-and-effect connections among the criteria. Finally, the weightings of the criteria were found using the fuzzy Best-Worst method (BWM) to indicate the roadmap for performance assessment.

Cost is found as the most important criterion, followed by greenhouse gas emissions, pollution prevention and control, and health and safety criteria. To improve the CE performance of textile companies, the managers and policymakers should first emphasize these criteria.

The methodological section includes data gathered through pairwise comparisons; therefore, it includes subjective opinions. The findings cannot be generalized. This is the main limitation of this study. Also, the implementation is applied in Turkey, which is an emerging country, which can be determined as another limitation of this study.

Potential future research could concentrate on the utilization of the suggested framework in various countries. Another future research may deal with the application in different industries. Also, the interpretive structural modeling method for causal relationships and the AHP or ANP method for weighting mechanism can be used to check whether the finding of this study is consistent.

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Man-Made Bio-based and Biodegradable Fibers for Textile Applications

Cansu Var and Sema Palamutcu

1 World Textile Fiber Market and Environmental Issues

Because of the prominent benefits of resilience, strength, durability, lightweight, chemical resistance, and low cost, synthetic fibers are those that the textile and clothing industry heavily relies upon. From 1975 to 2021, the production of textile fibers was proclaimed as raised from 24 million metric tons to 113 million metric tons, 25.4 million metric tons of which were natural fibers such as cotton or wool, where 88.2 million metric tons of which were chemical fibers including polyester, polyamide, and man-made cellulosic fibers (Statista, 2023c). In the frame of global chemical fiber production, 80.9 million metric tons of 113 million metric tons amounted to synthetic fibers, whereas 7.3 million metric tons of which were recorded for man-made cellulosic fibers like viscose in 2021 (Statista, 2023a). Also, fiber production was forecasted to ascend to 156 million metric tons by 2030 (Statista, 2023c). As can be seen in Fig. 1, among the synthetic fibers, the volume of polyester fiber production has the lion's share exceeding total natural fiber production and man-made cellulosic fiber production in 2021 (Statista, 2023b). Figure 1 also exhibits share of other commonly consumed textile fibers with the exception of polyester.

Today, synthetic polymers commonly used as raw materials in textile applications are derived from nonrenewable resources like petroleum oil. Derivation from nonrenewable resources brings about environmental incompatibility and nonbiodegradability as well (Rendón-Villalobos et al., 2016). In addition to this, characteristics of synthetic polymers, such as hydrophobicity, high crystallinity, surface topography, and molecular size are the important factors confining the

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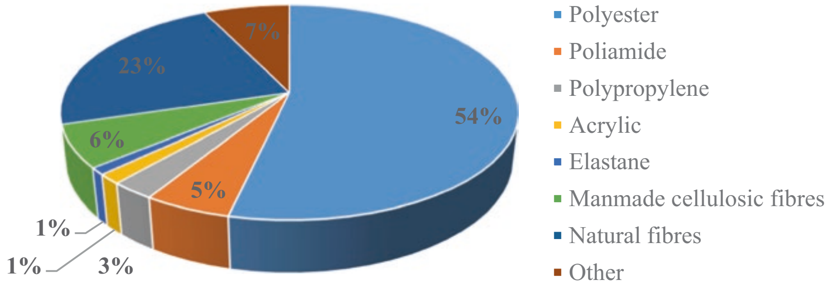

Fig. 1 Global textile fiber production rates. (Derived from Statista (2023b, c, d, e, f, g, h))

biodegradability of these fibers. The durability of these polymers, which makes them usable in a wide area, also makes these polymers difficult to degrade by ensuring their persistence in the environment. Synthetic fibers pose versatile environmental concerns including accumulation in landfills, the release of microplastics, pollution of water bodies, contribution to greenhouse gas emissions, chemical pollution, and habitat destruction. According to a global analysis of waste management of plastics, it was estimated that, from 1950 to 2015, 79% of the cumulatively generated waste was accumulated in landfills or the rest of the environment, where 12% of which was incinerated and 9% of which was recycled (Geyer et al., 2017). Nonetheless, recycling is one of the effective ways to decrease environmental impacts regarding the disposal of synthetics, and there exist some challenges concerning the following issues: sorting unsuitable products for recycling, requiring extensive cost, and generating mechanically weak products (Chidambarampadmavathy et al., 2017). Incineration, a management approach for waste, has the release risk of toxic chemical compounds such as dioxins, polychlorinated biphenyls, and furans. In addition to this, the generation of greenhouse gases such as carbon dioxide, methane, and nitrous oxide is considered a contributor to climate change (Chidambarampadmavathy et al., 2017; Hwang et al., 2017). Even though landfilling is accepted as the most convenient method to manage waste, the method for synthetics carries handicaps such as toxicity for soil microorganisms, inducing soil infertility, groundwater contamination, and releasing microplastics (Chen et al., 2020; Chidambarampadmavathy et al., 2017; Hwang et al., 2017). Also, chemicals used for synthetic fiber coloration may display carcinogenic and ecotoxic characteristics during landfill and incineration because zinc, copper, nickel, and mercury are released from the pigment waste (Yacout & Hassouna, 2016). In the frame of microplastics, exposure of the synthetic waste to several conditions such as leachate pH (in the range of 4.5–9), physical abrasion, fluctuating temperature, UV irradiation, high salinity, microbial degradation, and even incomplete incineration leads to convert plastics to microplastics. Landfills are believed a source of microplastic release by landfill leachate due to the abovementioned factors (Chen et al., 2020; He et al., 2019).

Another route of microplastic is the laundry of synthetic textiles. It was estimated that 16–35% of total microplastic released to oceans originated from the wash-water of synthetic textiles (European Environment Agency, 2023). It is noted that microplastic was predominantly constituted by the following fibers: polyester (56%) and acrylic (23%) (Bergmann et al., 2015). Ingestion of microplastic released from domestic laundry to marine water media by aquatic animals such as deposit and suspension feeders, crustaceans, marine mammals, and seabirds poses a risk to marine ecosystems (Bakir et al., 2016; Stone et al., 2020). In addition, microplastic ingested by aquatic animals has the potential of contaminating the human food chain with risks to human health.

On the other hand, the synthesis of some polymeric materials requires the utilization of toxic compounds or produces toxic by-products, which bring about both environmental and health concerns. Polyethylene terephthalate (PET), having a dominating position among polyester fibers in the textile industry, is produced by condensation polymerization of two monomers: terephthalic acid and ethylene glycol (Grishanov, 2011). Para-xylene, a component needed for developing terephthalic acid, is considered toxic. It is reported that exposure to high vapor concentrations of xylenes raises some side effects such as hear loss and transient liver or kidney toxicity (Mirkin, 2007; Pouyatos et al., 2011). In another case, manufacturing elastane fibers relies on solvents such as dimethyl formamide (DMF), dimethyl sulfoxide (DMSO), or dimethylacetamide (DMAC) (Singh & Bhalla, 2017). DMF is considered to have impacts on human health concerning the liver, kidneys, and reproductive system, where DMAC is reported to have moderate acute toxicity (Hu et al., 2020; OECD SIDS, 2001).

It is possible to cope with all drawbacks of synthetic fibers by the way of sustainable approaches, for example, it is possible to reduce greenhouse gases by reusing heat generated because of incineration of synthetic fibers (Hwang et al., 2017). On the other hand, in the case of gasification, pyrolysis, and mechanical/biological methods utilization for disposal, dioxins are not allowed to be released contrary to the incineration process (Chidambarampadmavathy et al., 2017). Another approach is achieving biodegradation mechanisms utilizing enzymes and/or microorganisms (Egan & Salmon, 2022; Lens-Pechakova, 2021). Another eco-friendly approach is the generation of sustainable polymers, such as bio-based polymers, biodegradable polymers, and bio-based biodegradable polymers. Among these polymers, bio-based biodegradable polymers manufactured from renewable resources have the potential to remove the hazards occurring during production as well as the waste management process. They have also the potential to reduce CO_2 emissions and the size of carbon footprint (Imre & Pukánszky, 2013; Palamutcu, 2017). However, it is highlighted the fact that these properties highly depend on chemical structure and the manufacturing process (Rosenboom et al., 2022). In this chapter, the world fiber market analysis is carried out, and the negative effects of the production and use of synthetic fibers on the environment are remarked. Then, market data, usage areas, and categorization of bio-based biodegradable polymers are shared. Also, the types and resources of synthetic bio-based biodegradable polymers are discussed in detail. In addition, a detailed review was made about the isolation and extraction of the polymers. In the follow-up, chemical resistance, thermal, and mechanical properties of bio-based biodegradable polymers are generally mentioned. Filament production methods including melt spinning, wet spinning, and electrospinning are analyzed in detail for each polymer. Finally, potential textile applications of the polymers are referred and outlook and trend analysis is made.

2 Bio-based Biodegradable Polymers

According to market forecast reports, global biopolymer manufacturing capacity is reported to increase from 2.2 to 6.3 million tons from 2022 to 2027. Biodegradable polymers, including polylactic acid (PLA), polyhydroxyalkanoates (PHA), starch blends, and others, correspond to more than 51% (over 1.1 million tons) of the global biopolymer manufacturing capacities. The manufacturing of biodegradable plastics is anticipated to increase by over 3.5 million tons in 2027 due to several factors contributing to the growth of the market. Bio-based nonbiodegradable polymers including bio-based PE (polyethylene), bio-based PET, and bio-based PA (polyamides) amount to more than 48% (almost 1.1 million tons) of the global biopolymers manufacturing capacities. Graphically redesigned data about the manufacturing capacities of biopolymers are shown in Fig. 2. Biopolymers are utilized in a wide variety of industries including packaging, building/construction, automotive, agriculture/horticulture, electrics/electronics, coatings/adhesives, toys, and textiles. Among them, the packaging industry has the largest market segment with 47% of the total biopolymer market in 2022. Highlight the fact that, the packaging industry is followed by the fiber (incl. woven and nonwoven) industry, namely, the textile construction industry (european-bioplastic, 2022). This remarkable share of the textile industry could be attributed to several factors that contribute to the growth of the bio-based biodegradable textile fibers market, including environmental concerns, consumer demand owing to the awareness of the environmental damage of their purchasing trends, government policies, and regulations on promoting the adoption

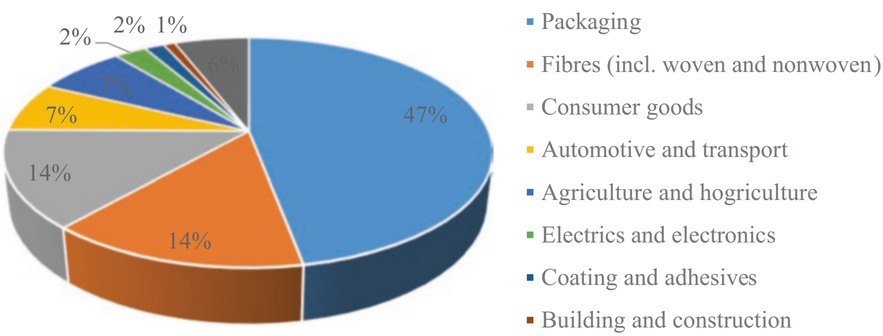

Fig. 2 Global manufacturing capacities of biopolymers 2022 by market segment. (Derived from european-bioplastic (2022))

of sustainable approaches in the textile industry. Also, research and development activities in the field of bio-based biodegradable fibers with improved properties will lead to growth in the market.

The terms "biopolymers," "bio-based," and "biodegradable" are widely utilized unclearly and are not strictly differentiated yet. Highlight the fact that "bio-based" and "biodegradable" polymers do not have conceptually the same meaning. "Bio-based polymers" are derived from renewable resources, whereas "biodegradable polymers" are those that have the ability to degrade biologically by the activity of microorganisms, which results in the lowering of the molar masses of macromolecules. Rather than the carbon resource of the polymer, the biodegradability of polymers depends on the degree of crosslinking, chemical structure, glass transition temperature, inherent characteristics such as molecular weight and crystallinity, and even incorporated additives such as plasticizers, metallic initiators, and catalysts. In other words, a bio-based polymer does not meet the necessity of biodegradability. From another perspective, a biodegradable polymer is not necessarily derived from a renewable source. For instance, while some bio-based polymers such as polypropylene carbonate (PPC), bio polyethylene terephthalate (Bio-PET), and bio polyethylene (Bio-PE), are not biodegradable, some other fossil-based polymers, such as polycaprolactone (PCL) and polybutylene adipate terephthalate (PBAT), are biodegradable (Huang, 1989; Lambert & Wagner, 2017; Parthasarathy & John, 2023; Ray & Banerjee, 2022). To make the "biodegradation" process clear, conversion to small fragments of polymers because of reduced molecular mass occurs either through oxidation or hydrolyze. After that, these fragments are exposed to degradation by microbial activities.

3 Types and Resources of Synthetic Bio-based Biodegradable Polymers

There exist several types of synthetic bio-based biodegradable polymers that can have the potential use for textile fiber manufacturing. Whereas it is possible to broadly categorize these polymers into three groups based on their origin: polysaccharides, proteins, and polyesters, graphical arrangements data about categorization of bio-based biodegradable polymers are shown in Fig. 3. Cellulose, chitin, and starch are the typical members of polysaccharides, whereas collagen, keratin, soy protein, and casein are the typical members of proteins. Bacterial polymers that comprise PLA and PHA polymers are another group of bio-based biodegradable polymers (Vroman & Tighzert, 2009).

Bio-based polymer feedstocks can be classified as "first-generation," "second-generation," and "third-generation" feedstocks. First-generation feedstocks are usually attained from carbohydrate-rich feedstocks such as corn, sugar beet, or plants. In other words, first-generation feedstocks are based on edible resources. Second-generation feedstocks are based on nonedible resources or obtained from

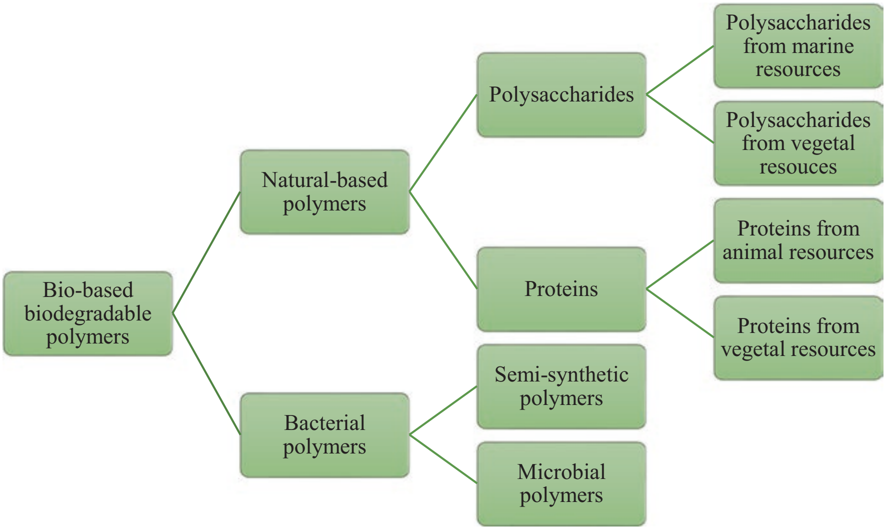

Fig. 3 Categorization of bio-based biodegradable polymers. (Derived from Vroman and Tighzert (2009))

agricultural by-products, whereas third-generation feedstocks comprise algae, municipal, and industrial waste (Wellenreuther & Wolf, 2020). On the other hand, source selection depends on several factors such as the availability of feedstock and agricultural factors regarding climate and soil, agricultural yield, feedstock efficiency, and chemical composition (Bolaji et al., 2021; Jamshidian et al., 2010; Lim et al., 2008; Lovett et al., 2022; Rajeshkumar et al., 2021; Wellenreuther & Wolf, 2020).

3.1 Natural-Based Polymers

3.1.1 Polysaccharides

Polysaccharides are long-chain carbohydrates composed of monosaccharide units. Cellulose, starch, alginate, and chitin are the most studied polysaccharides in the literature. Cellulose can be processed into various forms, like cellulose acetate, which is used for textile fiber production. Chitin can be processed into chitosan which is a more soluble and processable derivative of chitin and has potential applications in the textile industry. Starch can be chemically or enzymatically modified to generate various derivatives that are suitable for different textile applications with tailored properties.

3.1.1.1 Polysaccharides from Vegetal Resources

Cellulose

Cellulose is the most prevalent organic polymer on Earth, constituting the main structural component of plant cell walls. It is a linear and crystalline polymer composed of glucose units connected by β (1 → 4) glycosidic bonds. Notwithstanding cellulose can be derived from various plant resources including cotton, flax, hemp, wood, and agricultural residues such as wheat straw and corn stover, wood is a primary resource of cellulose, especially to produce dissolving pulp for textile applications. Also, softwood species such as pine, spruce, and fir are particularly rich in cellulose, which can be extracted through pulping processes. In addition to this, agricultural residues such as wheat straw, corn stover, and rice husk are abundant and low-cost resources of cellulose. Owing to its infusibility and insolubility, cellulose should be converted to be suitable to process (Vroman & Tighzert, 2009). Because the length of wood pulp fibers is too short to utilize in textiles, they must be processed via a regenerating technology. In this direction, viscose rayon, lyocell rayon, and cellulose acetate are the major raw materials of man-made regenerated textile fibers having biodegradable characteristics (Felgueiras et al., 2021).

Starch

Starch is an abundant plant-derived polysaccharide that serves as the main energy storage component in plants. It is a mixture of two components, amylose and amylopectin, both of which are glucose polymers. Starch can be chemically or enzymatically modified to produce various derivatives with tailored properties. Starch is obtained from variable plants including cereal grains (e.g., corn, sorghum, wheat, and rice), roots and tubers (e.g., tapioca, potatoes, yam, and cassava), and legumes (e.g., peas and beans). The major resources of starch are corn, potato, rice, cassava, wheat, sorghum, and yams (Temesgen et al., 2021).

Alginate

Alginate is derived from brown seaweed (*Phaeophyceae*). It is a polysaccharide composed of two different monomeric units, β-D-mannuronic acid (M) and α-L-guluronic acid (G). These monomers are linked together by 1,4-glycosidic bonds. The arrangement of M and G monomers in the alginate chain can vary and may be found in sequential blocks, such as MM, GG, or alternating MG blocks (Yang et al., 2011). The distribution and sequence of these blocks play an important role in determining the physical characteristics of alginate, such as its solubility, gel-forming ability, and viscosity. Brown seaweed is abundant in marine environments. Several species of brown seaweed are used as resources for alginate production (Zhu & Yin, 2015). These brown seaweed species are harvested from natural marine habitats or cultivated in seaweed farms. The alginate content in the seaweed can vary depending on some factors like species, age, and environmental factors. After harvesting, the seaweed is washed, dried, and processed to extract the alginate, which can then be used for various applications including the production of textile fibers, pharmaceuticals, and biomedical applications. It is reported that commercial alginates are completely attained from brown seaweed including *Laminaria*, *Sargassum*, *Macrocystis*, *Ascophyllum*, *Lessonia*, *Ecklonia*, and *Alaria* (Yarkent et al., 2022).

3.1.1.2 Polysaccharides from Marine Resources

Chitin and Chitosan

Chitin, the second most abundant polysaccharide after cellulose, is a linear and semi-crystalline polymer composed of *N*-acetylglucosamine units linked by β (1 → 4) glycosidic bonds (Yadav et al., 2019). There exists a wide variety of chitin resources including exoskeletons of the crustaceans (e.g., shrimps, crayfish, lobster, and barnacles), mollusks (e.g., cuttlefish, octopus, snails, clams, oysters, and squids), algae (e.g., brown algae, green algae, and diatoms), insects (e.g., beetles, housefly, ants, spiders, silkworms, cockroaches, scorpions, and brachiopods), and cell wall of fungi (*Basidiomycetes*, *Ascomycetes*, and *Phycomycetes*, for instance, *Penicillium notatum*, *Aspergillus niger*, *Trichoderma reesi*, and *Mucor rouxii* cell walls). Crustaceans, a major by-product of the food industry, are dominantly utilized in industrial applications. Chitin can be processed into chitosan which is a more soluble and processable derivative. Chitosan, which consists of *N*-acetyl glucosamine and glucosamine, is generated from the deacetylation of chitin (Pellis et al., 2022; Yadav et al., 2019). The transformation of chitin to chitosan improves utilization in food, textile, medical, cosmetic, and agriculture industries (Yadav et al., 2019).

3.1.2 Proteins

Protein-based bio-based biodegradable polymers are generated from both animal and plant resources. These polymers consist of amino acid monomers linked by peptide bonds. Silk, wool, soy protein, zein, collagen, and wheat gluten are examples of protein-based bio-based biodegradable polymers having the potential of utilization in the textile industry. In addition to this, recombinant protein fibers generated from genetically modified organisms such as plants, bacteria, and yeast would have the potential in the textile industry.

3.1.2.1 Proteins from Vegetal Resources

Soy protein, zein, and wheat gluten are the most studied protein-based polymers from vegetal resources (Reddy & Yang, 2007; Vroman & Tighzert, 2009).

Soy Protein

Soy protein, derived from soybean, includes four main components of 2, 7, 11, and 15S globulins. The globulins of 7S and 11S represent 60% of the storage protein in soybeans (Visakh, 2017).

Zein

Zein, a prolamin protein, is derived mainly from corn (Saha et al., 2020). The chemical structure of zein includes a high proportion of hydrophobic amino acids such as glutamine and proline (Kariduraganavar et al., 2019).

Wheat Gluten

Wheat gluten, which is isolated from wheat, is a combination of two main proteins, namely, gliadin, which is soluble in aqueous alcohol, and glutenin, which is insoluble in aqueous alcohol. The mixture of gliadin and glutenin gains viscoelastic properties to wheat gluten (Lacroix & Vu, 2014).

3.1.2.2 Proteins from Animal Resources

Collagen, keratin, casein, and silk fibroin are the most studied protein-based polymers from animal resources. In addition, studies about some specially engineered polymers such as recombinant spider silk and bioengineered silk proteins using genetic engineering methods are ongoing.

Collagen

Collagen, the most abundant protein in animals, is a fibrous protein. The chemical structure of collagen is constructed from polypeptide chains having the repeating sequence of $(Gly\text{-}X\text{-}Y)_n$, in which X and Y are often proline and hydroxyproline. This exclusive sequence enables collagen to form a unique secondary structure called the collagen helix. By the way that three polypeptide chains are intertwined, a triple helix structure, which is known as a collagen molecule, is formed. Stacked collagen molecules create collagen fibrils. In collagen fibrils, adjacent collagen molecules are linked by covalent crosslinks, which make them resilient and mechanically resistant (Jafari et al., 2020; Khan & Khan, 2013; Walimbe & Panitch, 2020). Sternal cartilage from chickens, quails, ducks, turkeys, and geese; cartilage from bovine and porcine; skin from equines, sheep, frogs, fish, and bovines; tendon from rat tail and equine; bones and tendon from buffalos, porcine, bovine, and rabbits; and egg-shell membrane are the group of collagen resources that are mostly used (Avila Rodríguez et al., 2018; Hassabo et al., 2022). In addition to this, collagen could be generated in insect cell cultures, mammalian cells, and plant cell cultures by recombinant DNA technology (Avila Rodríguez et al., 2018).

Keratin

The composition of keratin, which is a cysteine-abundant fibrous protein, includes a polypeptide chain composed of various amino acids. α-Keratins and β-keratins are the two main categories of keratin proteins. α-Keratins predominantly occur in mammals, including humans form the fundamental structural component of hair, nails, and epidermis, whereas β-keratins are found in reptiles, birds, and amphibians and compose the components such as bird feathers, reptile scales, and turtle shells (Feroz et al., 2020).

Casein

Casein is extracted from mammalian milk. Casein protein accounts for 80% of the total bovine milk proteins (Nagarajan et al., 2019). Also, it is found in by-products generated from the dairy sector (Bonnaillie et al., 2014).

Silk Fibroin

Generated by silkworms, silk possesses a core−sheath structure composed of a sericin sheath and two fibroin cores. Silk fibroin is composed of amino acids of alanine, glycine, serine, and tyrosine. These amino acids facilitate the construction of the structures of antiparallel β-sheet microcrystallite (Ng et al., 2019).

3.2 Bacterial Polymers

Semi-synthetic polymers, a group of bacterial polymers, are developed through the polymerization of monomers generated via the fermentation mechanism. Microbial polymers, another group of these polymers, are derived from a range of microorganisms exposed to different environmental and nutrient conditions.

3.2.1 Semi-synthetic Polymers

PLA (Polylactic Acid)

PLA is constructed from 2-hydroxy propionic acid molecules, which are known as lactic acid (LA) (Castro-Aguirre et al., 2016). Whereas PLA polymers are derived from variable carbohydrate resources such as sugar cane, corn, wheat, sugar beet, rice, cassava, and sweet potato, industrial production of PLA overwhelmingly relies on corn and sugarcane resources. In fact, source selection depends on several factors such as the availability of feedstock and agricultural factors regarding climate and soil, agricultural yield, feedstock efficiency, and chemical composition (Bolaji et al., 2021; Jamshidian et al., 2010; Lim et al., 2008; Lovett et al., 2022; Rajeshkumar et al., 2021; Wellenreuther & Wolf, 2020). Currently, corn and sugarcane are the most used resources. However, a wide variety of studies on alternative resources have been carried out. Using second- or third-generation feedstocks brings about to be relaxed some concerns about food prices, land use, waste management, and feedstock consumption (Jamshidian et al., 2010; Wellenreuther & Wolf, 2020). Various alternative resources can be stated as dairy whey, extraction of curcuminoid, orange peel waste, coffee pulp, sugar beet pulp, seaweed *Ulva* spp., brown algae, lignocellulose/hemicellulose hydrolysates, corn stover, cottonseed hulls, beet molasses, sweet sorghum, wheat bran, rye flour, sugarcane press mud, cassava, cellulose, barley starch, carrot processing waste, corn fiber hydrolysates, potato starch, kitchen wastes, fish meal wastes, and wastewater generated by processing of potatoes (Jamshidian et al., 2010; RameshKumar et al., 2020; Wellenreuther & Wolf, 2020).

3.2.2 Microbial Polymers

PHAs (Polyhydroxyalkanoates)

PHAs are intracellular microbial polyesters derived by many species of microorganisms under the conditions of excessive carbon and limited nutrients such as nitrogen, phosphorous, sulfur, and magnesium (De Paula-Elias et al., 2021; Gutschmann et al., 2022; Tan et al., 2014). PHAs are stored as inclusions in the cytoplasm of microorganisms and their function is to provide carbon and energy reserve (Gomes et al., 2008). In other words, PHAs assist microorganisms in their survival under stress conditions (Sehgal & Gupta, 2020). The carbon resources are reported as saccharides (e.g., lactose, fructose, maltose, and arabinose), n-alcohols (e.g., methanol, ethanol, and glycerol), n-alkanes (e.g., hexane and octane), n-alkanoic acids (e.g., acetic acid, propionic acid, butyric acids, valeric acid, and oleic acid), and gases (e.g., carbon dioxide and methane). PHA monomers could be categorized based on the count of carbon atoms as "short-chain length PHA (scl-PHA)," "medium-chain length PHA (mcl-PHA)," and "long-chain length PHA (lcl-PHA)." Scl-PHA consists of monomers having five or fewer carbon atoms, such as 3-hydroxybutyrate and 3-hydroxyvalerate. Mcl-PHA is made up of monomers having 6–14 carbon atoms, like 3-hydroxyhexanoate, 3-octanoate, and 3-hydroxydecanoate. Lcl-PHA, the least studied ones, consists of monomers having over fourteen carbon atoms (Kunasundari & Sudesh, 2011). PHAs can be produced by using over 100 monomers based on P3HB, P4HB, PHB, and PHV (Greene, 2019). However, the most commercialized types are P(3HB), P(3HB-co-3HV), P(3HB-co-4HB), P(3HB-co-3HHx), and P(4HB) (Koller & Mukherjee, 2022).

Azohydromonas, *Burkholderia*, *Cupriavidus, Cupriavidus necator, Methylobacterium extorquens, Paracoccus denitrificans, and* Pseudomonads including *Pseudomonas putida mt-2, Pseudomonas marginalis, Pseudomonas mendocina, P. putida GPo1, Pseudomonas oleovorans, P. putida F1, Pseudomonas aeruginosa, P. putida GO16, P. putida GO19, Pseudomonas frederiksbergensis GO23, P. putida CA-3,* and extremophile bacteria including *Halomonas boliviensis* and *Thermus thermophilus HB8* are the Gram-negative bacteria that produce PHA. However, the main issue with Gram-negative bacteria is the availability of lipopolysaccharide (LPS) endotoxins in their outer membrane component. During extraction, lipopolysaccharide endotoxins have the possibility of being simultaneously purified with pristine PHA polymer. LPS endotoxin has the potential to display inflammatory characteristics, which may restrict to use of PHA polymer in biomedical applications. On the other hand, it is reported that Gram-positive bacteria are absent of LPS, which may enable them to be a suitable resource for PHA in biomedical applications. However, some Gram-positive bacteria are considered to exhibit immunogenic characteristics owing to the generation of lipidated macroamphiphiles including lipoglycans and lipoteichoic acids (LTA). *Bacillus*, *Caryophanon*, *Clostridium*, *Micrococcus*, *Microcystis*, *Nocardia*, *Staphylococcus*, and *Streptomyces* are the Gram-positive bacteria producing PHA.

Additionally, PHA is also produced by archaea. Most known types are haloarchaeal species including *Haloferax*, *Haloarcula*, *Halalkalicoccus*, *Halobiforma*, *Halococcus*, *Halopiger*, *Halorhabdus*, *Halostagnicola*, *Halorubrum*, *Haloterrigena*, *Natrinema*, *Natronobacterium*, *Natronorubrum*, and *Natronomonas* (Tan et al., 2014).

4 Isolation and Extraction of Polymers

4.1 Cellulose

Extraction of cellulose from plant resources comprises a series of steps including pretreatment, pulping, purification, dissolution, and regeneration. Through the pretreatment process, noncellulosic components, such as pectin, lignin, and hemicellulose, are removed. Mechanical pulping, chemical pulping, and enzymatic treatments are the most common pretreatment techniques. Mechanical pulping relies on grinding the cellulose source, whereas chemical pulping utilizes chemicals such as sodium hydroxide or sulfites. Enzymatic treatments utilize enzymes, such as cellulases and xylanases. The cellulose pulp is then purified by washing and screening in order to eliminate residual impurities. After purification, cellulose is processed into several raw materials for textile forms including cellulose acetate, and regenerated cellulosic fibers (e.g., rayon, lyocell, modal, and cupro). To obtain cellulose acetate, cellulose is acetylated with acetic anhydride. On the other hand, the manufacturing of regenerated cellulosic fibers relies on dissolving cellulose in a solvent (Chen et al., 2016; Zhang et al., 2018).

4.2 Starch

Extraction of starch from plant resources comprises a series of steps to separate the starch granules from other components, such as protein, fat, and fibers. The size reduction process is achieved through milling, grinding, or crushing. Size-reduced plant source is blended with water to obtain a slurry form. Water assists in separating the starch granules from other components. As starch is insoluble in water, they are separated by several methods including centrifugation, decantation, and filtration. Extracted starch is then purified to eliminate residual impurities by multiple washing and centrifugation steps, even using chemicals or enzymes. Purified starch is eliminated from excess water and then dried through variable techniques such as hot air, spray drying, or other drying methods (Kringel et al., 2020). Dried starch is milled and sieved, providing that the starch powder is suitable for process techniques including extrusion, injection molding, or thermoforming.

4.3 Alginate

After brown seaweed is harvested, it is washed to eliminate impurities including stones and sand. The washed seaweed undergoes a size reduction process, such as grinding and chopping to get easy extraction of alginate. The size-reduced seaweed is pretreated with an acid or alkaline solution to provide a ruptured cell wall of the plant, which is followed by the extraction process. The extraction process utilizes sodium carbonate and other alkali-sodium salts, including sodium hydroxide, sodium bicarbonate, or sodium chloride. After water-soluble alginate is obtained, filtration is applied to the mixture to eliminate the insoluble residues from the solution. The alginate precipitation technique is divided into three pathways: sodium alginate, calcium alginate, and alginic acid routes. The sodium alginate route process uses organic solvents, such as ethanol, acetone, and isopropanol, added to sodium alginate solution to obtain insoluble alginate. The calcium alginate route process uses calcium chloride so that sodium alginate can be transformed into insoluble calcium alginate. In the alginic acid route, the transformation of sodium alginate into alginic acid through the addition of hydrochloric acid provides precipitation of alginate. The sodium alginate/calcium alginate/alginic acid is washed using water to eliminate residual salts. A dewatering process, such as vacuum filtration, centrifugation, or pressing, is further applied to the purified alginate to eliminate excess water. In order to attain the final powder of alginate, the alginate cake is subsequently dried utilizing variable drying techniques. The dried alginate is exposed to milling to accomplish a uniform particle size (Saji et al., 2022).

4.4 Chitin and Chitosan

In the extraction of chitin, the elimination of other components such as protein, lipid, and minerals is required. Chemical treatments, biological methods, and microwave-assisted techniques are the most widely utilized techniques for the extraction of chitin. Chemical extraction contains steps of demineralization and deproteination. Demineralization is achieved by exposing chitin resources to acidic media by using acetic acid, hydrochloric acid, and citric acid. Deproteination is achieved by exposing the source to alkaline media by using predominant sodium hydroxide. This acid–alkaline technique is commonly utilized in the industry because of its low cost and simplicity. Another approach for extraction is using ionic liquids, containing dialkylimidazolium-based ionic liquids and tetraalkylammonium hydroxides or using deep eutectic solvents containing choline chloride/organic acid mixtures. On the other hand, biological methods for chitin extraction comprise enzymatic methods or fermentation methods. Where enzymatic methods utilize enzymes in order to rupture the chitin resource, fermentation methods utilize bacteria for the digestion of the resource. Apart from the abovementioned extraction techniques, ultrasound-assisted, microwave-assisted, subcritical water, and electrochemical methods are some other techniques that carry the potential to remove negative impacts on the environment of chemical techniques (Kozma et al., 2022; Mohan et al., 2022). The transformation of chitin into chitosan is carried out by deacetylation. The conventional method is the exposure of chitin to concentrated alkaline solutions by predominantly using sodium hydroxide at a temperature of above 100 °C. The biological method of deacetylation, a rare method, relies on an enzyme obtained from fungi. Also, it is possible to enhance the activity of chitin deacetylase by utilizing several ionic liquids (Kozma et al., 2022).

4.5 Soy Protein

The most utilized technique for the extraction of soy protein is the "alkali solution–acid precipitation" method. In addition to this, novel extraction techniques such as enzyme-assisted extraction, reverse micelle extraction, and ultrafiltration membrane extraction have emerged with the aim of removing the drawbacks of conventional extraction methods (Zhao et al., 2023).

4.6 Zein

To ruin corn kernel and thus facilitate reaching the zein protein, grinding, which is a preparation process, is performed. "Wet milling," "dry milling," "dry grind," or "alkali treatment" are the techniques thatare utilized to obtain zein. Among them, the wet-milling technique that generates the zein-rich portion is utilized for the extraction of zein commercially. This technique provides the separation of protein from other components. After a further separation step is applied, washing with water is performed. Utilizing ethanol or isopropanol in the extraction solvent is reported to enhance the yield of zein. Following the extraction process, filtration, protein precipitation, washing/separation, drying, and milling process are performed (Jaski et al., 2022).

4.7 Wheat Gluten

To provide the separation of the protein portion of wheat, a milling technique that is a separation method categorized as dry milling and wet milling is carried out. After dry milling, obtained wheat flour contains other components than protein including starch, fat, and fiber. Protein proportion is separated from other components through a wet process. The wet process includes several steps. One of them is softening the flour with water to obtain a dough. Other steps are separation treatments (e.g., centrifugations, sedimentations, filtrations, and distillations) to separate protein from other components (Al-Rahim, 2021; Patni et al., 2014). Water or a mixture of water/other chemicals is added to the flour to obtain dough form. Then, techniques such as centrifugation, decantation, and hydroclones are performed to isolate starch and gluten from the wheat flour. Processing aids including acids and enzymes are also utilized during gluten extraction from flour to improve the efficiency of the process and enhance the quality of the extracted gluten (Van Der Borght et al., 2005). Insoluble proportion is separated, rinsed, and dried. Nonetheless, the dough method that guarantees the network structure of gluten proteins is the most widely utilized method to separate protein, and alternative methods including alkali extraction have been developed (Deleu et al., 2019).

4.8 Collagen

Nevertheless, the extraction process of collagen can be variable based on the collagen source, and the main aim is to eliminate the noncollagenous components and recover a resulting collagen product. When the skin is utilized as a collagen source, skin is first prepared by fleshing, dehairing, and cutting if it is a necessity. With the intention of rupture of covalent crosslinks between collagen molecules, pretreatment is applied. Because it is quite slow to break down the crosslinks in boiling water, dilute acids, alkalis, or specific enzymes are utilized in the pretreatment process. Calcium hydroxide and sodium hydroxide are alkalis utilized for pretreatment. The most utilized extraction techniques are mainly constructed on chemical hydrolysis utilizing alkali, acid, or salt solubilization. However, it is possible that chemical extraction is assisted by ultrasound or microwaves and enzymes. In acid hydrolysis, acetic acid, chloroacetic acid, citric acid, and lactic acid are the most widely utilized organic acids, whereas hydrochloric, sulfuric, and nitric acids are the most widely utilized inorganic acids. On the other hand, the alkali hydrolysis process relies on mainly aqueous sodium hydroxide or potassium hydroxide, whereas it is possible to use other extractants such as calcium hydroxide, sodium carbonate, and calcium oxide. Salt solubilization is a less common technique. Sodium chloride, citrates, phosphates, and tris hydrochloride are some examples utilized in the process. Enzyme hydrolysis that can be employed in combination with other conventional methods uses proteolytic enzymes. Another approach is ultrasound application during extraction which has been reported to enhance yield and reduce extraction time. Another approach is microwave assistance which is known to accelerate the acid and enzyme reactions compared with treatments without microwave assistance. As the collagen becomes soluble by the abovementioned methods, precipitation of it from the solution is necessary. Salts are most frequently utilized for this purpose. As collagen extract contains neutral salts and noncollagen proteins, collagen is purified from the extract by using multiple steps including filtration and centrifugation (Matinong et al., 2022).

4.9 Keratin

For keratin extraction from the wool, the first step is the elimination of the lipid layer by multiple washing the of wool, followed by shredding. The further process is milling, which converts wool into powder form. The methods that are utilized to get solubilized keratin can be broadly categorized as thermal, chemical, and biological treatments. Microwave extraction, superheated water hydrolysis, supercritical water, and steam explosion techniques have been achieved in thermal treatment, where alkali and acid hydrolysis, oxidation, reduction, and ionic liquids, and deep eutectic solvents are the most achieved techniques in chemical methods. On the other hand, biological treatment relies on purified enzymes or keratinolytic microorganisms (Giteru et al., 2023; Shavandi et al., 2017). However, among all of them, alkali hydrolysis, oxidation, reduction, ionic liquids, microwave extraction, and steam explosion are the major techniques to extract keratin (Shavandi et al., 2017). In the reduction technique, disulfide linkage is reduced by using agents such as thioglycolic acid, thiosulfates, l-cysteine, sulfites, and 2-β-mercaptoethanol. Protein denaturing agents such as urea, SDS, ethylenediaminetetraacetic acid, or tris hydrochloride, which disrupt the hydrogen bonds, are often used in reduction technique (Giteru et al., 2023; Shavandi et al., 2017). In the alkali technique, solubilization is facilitated using a high concentration of alkali solution (Shavandi et al., 2017). In the oxidation technique, the breakdown of inter and intramolecular cystine cross-links in wool via reaction with oxidizing agents, such as hydrogen peroxide, peracetic acid, or performic acid, provides the separation into their constituent components. In the ionic liquids technique, ionic liquids having the ability to dissolve biological components are utilized (Giteru et al., 2023).

4.10 Casein

Casein is primarily extracted from milk by acid precipitation technique or enzyme coagulation technique. In the acid precipitation technique, an acid, such as hydrochloric acid, acetic acid, or lactic acid, is added to the milk, which enables the casein to coagulate and form a curd. Another approach is enzyme coagulation which relies on the use of enzymes. After the coagulation of casein, it is separated from the liquid whey via methods such as filtration, centrifugation, or decantation. The obtained curd is further washed to eliminate residual whey proteins and lactose. The curd is dewatered and dried to attain the resulting casein powder (Ryder et al., 2017).

4.11 Silk Fibroin

Removing sericin, known as degumming, is the first step of silk fibroin extraction. The cocoons are boiled in a water-based solution of sodium carbonate, which removes sericin. The degumming step is followed by rinsing fibroin fibers detergent or alkaline solution to eliminate residual sericin. Rinsed fibroin fibers are further dried in controlled conditions. Dried fibroin fibers are treated in a suitable solvent or mixture of solvents, such as lithium bromide, calcium chloride/ethanol, or ionic liquids, which creates a silk fibroin solution. A purification process may be performed to eliminate any residual salts or other impurities. The purified fibroin is finally concentrated through evaporation to obtain a suitable concentration for further processing such as electrospinning or casting (Nguyen et al., 2019).

4.12 PLA

In the case of corn, harvesting is followed by starch extraction from the corn grains. The decomposition process of starch molecules to glucose molecules by hydrolysis mechanism is achieved. After that, dried glucose undergoes a bacterial fermentation procedure. Lactide that is obtained from lactic acid solutions is purified by crystallization and polymerized to build PLA (Wellenreuther & Wolf, 2020). Two main methods to derive LA are bacterial fermentation of carbohydrates (homofermentative and heterofermentative) and chemical synthesis (Castro-Aguirre et al., 2016; Wellenreuther & Wolf, 2020). In the industrial production of LA, the fermentation method is used instead of chemical synthesis. There exist two optically active enantiomers of LA, L and D, created by bacterial fermentation of carbohydrates. The ratio of L- and D-isomers of LA has great importance in the degradation, crystallinity, and processing attitude of PLA.

4.13 PHAs

PHAs can be synthesized by microorganisms through the fermentation of at least 75 different bacterial species (Kaniuk & Stachewicz, 2021). PHA is generated in the bacterial cells from at least five different PHA biosynthetic pathways. Up to the present, most PHA-producing bacteria were identified as Gram-negative bacteria (Tan et al., 2014). Stored as intracellular granules, microbial PHAs are recovered by the following stated steps: cell wall/cell membrane lysis, solubilization, purification, and precipitation of PHA polymer. Common ways to recover PHA polymer from microbial biomass are solvent extraction methods, digestion methods including chemical digestion and enzymatic digestion, mechanical disruption methods including bead milling and high-pressure homogenization, supercritical fluid method, cell fragility, flotation, aqueous two-phase system, and gamma irradiation (Kunasundari & Sudesh, 2011).

5 Chemical Resistance, Thermal, and Mechanical Properties of Polymers

Research purposed studies and product development works about bio-based and biodegradable polymers are constantly increasing world widely both on the lab and commercialized scales. Mechanical, chemical, or thermal properties of the improved polymer types are not strictly defined yet, where many influential factors—polymer resources, extraction methods and conditions, incorporated additives, fiber spinning methods and conditions, and synergistic effect of fiber spinning parameters—restrict the precise and general expression of those properties. The number of commercially successful bio-based biodegradable polymer types is yet only about a dozen which are precisely processed with tailored solubility, fluid dynamics, and gel formation to maintain their promised mechanical, chemical, and thermal characteristics. In this section of the chapter, characteristics of the abovementioned bio-based and biodegradable polymers are introduced with current literature.

PLA has a solubility in chloroform, acetonitrile, methylene chloride, 1,1,2-trichloroethane, and dichloroacetic acid. However, it is only partially soluble in toluene, tetrahydrofuran, ethyl benzene, and acetone and only when heated to boiling point. It has no solubility in water and alcohol. The tensile strength of PLA polymer is in the range of 21–60 MPa, where its breaking elongation is in the range of 2.5–6%, and its Young's modulus value is in the range of 0.35–0.5 GPa (Casalini et al., 2019). It is reported that PLA has weak heat resistance. Its melting temperature is in the range of 125–178 °C, where its typical glass transition temperature is 63.8 °C (Pan et al., 2016; Peelman et al., 2015).

PHAs are reported as soluble in chloroform and other chlorinated hydrocarbons. They have also weak resistance to acids and bases. Even though PHAs differ in their characteristics depending on their chemical composition, their average mechanical properties are as follows: tensile strength is in the range of 15–40 MPa, where their breaking elongation is in the range of 1–15%, Young's modulus value is in the range of 1–2 GPa, and melting temperature is in the range of 153–175 °C (Bugnicourt et al., 2014; Peelman et al., 2015).

Collagen is reported as soluble in acidic liquids. On the other hand, in case of exposure to high pH, its solubility decreases (Ramle et al., 2022). Collagen displays poor strength, low dimensional stability, and low elasticity (Bazrafshan & Stylios, 2019; Tonndorf et al., 2021).

Keratin is reported as insoluble in water, weak acids, alkalis, and organic solvents (Sinkiewicz et al., 2018).

Casein fibers were reported to be stable in white spirit and perchloroethylene. They are also more sensitive to swelling in alkali baths, where they are reported as stable to acids of moderate strength and sensitive to alkali (Brooks, 2009; Thangavelu & Subramani, 2016). Casein has a tensile strength of 2.8 cN/tex with a breaking elongation of 60–70% (Thangavelu & Subramani, 2016). It is reported that casein fibers are inflammable, even though they have the propensity to yellow when exposed to short periods of heating at 100 °C and rapidly decomposed at 150 °C (Brooks, 2009). Casein fibers display brittle behavior and yellow on prolonged heating (Thangavelu & Subramani, 2016).

Zein is reported as insoluble in water and soluble in alcohol, high concentration of urea, alkali, or anionic detergents (Menezes & Athmaselvi, 2018). It undergoes denaturation at 73 °C. It exhibits a glass transition temperature of around 165 °C and remains thermally stable up to 280 °C, with degradation beginning beyond this temperature (Jaski et al., 2022).

Silk fibroin fibers have good mechanical characteristics such as high tensile strength (300–740 MPa), toughness (70–78 $MJ \cdot m^{-3}$), and a large breaking elongation range (4–26%) (Li & Sun, 2022).

Alkali resistance of soy protein was found at a general level, while acid resistance was found at an excellent level. Also, it is reported that soy protein fibers are insoluble in acetic acid, chloroform, acetone, and dimethylformamide, while the fibers are partially soluble in concentrated nitric acid and concentrated sulfuric acid. Young's modulus of fiber from soy protein is reported as 5.08 GPa, where its breaking elongation value is reported as 37.75% (Rijavec & Zupi, 2011).

Wheat gluten exhibits good stability to weak acidic and weak alkali conditions at high temperatures (Reddy & Yang, 2007). It is reported that the adsorption capacity of wheat gluten fibers can be improved through glycosylation modification (Lei & Ma, 2021). Young's modulus of fiber from wheat gluten is reported as 5 GPa, whereas its breaking strength is reported as 115 MPa. Additionally, it has a breaking elongation value of 23% (Reddy & Yang, 2007).

It is reported that chitosan has high organic solvent resistance. Also, its alkaline resistance is reported at a high level (Ilyas et al., 2020).

Silk fibroin is reported as soluble in concentrated aqueous solutions of acids (sulfuric, formic, hydrochloric, and phosphoric) in concentrated aqueous, organic, and aqueous-organic solutions of salts (Sashina et al., 2006).

Alginate is reported as insoluble in pH below 3 (Haug et al., 1963). The breaking strength of alginate fibers has been reported in the range of 16.22–17.96 cN/tex, where their breaking elongation has been reported as 5.98–17.96% (Szparaga et al., 2020).

Starch has weak solubility in cold water (Jivan et al., 2014). Dimethyl sulfoxide is the best-known solvent for starch (Hu et al., 2016). Native starch lacks mechanical and thermal properties such as brittleness, fracture toughness, modulus, and thermal stability (Temesgen et al., 2021; Vroman & Tighzert, 2009).

Cellulose is insoluble in most organic solvents and water. However, some specialized solvents, such as ionic liquids and *N*-methylmorpholine-*N*-oxide, can dissolve cellulose. When temperatures range from 200 to 300 °C, cellulose undergoes thermal degradation.

6 Filament Production Methods

6.1 Melt Spinning Method

Melt spinning is a widely utilized method for manufacturing continuous fibers from thermoplastic polymers, such as PLA, PHA, and cellulose derivatives. The process relies on the steps of the heating and melting of the polymer, extrusion of molten polymer through a spinneret with multiple orifices, and cooling and solidification of the extruded filaments, respectively. The commercialization potential of the final fiber due to the high manufacturing rate, environmental benefit due to lack of solvents, and the possibility to manufacture fibers with various diameters are the advantages, while the need for high energy input is the disadvantage of the method. Also, the melt spinning process is considered unsuitable for polymers having poor thermal stability in some cases, which is another drawback.

6.1.1 PLA

Melt spinning is a common method for manufacturing filament from PLA polymer because of its thermoplastic nature. However, melt spinning could have some difficulties due to the degradation of polymer during melting in some cases. High temperature and pressure, shear stress during process stages, and exposure to atmospheric moisture can cause early degradation, which impacts the final properties of PLA fiber. Crystallinity and molecular weight are the critical properties of PLA polymer that construct the mechanical characteristics of yarn. Several process conditions at the melt extrusion stage and drawing process, such as residual moisture, melt temperature, residence time, rotational speed of the extruder screw, and spinning speeds at the drawing stage play an important role in the processability and properties of the final fiber (Gajjar et al., 2021). The major challenge regarding the melt spinning of PLA is its low thermal stability in the presence of moisture. However, it is possible to enhance thermal resistance and mechanical characteristics by manipulating process parameters (Gupta et al., 2007; Hufenus et al., 2020). It is reported that lower temperatures and higher draw ratios increase crystallinity (Gupta et al., 2007). Brittle characteristic is another challenge regarding PLA polymer. It is possible to enhance the toughness of the PLA through several techniques, such as copolymerization, plasticization, and blending with other polymers. Ethylene-vinyl acetate, polyvinyl acetate, polyvinyl alcohol, polycaprolactone, polyvinyl phenol, polybutylene succinate, polyester-amide, and polyethylene oxide/polypropylene oxide/polyethylene oxide triblock copolymer, starch, and wheat gluten are the most studied polymers for blending with PLA (Krishnan et al., 2016). The poor mechanical and thermal properties of PLA can be enhanced by increasing its crystallinity. Factors impacting its crystallinity can be stated as follows: molecular weight, D-lactide content, utilized nucleating agents or plasticizers, and processing conditions (Tábi et al., 2022).

6.1.2 PHAs

As PHAs are linear polymers, they are considered suitable for melt spinning. However, enhancing PHA fibers to meet the mechanical requirement for industrial textile applications would make them more desirable in the field. However, some challenges with the melt spinning of these polymers for manufacturing with desired characteristics led to the development of new approaches. The major challenge for the melt spinning of PHAs is the crystallization behavior of the polymer. Many studies have focused on the management of crystallization during the spinning process. Manipulating the process parameters, such as temperature and drawing, and utilizing additives are the most developed approaches for the abovementioned motive. Because the melting temperature of PHAs is near their thermal degradation temperature, the melt spinning application of these polymers poses another challenge. By using some methods, it is possible to cope with such a problem. A method to lessen thermal degradation is to get the polymer in a gel form instead of a powder or pellet form. Another method may be the utilization of additives. However, the utilization of additives causes some problems regarding biocompatibility and biodegradability in biomedical applications. Also, additives have the potential for cost increment. In addition to this, the use of copolymers or plasticizers that can decrease the melting temperature may be another way. On the other hand, the complicated cooling/solidification process to prevent filaments from sticking on godets or each other, which often requires a posttreatment like annealing to enhance the fiber's mechanical characteristics, is another challenge for the melt spinning process (Kopf et al., 2023).

6.1.3 Collagen

Because collagen has a complex and thermally sensitive nature, melt spinning process of collagen possesses remarkable difficulties. When exposed to high temperatures, denaturation of collagen can occur, which leads to damage to its unique helix structure and intrinsic properties (Bazrafshan & Stylios, 2019; Meyer, 2019). Displaying brittle behavior and exhibiting a poor mechanical characteristic of melt-spun collagen fibers is another drawback. However, it may be possible to remove such challenges by using different techniques such as using plasticizers and cross-linking agents (Meyer et al., 2010).

6.1.4 Keratin

Having high cysteine content, which forms disulfide bonds that gain strength and stability to protein structure, complicates the melt spinning process of keratin. High temperature in melt processing has the potential to breaking of disulfide bonds bringing about weakening of the intrinsic strength and stability of the polymer.

However, some approaches such as blending with other polymers and utilization of reducing agents may be applied to improve melt processing (Ghosh et al., 2017).

6.1.5 Casein

The characteristics of casein such as hard and brittle behavior, poor mechanical characteristics, and moisture sensitivity, can complicate the melt spinning process of casein (Brooks, 2009; Cook, 1984; Ucpinar Durmaz & Aytac, 2021). Also, fibers possess a propensity to stick to each other, which may intricate the melt spinnability of casein fibers (Brooks, 2009).

6.1.6 Zein

Thermal sensitivity and brittle characteristics of zein protein may be the challenging factors for melt spinning process. To improve melt spinning of zein, the addition of plasticizers, such as polyethylene glycol and glycerol, and blending with other polymers should be evaluated (Zhou & Wang, 2021).

6.1.7 Silk Fibroin

Like other protein-based polymers, the melt spinning process of fibroin poses some difficulties because the high temperature induces the denaturation of the polymer. Also, rigid and brittle characteristics of silk fibroin may possess another challenging factor for the melt spinning of the protein. However, it may be possible to improve the melt spinnability of the fibroin by the approaches of plasticizer utilization or mixing zein with ice water (Brown et al., 2016).

6.1.8 Soy Protein

Denaturation possibility due to its thermal instability, poor mechanical strength, and brittleness of soy protein are considered factors that make the melt spinning of soy protein challenging. However, it may be possible to improve the melt spinnability of soy protein by blending with other polymers, plasticizer utilization, and manipulating process conditions (Huang et al., 1995; Tummala et al., 2006).

6.1.9 Wheat Gluten

Denaturation possibility due to thermal sensitivity, fiber swelling, poor mechanical strength, and brittleness of wheat gluten are considered restrictive factors for the melt spinning of wheat gluten. Like other proteins, the methods of plasticizer utilization, blending with other polymers, and manipulating process conditions for improving melt spinning of wheat gluten could be investigated (Attenburrow et al., 1990).

6.1.10 Chitosan

Denaturation possibility due to thermal sensitivity and infusibility characteristic of chitosan are considered the key challenging factors for the melt spinning process of chitosan fibers. On the other hand, blending chitosan with other polymers such as polybutylene succinate, polylactic acid, polybutylene terephthalate adipate, polyvinyl alcohol, polyacrylonitrile, polycaprolactone, and polybutylene succinate adipate may increase the potential of melt process for the chitosan (Correlo et al., 2005; Min & Kim, 2002).

6.1.11 Alginate

Melt spinning of alginate is a challenging process due to several factors. Thermal sensitivity, high absorption capacity water, and gelation propensity are the major challenging factors. Thermal sensitivity can lead to degradation, which intricates the process. The issue of having gelation propensity of alginate in the existence of divalent cations may cause nozzle clogging during the process, which can further complicate the process (Hu et al., 2022). On the other hand, it is reported that poor solubility and weak compatibility with additives or other polymers could be stated as the other challenging factors (Zhang et al., 2020).

6.1.12 Starch

The degradation possibility of thermal sensitivity complicates the melting process of starch. On the other hand, its weak mechanical characteristic brings about some difficulties in the process. Chemical and physical modifications, such as crosslinking, acetylation, and hydroxypropylation, to enhance thermal stability have been studied. Utilization of plasticizers such as sorbitol, polyethylene glycol, glycerol, and urea and blending with other polymers such as polyvinyl alcohol, polylactic acid PLA, polybutylene succinate, polyesteramide, and ethylene–vinyl alcohol copolymer to promote mechanical properties and processability have been investigated (Curvelo et al., 2001; Temesgen et al., 2021).

6.1.13 Cellulose

Degradation possibility due to thermal sensitivity and viscoelastic characteristics of cellulose are the challenging factors that restrict the melt processing of cellulose. The methods of blending with other polymers, such as polypropylene, and utilization of plasticizers such as diethyl phthalate and triacetin may improve the mechanical properties of final fibers and enhance melt spinning processability of cellulose (Charvet et al., 2019; Lo Re et al., 2023). Also, chemical and physical modification techniques such as acetylation, carboxymethylation, and hydroxypropylation may enhance the melt processibility of cellulose (Candido & Gonçalves, 2016; Rahman et al., 2021).

6.2 Wet Spinning

Wet spinning is a widely utilized method for manufacturing fibers from polymers that are not thermoplastic and have poor thermal stability, such as cellulose, chitin, and some starch derivatives. The process relies on the steps of the dissolution of the polymer in a suitable solvent to obtain a spinning dope, extrusion through a spinneret with multiple orifices into a coagulation bath containing nonsolvent for polymer, washing coagulated fibers, drying of washed fibers, drawing/stretching of dried fibers, and winding drawn fibers onto spools or bobbins, respectively. The ability to manufacture fibers from polymers having low thermal stability is the most unique advantage of this spinning process. On the other hand, having a more complicated process because of additional steps, like solvent exchange, and the necessity of longer times compared with melt spinning are the drawbacks of the wet spinning process. Also, selected solvents and coagulants can possess environmental concerns.

6.2.1 PLA

After PLA solution preparation with a suitable solvent using dichloromethane, chloroform, chloroform/hexafluoro propanol mixture, or dimethylformamide, the obtained spinning dope is extruded into a coagulant bath containing methanol, ethanol, or dichloromethane (Fabris et al., 2022; Puchalski et al., 2017). Factors such as PLA concentration in the dope and the presence of additives, such as surfactants, plasticizers, or other polymers, are considered influential on the properties of final PLA fibers (Fabris et al., 2022). However, some challenging factors make the process difficult. Controlling fiber diameter, orientation, and fiber properties is challenging regarding the process because of the complex interactions of process conditions. Reproducibility and scalability are the other challenging factors. On the other hand, hydrolytic degradation because of its sensitivity to water brings about a decrease in molecular weight and deterioration of mechanical characteristics.

Ongoing research has been focused on the abovementioned challenging factors (Giełdowska et al., 2020).

6.2.2 PHAs

After PHA solution preparation with a suitable solvent using chloroform, tetrahydrofuran, methylene, or dichloride, the obtained spinning dope is extruded into a coagulant bath containing methanol, ethanol, propanol, or reagent alcohol (Degeratu et al., 2019; Singhi, 2019). Factors such as PHA concentration in the dope and the presence of additives, such as surfactants, plasticizers, or other polymers, are considered influential on the properties of final PHA fibers. However, some challenging factors make the process difficult. Controlling fiber diameter, orientation, and properties is challenging because of the complex interactions of process conditions. Reproducibility and scalability are the other challenging factors.

6.2.3 Collagen

After extraction of collagen, the solubilized collagen is mixed with a solvent, generally organic solvents, such as hexafluoro propanol, trifluoroethanol, or acids (e.g., trifluoroacetic acid, acetic acid, or hydrochloric acid) (Bazrafshan & Stylios, 2019). Obtained spinning dope is then extruded into a coagulation bath containing a non-solvent (e.g., acetone or ethanol) or a neutral buffer such as phosphate-buffered saline (PBS) or a salt solution (Bazrafshan & Stylios, 2019; Caves et al., 2009). The coagulation step is followed by the drawing process to enhance the mechanical properties of fibers. After the drawing process, fibers are washed to eliminate residual solvent and neutralized to obtain a suitable pH for further processes. In the process, the factors regarding extrusion and coagulation steps such as spinneret design, extrusion rate, and coagulation bath composition have effects on the mechanical properties of the fiber.

The manufacturing of collagen fibers by wet spinning technique presents some challenges. The main concern about collagen is its poor mechanical characteristics. After the purification/extraction process, it loses its properties such as mechanical strength arising from the hierarchical structure in its natural texture. Collagen displays poor strength, low dimensional stability, low elasticity, as well as a high degree of hydration and eventually rapid degradation (Bazrafshan & Stylios, 2019; Tonndorf et al., 2021). On the other hand, attaining a high-quality collagen source is quite important in the initial process. Another challenge is that unstable spinning dope causes irregular fiber formation, aggregation, or gelation during the extrusion step. Another important concern about wet-spun collagen fibers is biocompatibility. The risk of immunogenicity and disease transmission from animal-derived collagen must be removed as collagen fibers stand out in medical applications. Recent studies on manufacturing collagen fibers by wet spinning techniques have focused on variable approaches. Some studies explored crosslinking techniques to create stronger intermolecular bonds to enhance fibers' resistance to degradation and retain their structure. Meyer et al. (2010) investigated the crosslinks of formaldehyde, glutaraldehyde, and ethyl dimethylaminopropyl carbodiimide (Meyer et al., 2010). Tonndorf et al. (2018) investigated riboflavin-induced photo-crosslinking (Tonndorf et al., 2018). Also, some studies focused on the modified wet spinning system, whereas some studies focused on blending with other polymers, such as polyvinyl alcohol, polyacrylonitrile, silk fibroin, and chitosan to develop stronger and more flexible fibers (Caves et al., 2009; Gwak et al., 2021; Malladi et al., 2020; Tonndorf et al., 2020; Zhang et al., 2008). Some other studies investigated obtaining collagen from sustainable resources such as transgenic plants, whereas some other studies rely on the addition of nanoparticles into collagen fibers to improve the functionalism of the fibers (Yaari et al., 2016; Yue et al., 2022).

6.2.4 Keratin

After keratin solution preparation with a suitable solvent using hydrogen-bond breakers and sodium carbonate/sodium bicarbonate mixture, the obtained dope is extruded into a coagulation bath containing ethanol/acetic acid, methanol/acetic acid, sodium sulfate solution/acetic acid, or ammonium chloride/hydrochloric acid (Bayanmunkh et al., 2023; Cao et al., 2020; Mi et al., 2020; Xu & Yang, 2014). Improving processability and mechanical characteristics of keratin fibers are subject to improvement. Blending with other polymers such as polyvinyl alcohol, cellulose, and cellulose acetate to develop the spinnability of the keratin solution has been focused on by researchers (Bayanmunkh et al., 2023; Cao et al., 2020; Katoh et al., 2004). To enhance the mechanical characteristics of the fibers, the utilization of crosslinking agents such as glutaraldehyde and 4,4′-methylenebis-phenyl isocyanate is another issue that researchers have investigated (Cao et al., 2020). Also, the wet spinning technique is considered a quite convenient system for the reuse of wool waste (Cao et al., 2020; Lebedytė & Sun, 2022; Mi et al., 2020).

6.2.5 Casein

After casein solution preparation using a suitable solvent such as an alkaline solution, the obtained dope is extruded into a coagulation bath containing an acid solution, such as sulfuric acid or acetic acid. In addition to typically employed process steps, a hardening step is needed to minimize the softening and swelling effects of water (Thangavelu & Subramani, 2016). Crosslinking using aluminum sulfate, formaldehyde, or citric acid and optional treatment with metal salts like zinc is considered a straightforward method to enhance the mechanical characteristics of fibers (Nechyporchuk & Köhnke, 2019; Yang & Reddy, 2012). Incorporation of nanoparticles, nanofibrils, or nanocrystals is a promising way to improve the properties of fibers (Nechyporchuk & Köhnke, 2019).

6.2.6 Zein

After the preparation of zein solution using a suitable solvent such as an alkaline solution, the obtained dope is extruded into a coagulation bath containing an acid solution. The parameters of temperature, pH, and concentration of the solvent have a crucial role in obtaining a homogeneous solution. Optimization of solvent system, blending with other polymers such as cellulose, and utilization of crosslinking agents, such as formaldehyde, citric acid, and butane tetracarboxylic acid, are the issues that researchers have been focused on till now (Chi & Chen, 2010).

6.2.7 Silk Fibroin

Following the extraction of silk fibroin, it is dissolved in a solvent that can be obtained utilizing organic solvents, concentrated salt solution, or ionic liquids. Several solvents utilized to obtain silk fibroin solution can be stated as hexafluoro propanol, tetrahydrate of calcium nitrate/methanol, calcium chloride/ethanol/water, lithium bromide/water mixture, calcium chloride/formic acid mixture, and 1-butyl-2,3-dimethylimidazolium (Ha et al., 2005; Mollahosseini et al., 2019; Ng et al., 2019; Yazawa et al., 2018). The fibroin concentration and the presence of additives such as salts, nanoparticles (e.g., polydopamine), or some other polymers (e.g., chitosan) are considered factors that affect the properties of final fibroin fibers (Chen et al., 2022a; Mollahosseini et al., 2019). Generally, the dialysis technique is applied to the fibroin solution to concentrate. The spinning dope is extruded into two consecutive coagulation baths (Mollahosseini et al., 2019; Yazawa et al., 2018). Obtained fibers are immediately washed and dried. However, some challenging factors make the process difficult. Controlling fiber morphology and properties is challenging because of complex interactions of process conditions such as spinning dope composition and coagulant bath parameters. Reproducibility and scalability are the other challenging factors (Li & Sun, 2022). On the other hand, wet spinning is considered a convenient method to reuse waste silk fibers (Mollahosseini et al., 2019).

6.2.8 Soy Protein

Dissolving soy protein in a suitable solvent in an alkaline solution, such as sodium hydroxide, is the initial step of wet spinning of soy protein fibers. Highlight the fact that temperature and concentration of the solvent have an important role in obtaining a homogeneous solution. The obtained solution is extruded into a coagulant bath containing an acidic solution with or without sodium chloride, zinc chloride, and calcium chloride (Huang et al., 1995). Coagulation is followed by drawing. To enhance the mechanical characteristics of soy protein fibers, some approaches including blending with other polymers such as polyvinyl alcohol, and crosslinking techniques have been investigated (Zhang et al., 1999). Also, some research investigates the addition of metallic salts into spinning dope to gain functionalism to soy protein fibers (Rijavec & Zupi, 2011).

6.2.9 Wheat Gluten

After wheat gluten solution preparation using a suitable solvent, such as an alkaline solution, the obtained dope is extruded into a coagulation bath containing an acid solution (Reddy & Yang, 2007; Schmandke et al., 1976). Furthermore, extrusion, washing, drying, drawing, and optionally annealing processes are employed. To introduce functionality to fibers, posttreatment processes such as heat treatment and surface modification may be applied (Reddy & Yang, 2007). To improve the mechanical properties of final gluten fibers, researchers should be focused on the issues: blending with other proteins such as casein and keratin, selection of solvent, process optimization, and modification techniques. Lei and Ma (2021) found that the mechanical characteristic of wheat gluten protein fibers is improved by glycosylation modification technique. Incorporation of nanoparticles and the use of crosslinking techniques may offer the possibility to enhance mechanical characteristics and processability.

6.2.10 Chitosan

After chitosan solution preparation using a suitable solvent such as dilute acidic solutions including aqueous solutions of citric acid, acetic acid, lactic acid, malic acid, and formic acid (Mohammadkhani et al., 2021), the obtained solution is then extruded into a coagulation bath containing calcium chloride, sodium hydroxide, a mixture of sodium hydroxide/ethanol, sodium hydroxide/methanol, or calcium chloride saturated water/methanol (Tamura et al., 2004; Yudin et al., 2014). Depending on the desired properties of the fibers, posttreatment such as heat treatment, crosslinking, or a surface modification could be applied. Achieving the optimal viscosity and solubility of the solution, management of fiber diameter, and poor mechanical characteristics of the fibers are the major challenges of the process. Some recent studies have focused on blending with other polymers, such as cellulose, silk fibroin, or synthetic polymers (Vega-Cázarez et al., 2018; Zhu et al., 2019). Studies on incorporating nanofillers and utilization of crosslinking agents such as sodium tripolyphosphate, glutaraldehyde, or citric acid, genipin, and adipic acid to enhance physicochemical and mechanical properties are ongoing (Falamarzpour et al., 2017; Jin et al., 2004; Nechyporchuk et al., 2020; Vega-Cázarez et al., 2018; Wegrzynowska-Drzymalska et al., 2020; Xiao et al., 2023). On the other hand, some of the studies rely on utilizing environmentally friendly or nontoxic solvents such as ionic liquids (Kostag & El Seoud, 2021; Kuznik et al., 2022).

6.2.11 Alginate

The wet spinning of alginate begins with the preparation of alginate (generally sodium alginate) solution (Ahmad Raus et al., 2021). The prepared alginate solution is extruded into a coagulation bath including divalent cations (generally Ca^{2+}). In addition to this, it is possible to combine Ca^{2+} with other metal ions such as Zn^{2+}, $Cu^{2+,}$ Ba^{2+}, and Al^{3+} (Hu et al., 2022). After the spinning, a neutralization step is sometimes employed, and the obtained fibers are then dried (Dechojarassri et al., 2018). Some recent research on the wet spinning of alginate fibers has focused on blending with other polymers, such as cellulose, chitosan, starch, or PVA to improve the mechanical characteristic of fibers (Ahmad Raus et al., 2021; Fan et al., 2006; Liu et al., 2019; Sailah et al., 2022; Wang et al., 2010). Some others rely on the incorporation of nanoparticles or nanocrystals to promote the functionalism of fibers (He et al., 2012; Liu et al., 2019; Neibert et al., 2012; Sa & Kornev, 2011). Also, research on optimizing process conditions, including nozzle diameter, alginate concentration, and coagulation bath composition, is ongoing (Brzezińska & Szparaga, 2015; Lin & Wang, 2012). Tuning of solution viscosity, optimizing parameters of coagulation bath, achieving consistent fiber diameter, drying with minimum shrinkage, and poor mechanical characteristics of obtained fibers are the major challenges for wet spinning of alginate fibers.

6.2.12 Starch

Manufacturing starch fibers by utilizing wet spinning poses some challenges. One challenge is that starch has poor solubility in water and solvents, which might make it difficult to dissolve and form a spinning dope (Kim et al., 2015). To improve processability in wet spinning, starch may be exposed to modification treatment including gelatinization, esterification, and crosslinking, which modify the structure of starch so that it could be suitable for wet spinning (Khan et al., 2017; Pérez-Pacheco et al., 2016; Temesgen et al., 2021). After modified starch is dissolved in a suitable solvent, the typical process steps are performed in order. Providing consistent fiber diameter and morphology during the process because of intricate interactions between the spinning dope, coagulation bath, and process parameters is another challenging factor. Designing optimum process conditions such as solvent type and concentration, spinning and coagulation bath composition, and process temperature is usually a challenge, which requires remarkable trial. Furthermore, the tendency to hydrolytic degradation as well as the moisture-sensitive characteristic of the starch impact its stability and durability (Wang et al., 2003). Research addressing blending with other polymers such as cellulose, chitosan, Polyhydroxyalkanoates, polylactic acid, and polyvinyl alcohol with the aim of promoting fiber formation and stability of resulting fibers should be ongoing (Afzal et al., 2021; Shang et al., 2019; Xu et al., 2005). Also, for the motive of decreasing environmental issues, research must investigate eco-friendly solvents such as ionic liquids.

6.2.13 Cellulose

Wet spinning is a common method to manufacture regenerated cellulosic fibers. As high temperatures are not necessary for the wet spinning technique, the drawback of cellulose degradation is eliminated. The step of dissolving cellulose in a suitable solvent is critical. *N*-methylmorpholine-*N*-oxide and the traditional viscose process using sodium hydroxide and carbon disulfide are the most utilized solvents (Azimi et al., 2022; Vehviläinen et al., 2008). On the other hand, the wet spinning process of cellulose fibers possesses some challenging factors. Defects in the fibers due to incomplete dissolution of cellulose or air bubbles in the dope, saving optimal coagulation bath conditions, and difficulties for consistent morphology because of variations in the spinning dope and process conditions are the major challenging factors for the process (Azimi et al., 2022). On the other hand, dope viscosity, the coagulation bath's composition, temperature, and draw ratio are the parameters that play an important role in both the processability of cellulose and resulting fiber properties. Some studies focused on physical or chemical pretreatments such as irradiation technique or enzymatic treatment to enhance the dissolution of cellulose, whereas some other studies focused on utilizing environmentally friendly solvents or special cellulose resources including agricultural residues (Gao et al., 2018; Henniges et al., 2013; Jiang et al., 2011; Vehviläinen et al., 2008). Researchers have investigated sodium hydroxide/urea solvent systems and different ionic liquids to optimize cellulose dissolution (Azimi et al., 2022; Miao et al., 2014; Olsson & Westman, 2013). Some other studies focused on chemical recovery systems, including switchable solvents and deep eutectic solvents (Bialik et al., 2020; Klar et al., 2018). Another approach is the wet spinning of cellulose nanofibrils and cellulose nanocrystals because of their outstanding mechanical properties (Gao et al., 2021; Iwamoto et al., 2011; Kim et al., 2019). Also, studies on functional additives such as antimicrobial agents, nanoparticles, or other additives of doped cellulose fibers for technical textile applications are ongoing (Nechyporchuk et al., 2017).

6.3 Electrospinning Method

Electrospinning is a versatile technique to manufacture nanofibers. The technique relies on the application of a high-voltage electric field to a polymer solution or melt. The electrospinning process comprises three main steps including polymer preparation, electrospinning setup, and the electrospinning process. The electrospinning method has the advantages of manufacturing ultrafine fibers, obtaining high surface area-to-volume ratios, controlling fiber morphology, and achieving porous structures.

6.3.1 PLA

Following the preparation of PLA spinning solution using a suitable solvent such as chloroform, dichloromethane, hexafluoroisopropanol, and dimethylformamide, the electrospinning process is employed. Controlling various process parameters enables the generation of fibers having varying diameters, orientations, and mechanical characteristics. It is possible to enhance the spinnability and properties of PLA fiber by some approaches such as blending with other polymers such as polyvinyl alcohol and polyhydroxyalcanoate, utilizing nanoparticles, utilizing plasticizers, achieving surface modification techniques, and employing coaxial electrospinning. Reproducibility and scalability may be considered challenging factors for the commercialization of fibers (Arrieta et al., 2020; Maleki et al., 2022).

6.3.2 PHAs

Following the preparation of the PHA spinning solution using a suitable solvent such as chloroform, dichloromethane, and dimethylformamide, the electrospinning process is employed. It is possible to enhance the spinnability of PHA and fiber properties by the addition of plasticizers or surfactants and blending with other polymers such as chitosan, collagen, zein, cellulose, polyvinyl alcohol, polylactic acid, polylactic glycolic acid, or polycaprolactone. Additionally, controlling various process parameters enables the generation of fibers having varying diameters, orientations, and mechanical characteristics. On the other hand, there exist some challenging factors for electrospinning of PHAs. The tendency to degradation of PHA fibers negatively affects the mechanical characteristics of final fibers. Reproducibility and scalability are also considered other challenging factors (Arrieta et al., 2020; Brunetti et al., 2020).

6.3.3 Collagen

Following the preparation of collagen spinning solution using a suitable solvent or a solvent mixture, such as acetic acid, hexafluoro isopropanol, trifluoroethanol, acetic acid, and phosphate-buffered saline/ethanol, the electrospinning process is employed. However, there exist challenging factors in the process. It is noted that the selection of a suitable solvent system is quite critical because the solvent can cause the denaturation of collagen and can possess toxic characteristics. Also, the utilization of crosslinking agents such as glutaraldehyde or genipin can also positively affect the stabilization of the fibers and enhancement of their mechanical properties. Poor mechanical characteristics and rapid degradation of collagen are considered a drawback in some cases. However, it is possible to overcome such challenges with several crosslinking techniques. Enzymatic crosslinking, which utilizes several enzymes such as lysyl oxidase or transglutaminase, is also investigated to improve the mechanical characteristics of the fibers. Another crosslinking approach is utilizing physical crosslinking techniques including ultraviolet irradiation, gamma irradiation, or dehydrothermal treatment. In addition to this, with the aim of generating collagen fibers displaying degradation resistance, mechanical resistance, and elasticity, a combination of collagen with other polymers including polycaprolactone, PHA, polylactic glycolic acid, or chitosan is frequently studied. Also, as a different approach to producing composite core–shell fibers, the coaxial electrospinning method has been investigated. Controlling fiber morphology is another challenging factor resulting from complicated interactions of parameters such as electric field strength and spinning solution composition. In addition, various process parameters such as spinning solution concentration, voltage, needle-to-collector distance, and flow rate must be optimized to obtain the desired fiber morphology. Reproducibility and scalability are the other challenges (Law et al., 2017; Lu & Guo, 2018).

6.3.4 Keratin

Following the preparation of keratin spinning solution using a suitable solvent such as formic acid, hexafluoroisopropanol, and water, the electrospinning process is employed. To improve spinnability and several properties of keratin, blending with other polymers such as polyvinyl alcohol, polylactic glycolic acid, polyethylene oxide, silk fibroin, or chitosan has been investigated (Choi et al., 2015; Li & Yang, 2014; Ru-Min et al., 2011). On the other hand, extraction and dissolution of keratin without denaturation, providing control of fiber morphology and properties, degradation sensitive characteristics of keratin, reproducibility, and scalability are considered major challenging factors for electrospinning of keratin fibers. Also, studies on crosslinking methods are ongoing (Chen et al., 2022b; Liu et al., 2015).

6.3.5 Casein

Following the preparation of casein spinning solution using a suitable solvent such as triethnolamine, the electrospinning process is employed. To improve spinnability and several properties of casein, blending with other polymers such as polyvinyl alcohol or polyethylene oxide has been investigated. Also, different crosslinking agents such as formaldehyde, glutaraldehyde, and toluene diisocyanate tannic acid have been investigated to enhance the mechanical characteristics and the functionality of casein fibers (Biranje et al., 2019; Flores-Nieves et al., 2022; Minaei et al., 2019). On the other hand, providing control of fiber morphology and properties, reproducibility, and scalability may be considered major challenging factors for the electrospinning of casein fibers.

6.3.6 Zein

Following the preparation of zein spinning using a suitable solvent such as ethanol/water, the electrospinning process is employed. However, major challenges may exist in electrospinning of zein fibers. Poor mechanical characteristics and moisture-sensitive structure of zein fibers can negatively affect the mechanical characteristics of the resulting fiber. However, it is possible to cope with this difficulty using cross-linking agents such as hexamethylene diisocyanate. On the other hand, solvent selection and dissolution without denaturation, management of fiber morphology, reproducibility, and scalability are the other challenges regarding the electrospinning of zein fibers. Recent research has been centered around alternative solvent systems and surface modification techniques including phosphorylation, deamidation, or blending with other polymers (Selling et al., 2007; Yao et al., 2007).

6.3.7 Silk Fibroin

Following the preparation of fibroin spinning solution using a suitable solvent such as hexafluoroisopropanol, formic acid, and water, the electrospinning process is employed (Chen et al., 2023). A combination of silk fibroin with other polymers such as polyurethane or polyvinyl alcohol can enhance the spinnability and properties of fibroin fiber. On the other hand, it is reported that the incorporation of nanoparticles such as graphene, graphene oxide, carbon nanotubes, and reduced graphene oxide/titanium dioxide enhances the mechanical characteristics and other properties of fibers (Chen et al., 2023; Zhang et al., 2021a). Dissolution of silk fibroin with the right concentration, controlling fiber morphology and properties, reproducibility, and scalability are the major challenging factors for the electrospinning process of silk fibroin fibers.

6.3.8 Soy Protein

Following the preparation of soy protein spinning solution using several organic solvents, the electrospinning process is employed. Solvent selection, management of fiber morphology, reproducibility, and scalability are the major challenges regarding electrospinning of soy protein fibers. Recent research has been centered around alternative solvent systems, blending with other polymers, and utilization of cross-linking agents (Budurova et al., 2021; Shankar et al., 2013; Vega-Lugo & Lim, 2008; Wongkanya et al., 2017).

6.3.9 Wheat Gluten

Following the preparation of wheat gluten spinning solution using a solvent such as propanol/propanol or hexafluoro propanol, the electrospinning process is employed (Dong et al., 2010; Woerdeman et al., 2005). However, major challenges may exist in electrospinning of wheat gluten fibers. The factors of selection of solvent to dissolve the gluten protein without aggregation or denaturation, management of fiber morphology, reproducibility, and scalability may be the challenging factors that research needs to focus on.

6.3.10 Chitosan

Following the preparation of chitosan spinning solution using a solvent or a solvent mixture such as acetic acid or trifluoroacetic acid, the electrospinning process is employed (Geng et al., 2005). Several parameters such as the electrospinning solution properties, viscosity, flow rate, voltage, distance between electrodes, humidity, ambient temperature, pH, and molecular weight are considered to have an influence on the resulting fiber properties (Antaby et al., 2021). However, some challenging factors make the process difficult. Some studies have investigated modifying chitosan to improve electrospinning performance. Some other research centered around obtaining composite fibers by blending with nanoparticles or other polymers including silk fibroin, collagen, and polycaprolactone with the aim of improving mechanical and thermal characteristics of fibers, where some of them centered around utilizing crosslinking agents such as glutaraldehyde and genipin. In addition to this, reproducibility and scalability are the other challenging factors (Islam et al., 2022; Qasim et al., 2018).

6.3.11 Alginate

Following the preparation of the alginate spinning solution using a suitable solvent or a solvent mixture such as water or a water/ethanol mixture, the electrospinning process is employed. Gelation possibility at low concentration and high surface tension is considered to restrict the spinnability of alginate. Researchers have investigated improving the spinnability and properties of alginate fibers using several methods including improving the functionalism of starch fibers incorporating nanoparticles, blending with other polymers, designing co-solvent systems, and modifying the alginate (Mokhena & Luyt, 2017; Mokhena et al., 2020).

6.3.12 Starch

Following the preparation of starch spinning solution using a solvent or a solvent mixture such as dimethyl sulfoxide and formic acid, the electrospinning process is employed (Afzal et al., 2021). With the aim of enhancing the mechanical characteristics of fibers, posttreatment such as heat treatment, chemical crosslinking, or surface modification can be employed (Liu et al., 2017). However, some challenging factors make the process difficult. Water-sensitive nature and brittle characteristic of starch are the major concerns. With the aim of enhancing mechanical characteristics and overcoming the water sensitivity of starch, posttreatments such as annealing or utilization of crosslinking agents such as glutaraldehyde and modification techniques have been investigated (Liu et al., 2017). On the other hand, controlling of fiber morphology and properties, reproducibility, and scalability are the other challenges (Afzal et al., 2021).

6.3.13 Cellulose

Electrospinning of cellulose includes several steps, such as the preparation of cellulose spinning solution, the electrospinning process, and the posttreatment. In the step of solution preparation, cellulose is dissolved in a solvent or solvent mixture such as *N*-methylmorpholine-*N*-oxide, ionic liquids, lithium chloride/*N*,*N*-dimethylacetamide, and sodium hydroxide/urea aqueous mixtures (Araldi da Silva et al., 2021; Prasanth et al., 2014; Zhang et al., 2021b). Factors such as cellulose concentration in the solution, the presence of nanoparticles, or the blending of other polymers such as poly lactic acid, polyvinylidene fluoride, and polyacrylonitrile are considered influential on the properties of final cellulose fibers (Miyauchi et al., 2010; Zhang et al., 2021b). On the other hand, some researchers explore manufacturing core–shell or composite fibers through coaxial systems utilizing nanoparticles or other polymers (Miyauchi et al., 2010; Yu et al., 2013). However, some challenging factors make the process difficult. One of the major challenges is the low solubility of cellulose. Therefore, the selection of a solvent that does not cause the degradation of cellulose is crucial. Controlling fiber morphology and properties, low production rate, reproducibility, and scalability are the other challenges that remarkable research is ongoing (Peranidze et al., 2023).

7 Potential Textile Applications of Polymers

PLA Apart from scaffold applications and drug delivery systems, medical products and healthcare textiles are among the textile applications of PLA polymer. In the literature, there is remarkable research on PLA yarn production by ring, rotor, or siro spinning system; PLA fancy yarns; knitted PLA fabrics; and woven PLA fabrics (Yang et al., 2021).

PHAs Whereas PHA polymer stands out in its tissue engineering applications, textile engineering applications of the polymer are also remarkable. Suture applications, wound dressings, and meshes for hernia repair in different constructions such as knitted and braided are its main textile applications (Aldohayan et al., 2020; Kopf et al., 2023).

Collagen Apart from scaffold applications and drug delivery systems, wound dressings, biodegradable surgical sutures, and coating material for textiles are the prominent textile applications of collagen polymer. On the other hand, collagen has the possibility to be used in T-shirts, leggings, and pants.

Keratin Scaffold applications and drug delivery systems, wound dressings, hygiene/medical textiles, and filters are the potential textile applications of keratin-based fibers. It is also reported that keratin can be also utilized in composite reinforcements (Lebedytė & Sun, 2022).

Casein Potential applications of casein are reported as underwear, t-shirts, children's garments, sweaters, sportswear, uniforms, eye masks, and bedding (Thangavelu & Subramani, 2016). It may also have potential usage in scaffold applications and drug delivery systems.

Zein Wound healing applications, air filters, textile finishing, coating agents, and adhesives could be considered textile usage of zein. It may also have potential usage in scaffold applications and drug delivery systems.

Silk Fibroin Apart from scaffold applications and drug delivery systems, surgical sutures, apparel, luxury clothing, and furnishings are the potential applications of silk fibroin (Koh et al., 2015).

Soy Protein Apart from scaffold applications and drug delivery systems, bedding, upholstery, skirts, suits, shirts, athletic wear, and infant clothing are the potential applications of soy protein (Hodakel, 2020). Highlight the fact that soy protein also stands out in its possible adhesive applications (Tian et al., 2022).

Wheat Gluten Wheat gluten stands out mostly in its scaffold and drug delivery applications.

Chitosan Apart from the wide usage area of chitosan when blended with other polymers, wound dressings are one of the most prominent applications (Zhou et al., 2019). Also, an intense study on its tissue engineering application has been carried out (Kalantari et al., 2019).

Alginate Apart from their tissue applications, alginate fibers are majorly utilized in wound dressings, especially in hemostatic and absorbent dressings (Qin, 2008).

Starch Starch polymer mostly stands out in its tissue engineering applications in the literature.

Cellulose Apart from their tissue applications, cellulose polymers are utilized in apparel and household textiles. Also, remarkable research on its wound dressing applications has been ongoing.

8 Outlook and Trends

The progress and adoption of bio-based biodegradable man-made synthetic fibers have come a long way, resulting from the increasing awareness of environmental issues and the necessity for sustainable alternatives to conventional synthetic fibers. These fibers, originating from renewable resources such as plant materials, contribute to minimizing the textile industry's environmental impact and have an important role in the global transition toward a circular economy. The outlook for bio-based biodegradable synthetic fibers is bright, with significant growth foreseen as the demand for sustainable textiles continues to increase. Governments, industries, and consumers are more and more preferring green alternatives, which will bring about further investments in both research and development and production lines. Several forthcoming trends in the bio-based biodegradable synthetic fiber industry are anticipated to construct the industry's future. As research on bio-based, biodegradable, and bio-based biodegradable polymers including exploring alternative resources for polymers, enhancing techniques for a better mechanical characteristic of resulting fiber, developing approaches for easy spinnability of polymers, and incorporating functionalism to polymers, it is anticipated that the development of more efficient and versatile bio-based biodegradable fibers will be ongoing. These innovations will allow further broadening of their potential applications in the textile and medical fields. Because of the abovementioned developments, it would be possible to reproduce and scale up to industrial-level manufacturing of man-made bio-based and biodegradable synthetic fibers. In summary, bio-based biodegradable man-made synthetic fibers have tremendous potential to revolutionize the textile industry and build a more sustainable future. Advancements in material science and technology and consumer awareness will play a crucial role in constructing this landscape.

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Sustainable Fashion Manufacturing System in the Korean Fashion Industry

Yoon Kyung Lee

1 Introduction

The importance of sustainability cannot be overlooked in the fast-paced and constantly evolving world of fashion and apparel. As production systems rely solely on new resources, it has become imperative to consider new approaches that are more environmentally friendly. However, sustainability in the fashion industry must be established carefully due to the industry's rapid pace and emphasis on staying in touch with the latest trends. To attain this, a systematic industrial approach must be adopted. By fusing design with social innovation and embracing a continuously fluid culture, the fashion industry can sustainably maintain its dominance. Manzini (2015) highlights the significance of this approach, which is being implemented across industries, such as the Korean fashion industry. In Korea, there is an active movement to build a virtuous cycle system of environment and consumption through sustainable production and distribution processes with sustainable fashion. This study aims to introduce fashion companies (RE;CODE and OVER LAB) that successfully conduct business using a sustainable system among domestic fashion companies and analyze their sustainable manufacturing methods.

The significance of sustainable practices is recognized across industries, and the fashion industry is no exception. In Korea, the negative impacts of blind consumption and fast fashion have been acknowledged, and there is a growing movement toward sustainable production and consumption. The objective is to create a virtuous cycle that benefits both the environment and consumers. In this context, this study focuses on two Korean fashion companies, RE;CODE and OVER LAB, which have leading sustainable manufacturing practices. The goal is to analyze their

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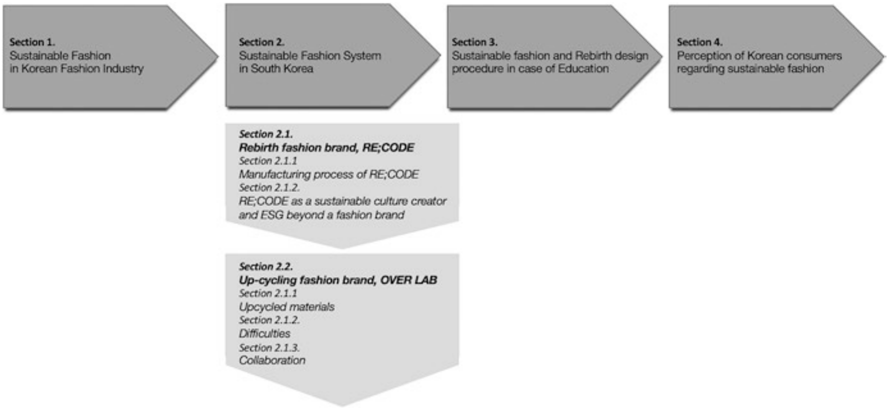

Fig. 1 A roadmap of this chapter

approaches and share information that can help other fashion companies build sustainable fashion systems for the future.

RE;CODE is a Re-Birth project that recreates unsold and returned goods into new products (Lee & DeLong, 2018a, b). It uses recycled industrial waste and sustainable materials. RE;CODE products are designed using off-the-shelf materials, patterns, and sensuous fuel. Unsold products, which are raw materials that they convert into new products, have various unresolved issues, such as delivery period, design, and last-minute sales agency, and their reckless use can damage the brand's image. Therefore, conducting design work that reuses stock products is a very sensitive and difficult task. Additionally, OVER LAB collects leisure sports materials that are discarded for safety reasons after a certain period of time but have no problems with actual use and introduces products that are created as new fashion products through a series of refining processes. The main materials of the OVER LAB are used leisure sports equipment including paragliders, tents, and yacht sails.

This study aims to provide the information necessary for fashion companies to successfully build a sustainable fashion system in the future and lay the foundation for sustainable fashion expansion (see Fig. 1).

2 Sustainable Fashion in the Korean Fashion Industry

South Korean industries are becoming increasingly aware of the importance of sustainability in social categories (Korea Institute for International Economic Policy, 2009). Among the actual domestic brands in South Korea, prices are determined based on the assumption that only one of three products will sell. Many brands pay high maintenance fees to warehouses and managers to maintain the value of their stocked products (Korea Institute for Industrial Economics and Trade, 2012). However, handling unsold and returned products is challenging because unselected products may have several unresolved issues, such as delivery period, design, and last-minute sales agency, which can damage brand image. Therefore, rebirth designs are products that were sent to headquarters because of a lack of sales and then redeveloped as new products by designers. Until this rebirth design was introduced, inventory management for Korea's leading fashion company, Kolon went through the selling process but failed to sell; therefore, it was collected, landfilled, or incinerated (see Lee & DeLong, 2018a). Rebirth design refers to a product that is in stock, released through the original distribution channel, sold to consumers, and returned to headquarters as it is not used, and then the designer redevelops it into a new product (Lee & DeLong, 2016a).

Kolon's RE;CODE is an upcycling brand that has developed and sold new designs using stock products for more than 3 years for all Kolon brands. It celebrated its tenth anniversary in 2022, owing to Kolon's sincere efforts to revive the brand, despite encountering difficulties in the early stages of the business. Recently, upcycling brands, such as RE;CODE, have steadily grown in the Korean fashion world, centering on new designers. For example, fashion accessories made from discarded sports equipment, fashion bags made from discarded firefighting suits, and fashion products made from car seats have been introduced.

3 Sustainable Fashion System in South Korea

Sustainable fashion design can be achieved through a better understanding of culture. Domestic businesses have also shown a lot of interest in sustainable fashion design. Environmental, ethical, and social concerns have a direct bearing on fashion sustainability when effort and social responsibility are required for sustainable fashion design (Black, 2013). In this context, fashion companies' efforts and active participation have a positive synergistic effect on the sustainability of the Korean fashion industry. Sustainable strategies that Korean fashion companies are attempting are extreme waste material reduction, upcycling design that recycles resources, fashion products that are created using discarded environment-friendly materials, and repair, remake, and recovery of versatility. Methods are currently being utilized to extend the lifespan of fashion products by improving their durability. The Re-Birth project being attempted by Kolon means that stocks distributed for sale to consumers through price channels are returned to the head office in an unsold state and are then newly redesigned by designers (Lee & DeLong, 2016a).

The rebirth design allows sustainable fashion products to be extended as an industrial system so that the reborn products can succeed in the production and sales stages in a form that can be continued in the life cycle through quality improvement (Lee & DeLong, 2016a). Rebirth products, according to Lee and DeLong (2016a), increased the sales rate by more than 40%. A total of 100 products were analyzed by randomly extracting the relevant products from each of Kolon's 11 brands. This is considered a de facto successful sustainable project. As shown in Table 1, they analyzed successful reverse designs at the manufacturing level with an apparel

Table 1 Rebirth design in five levels

Level		Stock 1 (sale %)	Re-Birth design 1 (sale %)	Stock2 (sale %)	Re-Birth design 2 (sale %)	Production cost recovery (%)	%	
Low	Level 1	 (22.0)	(94.6)	(85.0)	(97.9)	560.0	6.0 (*n*=6)	High Re-Birth design Frequent (91.0)
		(Re-touch) details: to changes in supplementary materials such as adding or removing decorations						
		 (52.0)	(58.5)	(7.0)	(35.7)	328.0	62.0 (*n*=62)	
		Pattern or materials: changes in patterns or materials (changes within the product)						
	Level 3	 (15.0)	(47.5)	(38.0)	(56.0)	217.0	23.0 (*n*=23)	
		Partial design: partial changes in design (leading to a new design)						
	Level 4	 (–)				-	4.0 (*n*=4)	RE;CODE (9.0)
		Other design: complete deconstruction and Re-Birth of the design						
High	Level 5	 (–)				-	5.0 (*n*=5)	
		Fashion accessories: the complete deconstruction and use of the design source for a new product that is not a garment						

Source: From Lee and DeLong (2016a)

company willing to collaborate using their unsold stock. Five levels of rebirth design were established during the process of redesigning products from a company's inventory. Rebirth level 1 involved changes in subsidiary materials or the addition or removal of embellishments. The main reason for poor sales of level 1 products may be a weak brand image or the absence of details that differentiate an existing product from other brands, which may increase the attractiveness of a product when worn. At level 2, changes in patterns or material characteristics were applied to the relevant stock items to enhance their practicality or functionality. At level 3, part of an existing design was combined with different materials to create a new design, simultaneously enhancing both its practicality and brand image. Level 4 involved completely taking the product apart and recreating it into a new design, thereby recreating stocks from different brands using the recombined designs to fit the new design concept. For example, men's suits became long vests for women, jackets were made from tent fabrics, and the back pockets of denim jeans were used in creative ways. Thus, designs have remained up-to-date despite their origin and have become unique items. Finally, rebirth level 5 was the category in which products were taken apart to be used as raw material for fashion items other than clothes; that is, a jacket became a purse, a padded jacket, or a bag. At each level, the degree of transformation increased with the skills required for the redesign process. The key point discovered in this Re-Birth project was to enhance the brand's concept and image and increase the practicality of products that fit the release period, product sales period, and consumer needs (Lee & DeLong, 2016a).

Patagonia and Freitag are the most successful international sustainable fashion brands worldwide. Patagonia collects and transforms discarded fishing nets from local fishermen off the coast of South America and turns them into recycled sports apparel products, such as NetPlus material for jacket shells, hat brims, and body fabrics in baggy shorts. Freitag bags are made of waterproof fabric and used to cover trucks that have already been touched at the time of purchase and are unclean. Therefore, even if a product is resold, it is difficult to observe significant changes to the original product. As it is an upcycled product, its value seems to endure. Thus, Freitag products are valuable. When sold, the price remains the same; however, the user can adjust the price at will. Sustainable Korean brands include RE;CODE and Over Lab. RE;CODE uses upcycling industrial waste and sustainable materials. Its products are designed using sensible fuels, unique materials, and patterns from stock products. Over Lab is discarded for safety reasons after a certain period, but it collects leisure sports materials that have no problems in actual use and undergoes a series of refining processes to introduce products that were born as new fashion products. Its focus is expanding from industry, art, and culture to sustainability and daily life. It pursues diversity beyond simple brand sales, shares technology, and disseminates methods of a sustainable virtuous cycle to society and culture. Sustainable brands in Korea are creating a sustainable virtuous cycle that goes beyond simply providing fashion-friendly products.

3.1 Rebirth Fashion Brand, RE;CODE

RE;CODE is an upcycling-based fashion brand developed by the Korean fashion company Kolon Industries FnC (hereafter Kolon FnC). RE;CODE is the most representative rebirth design among Kolon brands. "Rebirth Design" refers to the redesign of stocked products, originally released through the distribution route to be sold to consumers but returned to headquarters due to lack of use, subsequently supplemented and redeveloped by designers as new products. Upcycled products using currently stocked products have been released with actual brands RE;CODE, but a range of issues arose in commercialization as the designs were too unconventional to be worn by general consumers in everyday life, and prices were unreasonable. RE;CODE means changing the code, that is, the method. Like the name of the brand, what RE;CODE wanted to change in the first place was the temporary nature of fashion products. It entails converting the code of fashion that is temporarily used and discarded as fashion changes rapidly.

The fashion industry faced a serious problem with unsold inventory owing to trend changes. At that time, few brands thought as deeply about the environment or sustainability as they do now. RE;CODE was able to recreate new clothes from the existing stock by incorporating creative ideas from designers and artisans from various fields. RE;CODE has three lines: (1) inventory line in Fig. 2, (2) RE;NANO lines in Fig. 3, and (3) accessory line in Fig. 4.

The inventory line is a third-year inventory used by all Kolon brands. The inventory line presents designs created by integrating the specifics of existing stock, notwithstanding brand boundaries. Additionally, since the 2021 F/W season, RE;CODE has partially used recycled fabrics, such as nylon yarn extracted from waste fishing nets and inventory, and this will gradually expand in the future.

Second, the RE;NANO line is in a reasonable price range for recycling scrap and subsidiary materials left over from the production of the existing RE;CODE collection line. It is a line that offers a smart and sensuous look by partially utilizing the unique detailed elements of RE;CODE and pursues the value of zero-waste fashion within a reasonable price range.

Finally, the accessory line introduces industrial materials, such as airbags, car seats, and bags made of eco-friendly fabrics. The zero-waist bag, in which the

Fig. 2 Inventory line. (Source: RE;CODE)

Fig. 3 RE;NANO line. (Source: RE;CODE)

Fig. 4 Candy bag from the accessory line. (Source: RE;CODE)

sleeves, bodice, and hood of a jumper are created as one bag, is also a signature product of the RE;CODE.

3.1.1 Manufacturing Process of RE;CODE

Last year, in 2022, RE;CODE celebrated its tenth anniversary. It is a brand that has pursued "fashion as a social movement" as its mission for the past 10 years. RE;CODE started in 2012 with the idea of reviving the existing stock by adding a narrative in the style of a fashion company, instead of incinerating the 3-year-old inventory from around 30 brands operated by Kolon.

Han Kyung-ae, vice president of Kolon, who has observed RE;CODE's sideways movement for 10 years, said, "As a sustainable fashion brand, RE;CODE has identified problems to seek a better future from the beginning to the present, and has been steadily conducting business as a practice to solve them since the word 'sustainability' was unfamiliar to me, I have been walking down the same path for 10 years without change. From a fashion business perspective, 'sustainability' is difficult to say that simply using eco-friendly materials in the fashion industry has taken a genuine step toward the environment. Rather, it produces only what is needed and minimizes waste. Pollution and waste that occur when making new clothes must be minimized, and the clothes must be made well, so that they can be worn for a long time. To create a product with a new design, RE;CODE dismantles and recombines clothes that have already been made but are not sold and clothes that can cause additional contamination in the disposal process. This is the sustainability that RE;CODE aims to achieve." Beyond developing new products from subsidiary inventory, RE;CODE is currently searching for ways to upcycle the inventory of other brands through various brand collaborations and partnerships. Industrial materials such as discarded or defective airbags and car seats are also used. Additionally, it has taken the lead in operating repair and reform services to spread the culture of changing clothes and wearing them for extended periods.

3.1.2 RE;CODE as a Sustainable Culture Creator and ESG Beyond a Fashion Brand

RE;CODE provides repair (design repair) or reform (customized reform) services for old clothes that Box Atelier cannot discard. The Box Atelier is staffed with repair and reform experts, "Remakers," who provide services through one-on-one consultations with customers. In addition to general repairs, it provides customized upcycling services that transform old or worn-out clothes into completely new designs. Representative items include an apron created from pants, an eco bag created from a shirt, and a vest created from a sweatshirt. Additionally, RE;TABLE, a 1-day class workshop of RE;CORD, provides an upcycling experience during the exhibition period, as well as a box atelier and recollection, a repair/reform service. It propagates an upcycling culture by providing upcycling workshops and repair and reform services. It collaborates with approximately three independent designers each season.

RE;CODE organizes social activities such as Goodwill stores, Loside, and Re;light. The Goodwill store proceeds with the dismantling process of Kolon FnC products, with disabled and professional designers participating in the production process. Loside is a nonprofit arts organization that supports artistic activities for people with developmental disabilities. Re;light provides refugees with jobs and sewing training.

Collaboration projects: 2022 Wearing BTS record products and producing upcycling goods, 2022 RE;CODE by LACOSTE, 2022 RE;CODE by TOMMY JEANS, 2022 <<Re;Collective:25 Rooms>>: Exhibition commemorating the tenth anniversary of the brand launch.

At the 76th UN General Assembly held on September 20, the suits worn by BTS drew attention from all over the world. Contrary to the expectation that it would be an overseas luxury collection, it was a product of "RE;CODE," an upcycling brand created by the domestic fashion company Kolon FnC. With the concept of deconstructionism (a design that breaks away from standardized design methods and rules and creates a new form), the record, which is loved by fans, is drawing a lot of attention due to BTS. The collaboration between RE;CODE and Hive's (352820) music museum, "Hive Insight," was carried out to raise awareness regarding the value of sustainability by producing BTS stage costumes that fulfilled their purpose as upcycling goods. This collaboration product, which consists of three types of bags made from undyed industrial airbag material, is characterized by dismantling the costumes worn by BTS onstage and applying them as the patch details of the bag. All products are unique pieces, and the plan is to provide fans with special memorable souvenirs and goods that contain the value of sustainability, often known as upcycling.

Another collaborative project is the “RE;CODE by LACOSTE” collection. It was announced on the 27th that the “RE;CODE by LACOSTE” collection, in collaboration with the fashion sports brand “Lacoste,” will be released in advance. “RE;CODE by LACOSTE” is a collaborative collection with a global fashion brand that RE;CODE is working with for the third time, following Nike (2020) and Tommy Jeans (2022). In addition to displaying Kolon FnC’s inventory, the company also collaborates with major global fashion labels to continue educating consumers about RE;CODE’s distinctive deconstruction design. “RE;CODE by TOMMY JEANS (see Fig. 5)” uses the stock of Tommy Jeans T-shirts as a material and is characterized by an easier release of RE;CODE’s unique deconstructive design. Inspired by absolutist paintings that mainly express the appearance of pure geometry, it shows a relaxed and simple silhouette. Lee Do-eun, brand manager of RE;CODE, said, “This collection is the second global brand collaboration project that RE;CODE has carried out following RE;CODE by Nike, which was introduced in collaboration with Nike in 2020. The sustainable solution for fashion inventory proposed by RE;CODE is We were able to confirm that it is possible for other brands as well,” he said. “RE;CODE will do its best to promote the value of upcycling through collaboration.”

RE;CODE is an exhibition for the tenth anniversary <<RE; planning intention of collective:25 guest rooms>>. With the intention of conveying a message for a sustainable future to more people and urging them to take action, we planned an exhibition dreaming of a future with “worthy together.” The problems the world is experiencing right now are not something that can be solved alone. We must move together to practice the values of each other. In the not-too-short period of 10 years, RE;CORD breathed new life into tens of thousands of pieces of inventory and

Fig. 5 Collaboration bags with RE;CODE by NIKE and TOMMY JEANS and from accessory line. (Source: From RE;CODE)

collaborated dozens of times with many partners who pursued sustainability together with us. Just as RE;CORD fashions a better world through clothes, people who promote sustainability in their respective fields expressed sympathy and participated in the exhibition. In the exhibition, works created in collaboration with companies, brands, and creators, as well as record archives were presented.

RE;CORD has attempted to collaborate with many independent designers, artists, brands, and companies and has pursued the creation of a community that grows together through employment creation. It aimed to enhance the sustainability of society by carrying out various support activities such as education for the socially underprivileged, including single mothers, North Korean defectors, and refugees. Sustainability is not limited to the environment. RE;CORD is pursuing the value of "together" by considering the impact at the social level among the ESG concepts, which are a management form essential for many companies to pursue.

3.2 Upcycling Fashion Brand, OVER LAB

Over Lab is a sustainable design laboratory and an upcycling fashion brand that contemplates the creation of the next batch of leisure sports products that have reached the end of their life cycle. Owing to the expansion of the sports market, equipment and toys are being destroyed rather than recycled, thereby threatening the environment. Over Lab builds a virtuous cycle that protects the environment and consumers by upcycling end-of-life leisure sports equipment into fashion items. In the last lab, after a certain period, the abdomen for safety reasons was over, and leisure sports objects that had no problems with long-term practical use were collected and created as new products through a series of washing and manufacturing processes. Products such as paragliders, glamping tents, and yacht sails that have been discarded for safety reasons after a certain period but have no problems in practical use are collected, dismantled, washed, cut, and sewn to create new products.

Representative Park Jeong-sil, a record designer, launched Over Lab, an upcycling leisure product in 2019, after working at RE;CORD of Kolon for 7 years. He said that the brand launch was not planned from the beginning. While engaging in paragliding, he learned about the process of paragliders being discarded after being used and began thinking about ways to reuse them. At present, Over Lab uses leisure sports equipment, such as paragliders, tents, and yacht sails. Over Lab thinks beyond the lifetime of the product and dreams of a "Design Laboratory" based on sustainability.

3.2.1 Upcycled Materials

Over Lab materials are environment-friendly materials based on recycling. For example, a paraglider that flew in the sky for 2 years, a tent that faced wind and rain for 4 years, and a yacht sail that was used for 10 years were the main materials of Over Lab. Over Lab tackles the realistic problem of leisure sports equipment waste hidden behind the boom in the leisure sports market, recognizes the problem of equipment waste that has been overlooked, shares Over Lab's point of view, and proposes an alternative. Over Lab's products are fashion items that utilize the advantages of highly functional leisure sports equipment. All of Over Lab's products incorporate the unique functionalities of leisure sports equipment. Unique materials such as "paraglider," "glamping tent," and "yacht sail" are newly created as products containing the identity of Over Lab. Over Lab utilizes three categories of materials: (1) UV protection, lightweight, water repellent, quick drying, durable; (2) lightweight, water repellent, durable, windproof; and (3) lightweight, water repellent, durability, windproof, which upcycling materials go through the process of disassembly → washing → cutting → sewing → inspection → exploration (see Fig. 6 and Table 2).

3.2.2 Difficulties

The greatest difficulty in upcycling fashion brands lies in the supply of materials. Particularly, because upcycling fashion brands use recycled materials, the materials that can be supplied are limited, and there are few solutions for the situation when the order volume suddenly increases, or a large quantity needs to be processed.

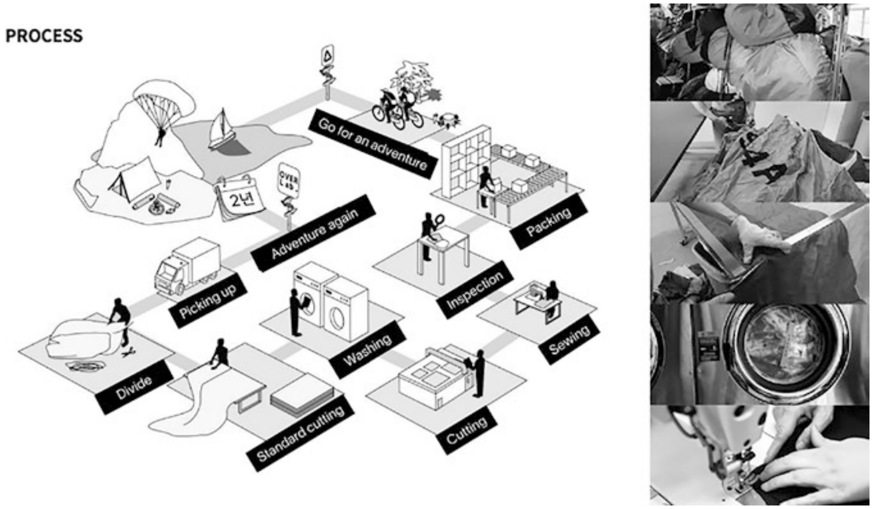

Fig. 6 Upcycling manufacturing process of Over Lab. (Source: From Over Lab)

Table 2 Over Lab brand categories

Upcycled material	Products
[*Another High*] *Object*: Paragliding *Material*: Canopy *Characteristics*: Lightweight and robustness *Color*: Various	
[*Another Mountain*] *Object*: Glamping *Material*: Tent *Characteristics*: Rugged waterproof windproof *Color*: Beige	
[*Another Wave*] *Object*: yacht sailing *Material*: Yacht sailing(sail) *Characteristics*: Firmness, water repellency *Color*: White and other	

Source: From Over Lab

Additionally, because recycled materials must be used, the collected materials are not clean, or materials with the same quality or physical properties cannot be uniformly supplied. Given that the non-uniformity of these materials affects the manufacturing process, it is not easy to maintain uniform quality every time.

In the case of Over Lab, the supply and demand for materials and preparations for regularly produced quantities are achieving some stability. The parts of the material preparation process that received the greatest attention were cleaning and subdividing the degree of contamination. One of the main challenges that Over Lab faces is maintaining the same product quality every time. Given that the material for upcycling leisure goods differs from brand to brand, and the equipment is not the same each time, flexible responses must be provided according to each situation. Even in the production process, problems that arise are different, depending on the thickness of the material, color match, and the limited quantity of the preferred color.

Regarding these characteristics, the CEO of Over Lab explained that upcycled products are very different from the production methods of general fashion products.

Additionally, Over Lab explained that the solution to this problem is matching communication and breathing with consumers. In the case of Over Lab, she explained that he was looking for solutions to the problems of material supply, demand, and product quality by communicating with consumers. We drew consumer sympathy by meticulously checking the purchase feedback of consumers unfamiliar with upcycling fashion products and providing product usage reviews and consumer

Fig. 7 Over Lab × LocknLock

Fig. 8 Over Lab × LG Chem

consultations. Through this, the special situation of upcycled products went through the process of understanding and consent from consumers, and finally, consumers repurchased. These courses were used as opportunities to show customers that the Over Lab brand has value beyond merely selling products. Through the process of the brand and its customers aligning themselves with the steps toward a sustainable society, the philosophy of a sustainable society pursued by the brand was shared with consumers and achieved together. Over Lab presents a solution to the irony of leisure sports, in which consumers, suppliers, and producers create a virtuous cycle, harmonizing with nature and destroying the environment. Over Lab hopes that consumers will continue to have a dynamic and enjoyable activity experience while using Over Lab products and wants to instill consumers with the perception that eco-friendliness and upcycling are not difficult, but enjoyable.

3.2.3 Collaboration

Korea's upcycled fashion brands are relatively small, and new brands are centered on young designers. Their new ideas and their collaboration with mid-sized, long-lived brands create various derivative effects. Over Lab collaborates with various companies. More than 50 companies have collaborated with Over Lab, including Lock&Lock (Fig. 7), Seoul Tourism Organization, LG Chem (Fig. 8), Innisfree Gwanghwamun Team (Fig. 9), KT, Tony Moly, Bear Better, Volvo, Strad Vision, Battleground, Yanolja, Volvo, Lotte Chemical, Nike-Trash Lab, Jeju Convention, and Air Busan. Companies in various industries that support Over Lab's brand philosophy have experienced overlapping fresh and positive influences on their corporate image through collaboration with Over Lab.

Fig. 9 Over Lab × Innisfree

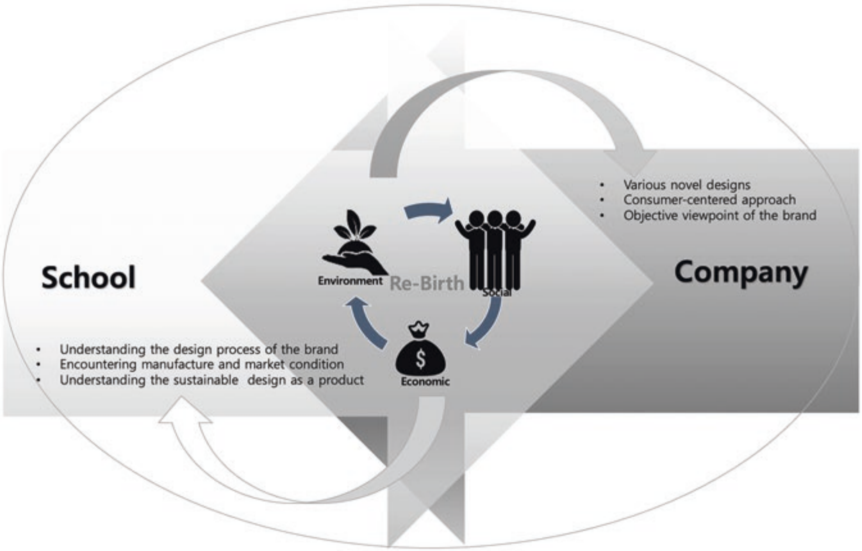

Fig. 10 Collaboration work between company and school with sustainability project. (Source: From Lee and DeLong (2018a))

4 Sustainable Fashion and Rebirth Design Procedure in Case of Education

The fashion industry, which is fast-paced and continuously evolving, is not exempt from the social demand for sustainability. Apparel production systems that previously relied solely on new resources have reached a point where further consideration is required. One product's life cycle can be related to a new product's life cycle, which ultimately means producing clothes that will never become waste prematurely. Instead, unused products become the motivation for new, high-quality products. In this sense, the quality of a product includes its vibrant contribution to nature, individuals, communities, and the economy. Thus, industrial systems can help restore nature and culture (Kaiser, 2015).

The rebirth project is sustainable because it offers mechanical and environmental benefits to schools and companies (see Fig. 10). A rebirth design study by Lee and

DeLong (2018a), conducted as collaborative design work between a fashion school and fashion company, applied a design process model (Lee & DeLong, 2016b) involving (1) pre-design, (2) design development, and (3) design evaluation for rebirth design development. After learning the proper methods for examining resources and the rudiments of collaborative product design with a company, students individually researched rebirth design opportunities. They participated in a rebirth design process involving collaborative design work between the company and studio classes. In the rebirth design project, Lee and DeLong (2018a) in Table 3 suggested that students participate in the rebirth design process by developing creative ideas and designing developmental models for sustainable design in their actual design classes. This helped design students understand consumer needs and the concepts and distribution processes of relevant brands through collaborative work with fashion companies (Lee & DeLong, 2018a).

Through the analysis of stock items, we were able to understand users' product evaluations and brands' inveterate issues, which were then reflected in the rebirth designs. This helped design students understand consumer needs and the concepts and distribution processes of relevant brands through collaborative work with fashion companies. For instance, a rebirth design should consider the user's perspective more than the designer's unique concepts. Most stock items had problems with the practical aspects of their use. This occurs when misunderstandings arise from the users' perspectives and/or different viewpoints between designers and consumers. Lee and DeLong (2018a) stated that the lowest cost recovery is a significant factor in rebirth design production because rebirth products do not sell at a lower price. Hence, one essential requirement of rebirth designs is to have attractive design features to increase customers' interest in the product through small design changes.

During the rebirth design process, stock items that had been released as fall/winter products were altered and rereleased as spring/summer products. When the product design factors and target consumers of the brand were considered, rebirth had a positive effect on sales when the products were manufactured and sold. The design was refined to the lowest rebirth level to reduce cost recovery; however, a study by Lee and DeLong (2016a) explored all levels of rebirth designs produced for resale by redesigning products, reusing existing resources, reducing energy consumption, and increasing environmental and economic efficiency.

5 Perception of Korean Consumers Regarding Sustainable Fashion

Consumers or users need to be educated on the growing need for sustainability for them to understand the value of high-quality consumer goods, to create a closer relationship between consumers and products that are limited in quantity, and for the user/wearer to learn the art of assembling a fashionable look. In a study by Janigo et al. (2017), women's clothing upcycling behavior was explored through

Table 3 Rebirth design procedure in fashion studio class

Pre-design			Design development		Design evaluation
Problem acceptance	Primary idea driving	Preliminary design analysis	Refining design	Compounded design development	Exhibition sale
Received stock	Research custom interview	Brainstorming idea exploring	Idea development design modification	Design selection manufacture	Design feedback
Stock 1  Stock 2  Stock 3  Stock 4  Stock 5 	-Selected stock for Re-Birth design  -Brand research series: urban generation -Problem analysis of required products  -Re-Birth design solution 	Image 1  Image 2  Image 3  Image 4 	Re-Birth Design 1  Re-Birth Design 2  Re-Birth Design 3  Re-Birth Design 4  Re-Birth Design 5  Re-Birth Design 6 	-Final complete Re-Birth design 	-Design feedback from brand designers -Showcasing design to consumers in the market

Source: From Lee and DeLong (2018a)

questionnaires, interviews, and visual analysis and was categorized according to the level or degree of upcycling encountered. Three categories were developed based on the amount and degree of difficulty of the women's upcycling experiences: upcycling consumers, upcycling enthusiasts, and upcycling professionals.

The fashion industry follows trends and directions derived from abstract notions of target markets and reports of what target consumers have purchased in the past, along with projections regarding their future purchases (Hethorn, 2015). However, as part of the design process, it is critical to penetrate the mindsets of individual consumers. Consumers are accustomed to shopping based on categories, and doing so helps them locate desired items while simultaneously helping retailers maintain an organized system (Hethorn, 2015). To create sustainable outcomes, we must begin by critiquing how design is accomplished and how design practices best serve consumers.

Design thinking is a framework for a human-centered approach to strategic innovation and a new management paradigm for value creation in a world of radically changing networks and disruptive technologies. Another study focused on whether there is enough demand to make a one-on-one upcycling of a service with consumers co-designing a garment with an expert's aid (Janigo & Wu, 2015). Participants' ideas were collected through brainstorming, designs were sketched and refined, and garments were created, often from clothing in their own wardrobes. Although the participants were mostly satisfied with the outcome, they were unwilling to pay a premium for the service.

Sustainable clothing behavior and extended clothing use vary according to the cultural characteristics of each country. Accordingly, training and learning are needed regarding the wearing of sustainable clothing that is suited to each country's characteristics (DeLong et al., 2016). In particular, in the case of Korean consumers, the frequency of using second-hand clothing stores was low; however, in the case of children's clothing, the frequency of inheriting and wearing other people's clothes was high (DeLong et al., 2016; Lee, 2019). Lee (2022) also stated that, for a sustainable fashion brand to successfully establish itself in the market, it should be able to provide consumers with the company's value standards and the process of manufacturing products based on fairness and ethics. In addition, Korean consumers must be provided with valid narratives to convince them to buy these products. Korean consumers want to buy a story about a product, not just the product itself. Furthermore, they want to demonstrate that they possess an eye that recognizes such virtuous products and the value required to own such products. Korean consumers who love sustainable products tend to make decisions based on their knowledge and information (Lee, 2022).

According to a study on Korean consumers in their 20s by Lee and DeLong (2022), a positive second-hand purchase experience is an effective means of influencing changes in the perception of sustainable clothing behavior. After the experience, all participants noted that they would continue to wear second-hand clothing and practice sustainable behaviors. Korean consumers who had positive perceptions of the limited availability of size, style, quality, and season when purchasing used clothing were creative in finding ways to successfully integrate used clothing into existing wardrobes and looks. Thus, when there are few clothes to choose from, the wearer can consider how to wear them and create as many styles as possible.

This enables access to the full potential of an item. It is difficult for people who have sufficient clothes to experience this possibility. A situation in which problems must be solved within limited resources induces more focus on the situation at hand, and flexible creative thinking that goes beyond the limited scope will be the key to moving toward a sustainable society.

6 Conclusion

This study aims to provide insights into sustainable design in the fashion industry and the inventory issues emerging in the market. By providing examples of practicing sustainability in the Korean fashion industry, we suggest a future-oriented direction for the sustainable fashion industry through examples of sustainable fashion brands that address the cultural distinctiveness of Korean consumers and make various attempts to address them. In particular, it is important to supply fashion products that consider the timely, cultural, and regional characteristics. Creating a market that is closer to consumer needs by providing the right products at the right time is the first step toward leading a sustainable fashion industry. Thus, a more effective solution can be obtained. In other words, focusing on quality rather than quantity of products can be the key to sustaining the fashion industry.

To practice sustainable fashion from the perspective of consumers and users, education on the value of high-quality consumer goods and education to understand sustainable fashion products must go hand in hand. Regarding sustainable clothing, clothing upcycling, and recycling, there is a need to increase clothing and consumer affinities. In addition, by teaching users/wearers the skills regarding assembling fashionable looks, various opportunities are required to develop a new perspective from which new things can emerge.

This study provides companies and consumers' perspectives on the information necessary for fashion companies to successfully build sustainable fashion systems in the future. We provide a new perspective on a systematic approach to creating a sustainable Korean fashion industry. Thus, this study contributes to providing the information necessary for fashion companies to successfully build a sustainable fashion system in the future and establish a foundation for such a system.

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Recycling Practices of Pre-Consumer Waste Generated from Textile Industry

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1 Introduction

The textile and fashion industry faces criticism from governments, non-government organizations (NGOs), environmental pressure groups, and other stakeholders around the world due to the rapid depletion of resources (to produce cotton, synthetic fibers, and other fibers), dramatic environmental pollution (e.g., water pollution, microplastic pollution, landfill hazards, and openly dumped litters), and lack of employee well-being. It is a complex manufacturing and retail supply chain going through a sustainable transformation phase of late. Sustainable manufacturing in textile and fashion is a relatively new area of research (Mishra et al., 2020). While textile processing was, and still is, environmentally hazardous in most manufacturing countries (Uddin, 2019), also the fashion industry (post-textile garment manufacturing and distribution) is labor-intensive and prone to human compliance issues

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(Anguelov, 2015). Almost all textile and garment manufacturing industries are based in developing countries such as China, Bangladesh, Vietnam, Turkey, India, Indonesia, and Cambodia, and many are still lagging in economic and human development. Hence, the textile and apparel industry has long been operated in an unsustainable manner. However, as the environment started taking its toll and the community became more concerned about compliance issues, sustainable practices began to take place in the textile and fashion industry, mainly in the last decade (Patwary, 2020). The circular economy is suggested as an effective approach for driving sustainable development by transforming the linear economy of take–make–dispose to a circular one by facilitating the reusing and recycling of materials and reducing waste (Skvarciany et al., 2021). For sustainable manufacturing practices in the textile and fashion industry, the circular economy has the potential to drastically reduce material waste and virgin material use. Material waste in the textile supply chain is a major environmental and economic issue. Empirical research done by Khairul Akter et al. (2022) showed that a typical cotton textile production chain generates a total of 126.4 kg of material waste on average in the subsequent production processes (spinning, weaving/knitting, dyeing–printing–finishing, and apparel manufacturing) for every 100 kg of fiber processing in each stage. A large portion of these material wastes are traded through the informal (undercover) market, and the rest ends up in open dumps (or, in a few cases, in landfills), causing different environmental problems. Bangladesh, the second largest apparel producer after China, generates approximately 577,000 tons of such post-industrial textile waste every year (Pavarini, 2021). China is expected to produce more than 100 million tons of pre-consumer textile waste yearly, one of the major contributors to environmental and human health problems there (Li et al., 2021). The circular economy can reduce the environmental loads from textile waste and potentially cease the materials going to the informal market and redirect wastes from the landfills (and open dumps) to increase value addition. However, implementing circularity in the textile supply chain is difficult due to its long production chain, supplier network, and technical complications (Kazancoglu et al., 2020). Recycling of the excess materials from production and unavoidable process leftovers (yarn leftovers and fabric leftovers) in the textile production chain is needed to implement circularity (Leal Filho et al., 2019).

This chapter is composed in a way to educate the readers about the concept of recycling, and recycling of textile materials, followed by case studies from Bangladesh's textile industry. Details of the solid waste generation from the textile–apparel manufacturing process and scopes of recycling textile materials are depicted. The three case studies have information drawn from real-time observations of the authors in three textile factories in Bangladesh. A complete process of transformation of *waste to recycled fiber* and *recycled fiber to recycled yarn* is covered. A discussion on circular economy in the textile supply chain is followed to impart complete knowledge on sustainable manufacturing in textile and fashion.

2 Concept of Recycling

Recycling is the third component of the most extensively used waste prevention hierarchy—the 3R: Reduce, Reuse, and Recycle. In Layman's terms, it is the process of converting waste into reusable material. The fundamental difference between reusing and recycling is that there is an additional processing or action needed for the conversion of the waste materials into something reusable. Though it sounds simple, recycling is complicated. How recycling is defined has an impact on the recycling outcomes. Scrutinizing different definitions of recycling given by different relevant bodies reveal interesting point of views.

The US Environmental Protection Agency (EPA)[1] defines, "recycling is the process of collecting and processing materials (that would otherwise be thrown away as trash) and remanufacturing them into new products." They identify three essential steps in recycling: (i) Collection, (ii) Processing, and (iii) Remanufacturing. The Waste Framework Directive of the European Commission[2] defines, "any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes." Here, the recycling process is defined as a recovery operation. This definition provides additional information that the recovered and/or reprocessed products or materials can also be used for other than the original purposes. The Solid Waste Association of North America (SWANA)[3] defines, "recycling is the collection, sorting, marketing, processing, and transforming or remanufacturing of recyclable materials into recycled materials and recycled products, including marketing thereof; and the purchase and use of recycled products." SWANA provides a more holistic definition with the idea of identifying recyclable materials, transforming recyclable materials into recycled materials leading to the processing of recycled products and the marketing of both recyclable materials and recycled products. The new dimension in this definition is the inclusion of the marketing of both recyclable materials and recycled products. It provides the notion that recycling cannot be successful if it does not make economic sense. Another notable definition can be mentioned given by Frank Ackerman (1997) in his book "recycling is an impressively pure form of altruism, a widespread commitment to the greater good/participation in recycling is, in addition to its more literal purposes, a ritual of environmental belief." He says that recycling is a behavior, a philanthropic act. Firm belief in environmental concerns drives participation in recycling.

The implication of the recycling definitions can be found in different research works, such as the idea of the two primary forms of recycling operations: internal and external recycling. Internal recycling involves reusing waste materials generated during a manufacturing process within the same process. This can include scrap materials, excess or leftover materials, and waste products. Waste materials from internal sources in many cases are unavoidable. On the other hand, external

[1] https://www.epa.gov/recyclingstrategy/us-recycling-system

[2] https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en

[3] https://community.swana.org/communities/community-home/librarydocuments/viewdocument

recycling involves the collection and processing of waste materials outside of the original manufacturing process. These materials are then transformed into new products, which may or may not be related to the original manufacturing process. An example of external recycling is the collection of old newspapers and magazines for re-pulping and their manufacture into new paper products or the collection of post-consumer textiles and recycling them back to produce fibers for remanufacturing new textile goods. Hence, it is understandable that internal recycling is the recycling of materials generated as waste in the internal industrial manufacturing system, i.e., the recycling of pre-consumer waste, whereas external recycling is the recycling of materials after collecting them from consumers who throw them out after the end of their use. An identification and quantification of the internal recyclable materials in textile–apparel manufacturing is shown by Khairul Akter et al. (2022) in their research. Kim and Jeong (2016) designed a closed-loop supply chain model for photovoltaic system manufacturing with internal recycling of materials from solar panel manufacturing plants. Zhao et al. (2017) showed how to utilize converter steel slag in internal recycling in steel industries.

Another aspect of recycling, as stressed by SWANA, is the commercialization of recyclable materials and recycled products. The role of a functional recycling sector is emphasized by many researchers and practitioners. Without adequate recycling infrastructure, policy, and market opportunities, recycling programs tend to become inefficient and ineffective. The collection of recyclable materials depends on the collection infrastructure. A well-designed infrastructure can ensure that recyclable materials are collected efficiently and sorted properly, resulting in a higher percentage of materials being recycled. It requires a separate business sector to handle collection, process, and market or distribute recycled products. Recycling infrastructure and trading of recycled products create thousands of jobs. Unfortunately, if there is no proper infrastructure in place, wastes are traded through the informal market channel, especially in developing countries. In Indonesia, one in every thousand people is found to work in the informal waste recycling and trading sector (Sembiring & Nitivattananon, 2010). More than 50 million people meet their livelihoods working in the "jhut" (textile waste) market in Bangladesh (Hamidul Bari et al., 2017).

Finally, according to Ackerman's definition, recycling is a philanthropic activity, stressing the need for environmental awareness as a driving factor for recycling. It involves individuals and communities taking action to protect the environment and improve the well-being of others. By participating in recycling, one can feel pride in diverting waste from landfills, conserving natural resources, and reducing pollution. Apart from environmental benefits, recycling also has economic and social benefits. It creates jobs providing livelihood to millions of people all over the world. Recycling involves community engagement and education, which can help build a sense of community and encourage people to work together toward a common goal. The development of community awareness and practices is highly stressed by the United Nations to achieve the Sustainable Development Goals (SDG) (Gui, 2020). As a part of sustainable practices, many industries are emphasizing on recycling. The textile and apparel industry has a great recycling scope due to the huge amount of material waste in the production process.

3 Recycling of Textile Materials

Textile and apparel production is a long and complicated chain of processes generating different types of materials as waste. The feed material is fiber: cotton, wool, hemp, etc., are natural fibers, and polyester (PET), nylon, acrylic, etc., are man-made or synthetic fibers. The use of man-made cellulosic fibers such as viscose-rayon, and lyocell is on the rise. The major fibers used in textile production in 2019 were PET (52%) and cotton (23%) followed by rayon and wool (14%) clearly indicating the dominance of synthetic fibers (Textile Exchange, 2020). The fiber content in clothing can be 100% cotton, 100% PET (or other synthetic fiber), or mixed like a 65/35 CVC blend (chief value of cotton—a popular blend with 65% cotton and 35% PET). Fiber-to-fiber recycling of both cotton and PET textile waste is already developed and in operation in many recycling facilities (Ruuth et al., 2022). However, for blended fiber materials, it is still a challenge to recycle. Technologies to separate the synthetic part from the cotton (or cellulosic) part are developed but still have scalability challenges (Matayeva & Biller, 2022). This chapter discusses textile waste generation, recycling scopes, technologies, and challenges for the circular economy (Fig. 1).

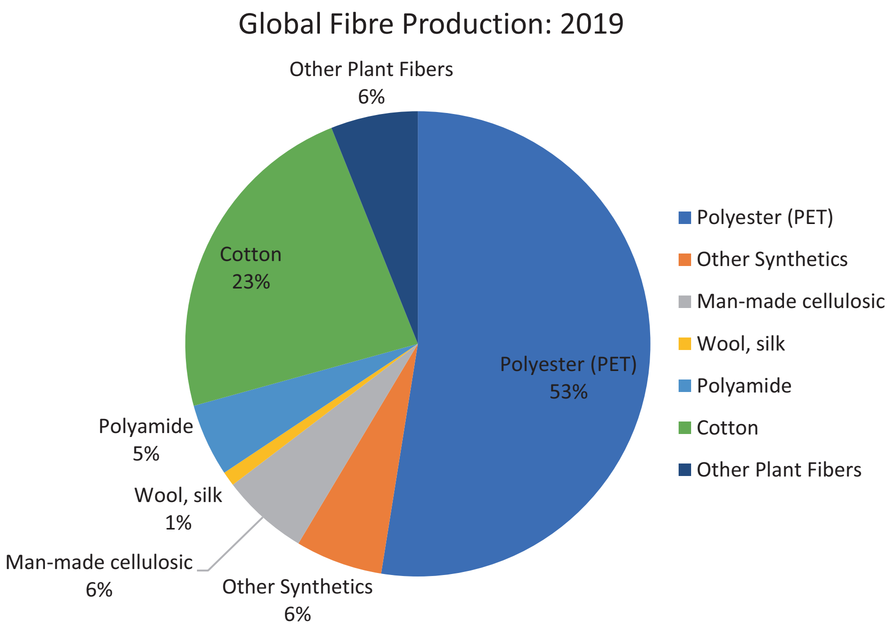

Fig. 1 Global fiber production, 2019 (Textile Exchange, 2020)

3.1 Textile Waste Generation and Recycling Scopes

Textile wastes are generated in the form of fiber, yarn, and fabric from subsequent production processes. Due to incomplete reporting, data on the amount of pre-consumer waste generated from the textile–apparel industry are sparse. However, an indication from the MacAurther Foundation (2017) can be obtained that reports 53 million tons of total fiber consumption in the global textile industry in 2015 of which only 1% was recycled. The textile–apparel production chain consists of at least four processing stages:

- Spinning: It is the yarn manufacturing process that turns cotton into cotton yarns. Spinning is a five-stage engineering process that comprises the blowroom, carding, drawing, combing, and ring section. Cotton is cleaned, stretched, and twisted in the subsequent stages turning it into a continuous web of yarn. The higher the average staple length of cotton is, the higher the quality of the yarn is possible. PET or other polymer-based fibers are manufactured in a different spinning process: wet spinning or melt spinning. Polymer chips are melted and extruded through spinnerets giving them a continuous filament form.
- Weaving/knitting: This is the fabric manufacturing stage. Weaving and knitting are two completely different production processes. Weaving looms are used to interlace two sets of yarn in different orientations resulting in different constructions of woven fabrics. Denim is one of the highest-produced woven fabrics where one set of white yarn is interlaced with another set of indigo-dyed blue yarns in a 2/1 twill construction. Knit fabric, on the other hand, is produced with circular knitting machines where only one set of yarn is turned into fabric form through inter-looping. Due to the inter-looping structure, the yarns are loosely connected resulting in elastic properties in the fabric. Due to its dimensional instability, the production of knitted fabrics is measured in weight units, whereas woven fabric is measured in length units.
- Dyeing–printing–finishing: This stage is termed wet processing as the greige knit or woven fabric from the previous stage is treated with required chemicals, regents, and dyes to impart desired color, properties, and hand-feel. The wet processing stage is the most energy- and water-intensive process and creates the most environmental hazards in the form of effluents. As a result, there is a growing need for sustainable and eco-friendly practices in the textile dyeing and printing industry.
- Apparel manufacturing: This is the final stage that involves assembling finished fabric into apparel. Apparel manufacturing consists of the cutting, patternmaking, sewing, and finishing process. Cut-fabric waste from the cutting section is one of the biggest sources of textile solid waste. Excess production (stock lots), unused fabric, and leftovers from the sewing section are the other sources of wastes.

The schematic of solid waste from the textile–apparel production chain and recycling is illustrated in Fig. 2.

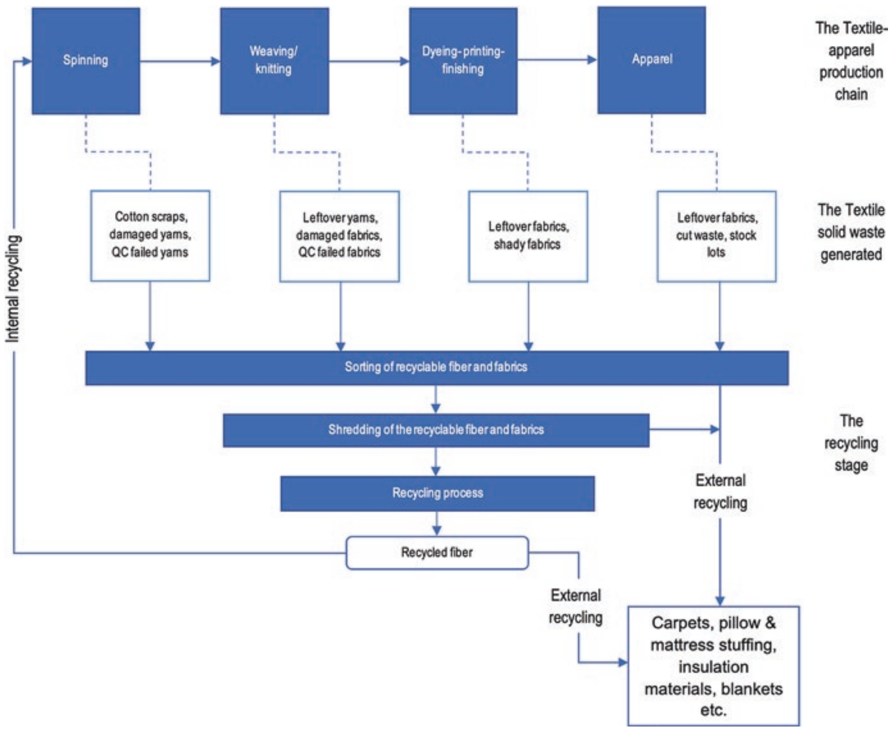

Fig. 2 Schematic of waste from textile–apparel production chain and recycling. (Author generated)

The illustration represents the cotton textile waste recycling process in the textile–apparel production chain. The solid wastes generated from the subsequent processes are fibers and fabrics that are damaged, rejected by the quality control team, or excess to the production need. Fabrics that fail the color requirement tests during the dyeing process are termed shady fabrics. Cutting waste from the apparel manufacturing stage is the largest source of fabric waste. The stock lots are the extra development samples and additional production outputs. The recycling stage starts with the sorting of the recyclable fiber and fabrics. Recyclable materials are sorted according to color, pre-treatment used, and quality. After sorting and shredding of the right quality of material, it is processed through a mechanical recycling system and eventually re-fed to the spinning system to make recycled yarn. However, the mechanical recycling process shortens the staple length of the recycled cotton fibers which creates non-uniformity (Ütebay et al., 2019). Hence, recycled cotton has limitations for making finer count yarns. Recycled cotton is generally used to produce coarser count yarns that are mostly used in denim production. Finer count yarns can be produced from recycled cotton after mixing it with new cotton fiber as per count requirement. The internal recycling system of using waste material generated from the production stages as the feed material of the same production line is an effective way of closing the material loop in textile production. However, pertaining to the loss of properties in cotton due to the mechanical recycling process, not all materials can be reused in the production system. Those inferior quality materials are downcycled (external recycling) to make inferior quality products such as materials for carpets, stuffing for pillows and mattresses, blankets, and insulation materials.

3.2 Technologies and Challenges

Recycling of cotton-made fabrics is a mechanical process. It is reported that the quality of recycled cotton depends on the type of waste and its origin, and the degradation of resultant apparel made from recycled fiber. However, studies on the properties of recycled fiber are limited only to yarn production, and more studies are required on how it affects the apparel quality (Ütebay et al., 2019). The quality of shredded fibers derived from waste materials is dependent on the inherent structure of the waste and the applied finishing processes. In the context of cotton recycling, a significant challenge pertains to the relatively inferior quality of the resulting fibers. Consequently, it is critical to identify the key parameters that influence the quality of the recycled fibers. To achieve superior clothing made from recycled fibers, an understanding of the impact of waste properties on recycled fibers is essential. The mechanical recycling technology of cotton textiles is in operation in most textile-producing countries such as China, Bangladesh, and the European Union. Though there are technological challenges, internal recycling of cotton textile waste is a big step toward a circular economy in textile production.

Recycling of polymer-based fibers or polymers (plastic waste) is a highly studied area of research. PET accounts for 8% by weight and 12% by volume of global solid waste, and the textile industry is one of the largest users of PET fibers (Atta et al., 2006). Data on pre-consumer PET textile waste are limited. However, as PET is the dominant fiber used in the textile industry, it can be inferred that most solid waste generated from apparel factories is PET or PET mixed with cotton fiber. Notably, 100% polyester textiles are technically plastic products, and recycling involves converting PET to its monomers. PET can be recycled practically by mechanical, thermal, and chemical recycling methods, of which chemical recycling (chemolysis) is the most successful method (George & Kurian, 2014). Recycled PET does not have quality issues like recycled cotton, as they are converted to its constituent monomers or oligomers. Hence, 100% internal recycling of PET is possible, and textiles are extensively produced from recycled PET bottles (Majumdar et al., 2020).

Furthermore, the scope of external upcycling of PET is higher than that of cotton, as plastics have diverse applications (Leonas, 2017). However, the challenge still prevails for mixed fiber textiles. Multifiber apparels are outnumbering mono-fiber ones due to their better properties and economic benefits, creating a big problem for recycling. The practice is to hand-sort the blended garments into recyclable categories such as white cotton, colored cotton, or polyester fabric (Ishfaq, 2015). An advanced sorting technology like Fibersort claims to sort textiles based on composition (e.g., wool, cotton, nylon, and PET) and even color but can only process mono materials (Harmsen et al., 2021). The latest innovation in separating cotton and polyester from textiles is the enzyme-based solution. A "cocktail" of enzymes in a mildly acidic solution is used to chop up cellulose in cotton, thereby separating components (Egan et al., 2023). However, such technology is still developing and requires further innovations to deploy it in an industry-level operation. Though challenges pertain, recycling textile solid waste is essential to developing a circular economy in the textile–apparel supply chain.

4 Opportunities of Recycling in Bangladesh Context

Bangladesh is a major textile and apparel manufacturing nation and the second-largest exporter of ready-made garments globally (Swazan & Das, 2022). Over 5000 apparel companies in Bangladesh employ more than four million people, and the RMG sector has emerged as the country's leading industry, contributing more than 10% of its GDP (Islam, 2021). According to the Bangladesh Textile Mills Association, there are 433 yarn manufacturing mills, 828 fabric manufacturing factories, and 251 dyeing–printing–finishing mills in Bangladesh (BTMA, 2020). Although the growth of the textile sector has significantly boosted the Bangladeshi economy, growing textile solid waste is causing alarming environmental impacts (Shamsuzzaman et al., 2023). Due to the huge amount of waste generated as a byproduct of textile production, Bangladesh also becomes a key player in the textile waste recycling industry (Saha et al., 2021). Only in the Narayonganj area (one of Bangladesh's prime locations of apparel industries), 120–125 tons of apparel waste is generated daily (Alom, 2016). Apparel factories produce waste as selvages, end-of-roll wastes, broken materials, and partially finished or finished apparel from design to bulk production in those factories. Determining the amounts and fiber composition of this waste is the prerequisite to utilizing it through recycling to develop new products for clothing, furniture, vehicle, filtering, mattress, paper, and other sectors (Dobilaite et al., 2017). Cotton yarn is the main raw material used in Bangladesh to produce knitted and woven fabrics in the knitting and weaving industry (Guha & Sadi, 2016). These factories generate unfinished fabrics, scrap yarn, and fly fiber material wastes as a byproduct of different stages of weaving or knitting. The dyeing, printing, and finishing industry produces rejected color fabric and excess finished fabric as material waste (Khairul Akter et al., 2022). An average apparel factory in Bangladesh can generate 250–300 kg of production leftover daily as waste, costing 0.1–3 USD per kg, depending on the quality and size of the waste (Islam & Khan, 2021). Bangladesh has a considerable underground market that deals with "Stock lot" (excess inventory apparel) and "*Jhut*" (leftover yarn, fabric, and cutting waste). Using unofficial practices, the traders purchase cutting waste or stock lots from the clothing manufacturers often twice a year, in January/February and October/November. The types of waste vary periodically and follow the local business's product category, much like the fashion trend and market need. Although it is an informal business, this market provides a good model of circularity. Figure 3 shows the traceability of Bangladesh's post-industrial textile and apparel waste. "Waste" generated from the export-oriented factories becomes the primary source of raw materials for the informal local apparel factories that make cheaper clothing for the domestic market. Moreover, the underground marketing of the *jhut* contributes to reducing the apparent environmental effect of textile waste (Khairul Akter et al., 2022).

In the context of a cotton spinning mill, it generates blowroom droppings, like in waste fiber, flat strips, carding waste, comber noil, sweeping wastes, hard waste, roving ends, rejected yarn, excess production, gutter fly, and micro dust waste in various processing stages, and they are highly heterogeneous. The cellulose content of cotton wastes varies significantly based on its geography and the processes from where it has been obtained. For example, cotton linter waste contains 99% cellulose content (Ranjithkumar et al., 2022). The spinning mill's waste is separated into two categories: soft and hard waste. "Soft waste" refers to fibrous waste produced from carding to the speed frame. Hard waste is defined as waste that cannot be reused. This waste is generated in the winding and ring frame departments. This spinning waste can be converted into value-added products by reclaiming fiber from soft wastes or yarn and mechanically recycling it into open-end yarn. Even fiber from yarn waste has better uniformity percentage and tensile strength than recycled fiber from rags (waste of weaving). The authors suggest that this recycled yarn can be used to produce higher-quality textile items such as denim and chino cloth for towels and pants (Jamshaid et al., 2021). Like cotton, polyester, wool, silk, and other

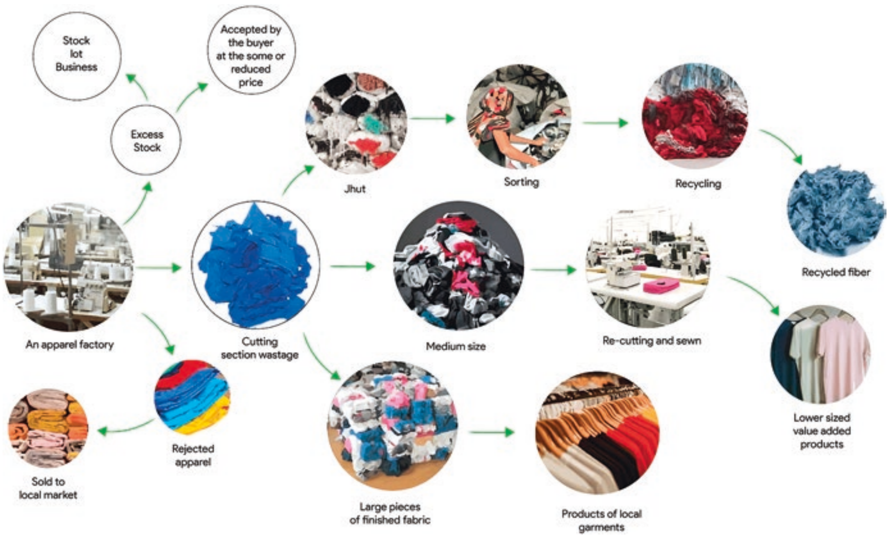

Fig. 3 Traceability of post-industrial textile and apparel waste in Bangladesh (Khairul Akter et al., 2022)

textile fibers from woven, nonwoven and knit fabric waste can be recycled, but it becomes challenging for composites when cotton and synthetic fiber are used simultaneously in yarn and fabric manufacturing. Choosing a particular recycling process is difficult for blended fabrics as natural and man-made fibers have distinct properties and often require multiple techniques to separate them. (Rashid et al., 2023). Ventura et al. created fiber-reinforced cementitious composite plates for the construction and building sector using recycled fiber from textile waste. Unidirectional fiber strands, meshes, woven textiles, or nonwoven fabrics are strongly recommended for recycling for greater tensile and structural strength (Ventura et al., 2022). Three case studies are presented here from Bangladesh, showing how the recycling process takes place in the recycling factories transforming textile waste into recycled fiber and yarn.

4.1 Case Study 1—Mechanical Transformation of Post-Industrial Textile Waste into Recycled Fibers

To convert textile waste into recycled fiber, mechanical transformation is the dominant technology in the fiber recycling sector due to its low cost and environmentally favorable (i.e., nearly no use of hazardous chemicals) operations (Yalcin-Enis et al., 2019). Three essential phases are involved in the mechanical recycling of post-industrial textile waste. Step 1 involves sorting the items that have been collected through various means. Step 2 involves cutting the sorted material to a length between 80 and 180 mm. After being shredded, the material is processed to create recycled fiber in Step 3, which is used by the yarn producer to create a recycled yarn with different blend ratios. The two main sources for collecting textile waste are either local markets or available textile factories such as spinning, knitting, wet processing, and apparel. In the following, the key steps are discussed in detail.

4.2 Sorting

The waste typically comes to a fiber recycling factory in bale form (Fig. 4a). Sorting is the first step the fiber recycling factory takes after receiving the waste from the local market. Although local waste vendors carry out some preliminary sorting, fiber recycling plant still needs more sorting before manufacturing due to various factors, such as less color homogeneity due to the mixture of different yarn and fabric lots, and the presence of buttons, labels, and zippers (Fig. 4b)—*a* high degree of sorting results in high-quality end products. After sorting, the materials are exposed to UV light to ensure disinfection and detect the presence of OBA (Optical Brightening Agent), especially for white cut pieces. Then the goods are passed through the metal detection section to ensure that no metal or metal particles are present in the material.

Fig. 4 Different sections of the mechanical fiber recycling industry: (**a**) collection of waste from available sources, (**b**) manual sorting and putting the pieces into the conveyor belt for cutting, (**c**) manual checking of the size of cut pieces for the required length after cutting, (**d**) main shredding operation to open fibres from fabric cut piece, (e) checking quality parameters of shredded fibers and (**f**) ready fiber for spinning. (Author generated)

4.3 Shredding

Shredding is a mechanical technique that reduces the post-industrial textile waste fiber length through a series of production processes (Shen & Worrell, 2014a, b). As the size uniformity of the cut-fabric waste is crucial for having the necessary recycled fiber qualities and cut-fabric waste from textile and apparel production consists of different sizes, cutting processes are applied to reduce the size of cut-fabric panels as the first step of the shredding process. Cutting has been carried out in two to three stages to achieve the highest level of size homogeneity consistently. The length of the fabric pieces that both cutters can simultaneously cut ranges from 80 to 180 mm, depending on the design of the machine. Beyond these limits, the machine may fail to cut the fabric to the desired size and malfunction. A post-cutting manual size checking is applied to confirm that the correct cutting size is attained (Fig. 4c). A conveyor belt then transports the cut pieces into a rotary tank, where a small amount of softener (usually cationic types) and an anti-static agent are added to ensure the smoothness of the shredding operation as well as to minimize the risk of tearing the fibers and fire owing to vigorous pounding during the subsequent process. The cut pieces are then placed in a designated receptacle to be sent to the shredding process later. Then the cut pieces are delivered to the super mixer through a special feeding system, chute feeding from the storage bin. The purpose of the super mixer is to ensure smooth and homogeneous mixing so that the shredding can produce fibers of homogeneous length. The material is then transferred to the shredding section, which is a single unit consisting of six to seven cylindrical shredding rollers, depending on different machine brands (Fig. 4d). A shredder consists of rotating blades driven by electric motors and a collection bin at the bottom incorporating carding technology to open the fibers. The first four rollers have comparatively long teeth, so they can do extensive shredding and then be delivered to the rest of the rollers, which have gradually small saw-type blades and open the fibers almost similar to its initial stage like in the virgin cotton bale. Once the fibers are open, the frontmost roller delivers the opened fibers into a conveyor belt. This belt is linked to an automated bale-press machine and produces the required bale of recycled fibers ready to use for yarn spinning. All the cut pieces missed to catch by the roller teeth fall through the two rollers and are collected by the bin below the rollers. Later, the pieces are returned to the super mixer to be prepared for re-feeding into the shredding section.

4.3.1 Testing of Recycled Fibers

After delivery from the shredding section, several lab tests are carried out to ensure that they meet the customers' requirements. Various test of chemical and physical properties are carried out on recycled fibers, such as average fiber length (Fig. 4e), neps, fiber composition analysis, color fastness, pH, dye bleach, dyeability, and toxicology.

4.3.2 Final Product

The fiber composition can be 100% recycled cotton (Fig. 4f) or blended with virgin or recycled polyester fibers. Regarding the product offer, it is possible to produce several varieties of fibers, i.e., solid colors and mixed colors with prescribed ratios to produce mélange effects. Solid colors are possible mostly on greige or bleached fibers, which can be dyed to any desired color later. Mélange fibers do not need to be dyed; with a prescribed ratio to mix with virgin fiber, they create the desired mélange shades, which are comparatively more sustainable recycled fiber than solid colors.

4.3.3 Limitations

As this industrial practice has enormous potential in terms of sustainability and resource efficiency, it has some limitations, such as all kinds of terry and fleece products that are heavier in structure (i.e., the average weight per square meter is approximately 300 g or above) having polyester filament yarn inside are not suitable for mechanical shredding. A similar result is also for the fabrics having polyamide (i.e., elastane) inside the structure. During shredding, polyester and polyamide do not open up as cotton but rather entangle with the rotating drum's teeth and impede production efficiency. Polyester and elastane are more suitable for chemical recycling.

4.4 Case Study 2—Conversion of Recycled Fibers into Finer Recycled Yarn (Ring Spinning)

Among the various industrial applications of the resulting recycled fibers from the shredding process, the most widespread industrial application is to spin these recycled fibers into yarn by mixing them with other available fibers (i.e., virgin cotton and virgin/recycled polyester). As yarns are produced by the technology used to create the final fabric, such as woven, knit, heavy knit (sweaters), and denim, the diameter of the yarn is also developed specifically. Often, finer yarns are required for most of the woven (except home textiles) and knit (except towels) items. Due to product production technique and end use, heavier knits and denim typically require coarser yarn (larger diameter). Ring spinning is the oldest technology to produce high-quality finer yarn (Shen & Worrell, 2014a, b) ranging from 60 Ne (~10 Tex) to 30 Ne (~20 Tex), and also, to some extent, coarser yarn up to 20 Ne (~30 Tex). However, a specific range of fiber length, 1.25–1.50 inches (Yin et al., 2021), is required for the ring spinning process; otherwise, short fibers are removed and turned into waste in the blowroom, carding, and combing process. Typically, short fiber contents are 25–30% higher in recycled fibers compared with virgin cotton

(Ütebay et al., 2020); therefore, at present, ring spinning can produce yarn with a maximum of 30% recycled fiber content ranging from 20 to 34 Ne.

4.4.1 Recycled Yarn Production Using Recycled Fiber from Post-Industrial Fabric Cutting Waste

According to the GRS (GRS—global recycle standard is an international standard that sets requirements for third-party certification of recycled content, social and environmental practices, and chemical restrictions) guideline, a yarn must include at least 20% recycled fibers by weight throughout the mixing process to be labeled "Recycled" (GRS, 2020). As mentioned earlier, the ring spinning process can handle recycled fiber in the mix up to 30% by weight, which will reduce the average length of the fibers and may result in frequent breakage during the production of slivers and yarn. Depending on the specifications of the final consumer, the remaining 70% could be either 100% virgin cotton, a blend of virgin cotton and virgin polyester, or virgin cotton and recycled polyester. Any mix of recycled fiber would increase hairiness, resulting in more pilling in the final products.

The mixing of recycled fiber with any virgin fiber would take place in the blowroom. During the blowroom and carding processes, along with other foreign materials, such as dust, leaves, and seeds, a small portion of the short recycled fibers is removed, decreasing the recycled fiber percentage relative to the initial mixing (Fig. 5a, b). Combing is not usually used for yarn with recycled fiber mix, as the process will remove a significant portion of the recycled fibers, eventually decreasing overall recycled fiber percentages. For this reason, GRS approved the yarn as "carded" and labeled it as such. Carded slivers are then delivered to the roving frame to impart a slight twist through the rotating flyers and create a bobbin of roving slivers to feed to the ring spinning machine. Then necessary twist is imparted by the ring spinning machine to generate the desired yarn between 20 and 34 Ne.

4.4.2 Recycled Yarn Production Using Recycled Fiber from Spinning Waste

Waste produced by various spinning processes is another source of recycled fibers (Fig. 5c). Dust, leaves, seeds, and a small amount of short fibers (approximately 6–8%, depending on the cleaning roller setting parameters) are removed during the blowroom and carding processes. However, short fibers removed during the carding process—often referred to as "noil"—are mostly used to produce recycled yarn due to their superior cleanliness and longer fiber length compared with blowroom waste materials. The combing procedure, however, is the main source of recycled fibers as the process removed higher percentages (approximately 8–10%, depending on the combing rollers setting parameters) of short yarn to produce superior quality yarn. Wasted and leftover yarn and slivers from yarn manufacturing processes are another source of recycled fibers. Particularly, auto-cone machines (approximately 1–1.5%

Fig. 5 Fiber recovery process from a different section of the spinning industry: (**a**) collection of waste from blowroom and carding process, (**b**) carding "Noil," (**c**) collection of leftover and rejected slivers and yarn, (**d**) feeding the spinning waste into the shredding machine, (**e**) shredding machine for spinning waste (i.e., noil, rejected slivers and yarns), and (**f**) recycled fibers after the shredding of spinning waste. (Author generated)

depending on the "cut length" setting parameters) and vortex spinning generate a lot of waste yarn (approximately 6–8% during auto splicing) that is shredded and used as recycled fibers (Fig. 5d). Spinning manufacturers occasionally buy rejected and leftover yarn from various knitting and weaving production facilities and mix it with waste yarn while shredding to boost the volume of recovered fibers. Due to higher fiber length and fiber uniformity, recycled yarn from spinning waste has some advantages over post-industrial fabric cutting waste. Another benefit is that the percentage of recycled fibers can reach up to 40%, while the remaining 60% could be either 100% virgin cotton, a blend of virgin cotton and virgin polyester, or virgin cotton and recycled polyester.

4.4.3 Laboratory Testing

Following yarn manufacture, several physical tests are carried out in the in-house lab, such as fiber length, mass variation, hairiness, thick and thin places, and neps to ensure that the end user's needs are fully met. The in-house laboratory does not conduct any chemical tests, but final customers occasionally verify the product's fiber content and toxicology before exporting it to the target countries.

4.4.4 Limitations

Even though ring spinning has numerous advantages over other spinning techniques, it has several drawbacks when producing recycled yarn. For instance, the amount of recycled fiber removed during the blowroom and carding processes cannot be accurately measured, leaving the amount of recycled fiber in the finished yarn unknown. Additionally, using more than 30% of recycled fiber is not possible.

4.5 Case Study: 3—Conversion of Recycled Fibers into Coarser Recycled Yarn (Rotor Spinning)

As indicated in Case Study 2, recycled fibers are used in ring spinning to create finer yarn, which is required to manufacture knit and woven fabrics. However, the amount of recovered fiber used in ring spinning is restricted to a maximum of 40%. On the other hand, heavy knits (sweaters and jeans) have a great demand for coarser yarn (6–24 Ne). To address this demand, rotor spinning is extensively employed as an alternative to ring spinning, which is unsuitable for production in this range. Another benefit of rotor spinning is that it can utilize up to 95% recycled fiber in a specific mixture, ensuring the greatest usage of recycled fibers and a significant step toward circularity.

4.5.1 Shredding

There is no need for a particular shredding method for rotor spinning. Similar shredding procedures are used as they are for ring and fiber recycling. On the other hand, rotor spinning is designed to accomplish spinning with relatively short fibers compared with ring spinning. Thus, it can produce yarn from fibers made from a fabric cut piece length of 50 mm compared with ring spinning, which requires at least 80 mm and above.

4.5.2 Fiber Mixing and Blending

Fiber mixing and blending take place in the blowroom, similar to the ring spinning. The blending is done in a machine called “blendomat,” placed before the blowroom (Fig. 6b). To produce a coarser count from 6 to 10 Ne, the percentages of recycled fiber can be up to 95%, which can be used in heavy-knit products. The remaining amount can be virgin cotton or polyester, sometimes recycled polyester to increase circularity. In most cases, these recycled polyester are outsourced, as most cotton spinning mills are not well-equipped to manufacture recycled polyester fibers from PET (polyethylene terephthalate) bottles. Combining organic cotton and regenerated cellulose, such as viscose and Tencel, is also feasible, usually sourced from China, India, and others (Fig. 6a).

4.5.3 Manufacturing of Rotor Yarn

Similar operations are carried out in blowroom and carding (Fig. 6c) for rotor spinning, as explained in Case Study 2. However, in rotor spinning, blowroom and carding opening and cleaning rollers are set to prevent the removal of short fibers on a significant scale (i.e., not more than 6–8% of the initial weight). As usual, the combing process is skipped. In addition to the spinning method, rotor spinning and ring spinning have different process routes. Compared with ring spinning, which requires roving after carding, rotor spinning does not. Carded slivers (Fig. 6d) are transferred directly to the rotor spinning machine, which makes yarns by adding the necessary twist (Fig. 6e).

Similar to the fiber recycling manufacturing unit, the rotor spinning unit features at least four distinct color-based production lines to prevent unintended color mixing. Another purpose is to shorten the time required to clean the machinery after the color changeover resulting in more production time. These four colors are typically grouped according to market demand. Black, greige (white), blue, and mélange are the top four colors in market demand.

4.5.4 Manufacturing of Heavy Knit (Sweater) Yarn

For the production of recycled yarn for woven, knit, and denim, there is no need for doubling operations, but for heavy knit (sweater), the doubling operation is necessary. Doubling is a unique procedure in which two yarns are joined and twisted together to make a single yarn so that the finished sweater items become flappier and more insulated (Fig. 6f). Double yarn is used in sweater knitting machines with a finer gauge (GG 10 to GG 14) to produce yarn of 16/2 Ne to Ne 30/2 Ne count. In some cases, instead of using doubled yarn, more ply of yarn are used to make the fabric more flappy, especially when using a coarser gauge sweater knitting machine (GG 3 to GG 7), which requires yarn counts from 6 to 10 Ne.

Fig. 6 Different sections of rotor spinning industry: (**a**) collection of recycled polyester and organic cotton fiber for mixing, (**b**) Blendomat, (**c**) carding machine for rotor spinning to handle short fibers, (**d**) carded slivers, (**e**) rotor spinning machine, and (**f**) doubling and twisting of sweater yarn. (Author generated)

After the yarn is produced, numerous physical tests are carried out in the lab, such as mass variation, hairiness, thick and thin place, and neps, to ensure that the end user's requirements are fully respected. Although the final customer occasionally checks the fiber content and toxicology before exporting to the destination counties, the in-house laboratory does not conduct chemical tests.

4.5.5 Prototype Fabric Production (Sweater)

As heavy knit manufacturers (sweaters) are the primary customers for rotor yarn, the firm has prototype automatic sweater manufacturing machines to test the feasibility and efficacy of the produced yarns. A center specifically dedicated to studying different sweater knitting structures with recycled yarn is sometimes available. Its goal is to provide clients with recycled yarn and offer attractive, trendy sweater designs.

4.5.6 Circular Economy in Bangladesh Textile Supply Chain

Post-industrial textile waste represents the textile–apparel manufacturing part of the entire textile supply chain. The circular economy in the textile–apparel manufacturing chain in Bangladesh perspective encompasses the entire formal manufacturing factories to the informal markets trading the textile wastes and the formal textile recycling factories. Establishing the textile waste recycling strategy in Bangladesh can mitigate the environmental burden of textile waste, supporting sustainable practices in the long run in textile production. Recycling and reusing textiles could reduce the production and consumption of virgin materials, which would be positive for the environment (Sandin & Peters, 2018). Bangladesh has 100% export-oriented apparel factories and does not sell the products directly to the consumer, having a huge opportunity to co-create a CE model where factories are ready to look for circularity in their business (Uddin, 2018). The textile and apparel sector has long practiced recycling and material reuse. There are many benefits to it, including the availability of the raw materials needed to create new products, new employment opportunities, a reduction in waste and the use of natural resources, the need for less energy to produce virgin goods, the prevention of global warming and water pollution, the preservation of wildlife, and economic benefits (Uyanık, 2019).

Waste recycling in the textile sector greatly impacts Bangladesh's economy in terms of employment generation. Many people are engaged in textile and apparel waste recycling activities for their income. If the textile and apparel waste are recycled nationally in Bangladesh, the industry's revenue may increase by USD 4 billion, adding to the economy and generating new job possibilities (Ahmed et al., 2022). Two forms of apparel waste processing stores are currently prevailing in Bangladesh. The small shops contain three to five workers, allocating a monthly salary of 25–30 USD, processing 3–3.5 tons of waste monthly. Large businesses employ 10–15 people paying 35–60 USD monthly to process 10–15 tons of waste monthly. The waste processed here is woven, net, and shirting fabric pricing

0.25–2.5 USD/kg depending on the waste's size and quality, while the recycled fiber's selling price is 0.4–3.5 USD/kg (Quazi, 2017). A study reports that Filotex Ltd. is the first factory in Bangladesh to work with the "Circular Fashion" implementing the recycling concept (Team, 2018). Simco Spinning and Textiles Ltd. in Bangladesh has been recycling 200 tons of textile waste each month for the last 3 years. It produces yarn from discarded cotton clips. It uses 95% recycled fiber instead of virgin fiber (fresh or unused fiber) in production. Simco collects textile waste for a specific buyer to recycle and then upcycles (reuses) it into raw materials (Jui, 2022). After background analysis and considering the current state, it is predictable that, with proper infrastructure, stakeholder collaboration (Saha et al., 2021), and policies (Hartley et al., 2020), Bangladesh can harness the potential of textile material recycling as a sustainable solution for managing textile waste and promoting CE in the textile supply chain.

4.5.7 Conclusion

Recycling pre-consumer and post-consumer waste has enormous potential, yet implementing waste recycling poses a unique set of challenges. The increasing consumption of fibers, increasing demand for fiber mix, often more than two fibers, increasing use of performance finishes, and color pellet used in different seasons all create a scenario that is difficult for processing further. The second challenge remains for the collection of textiles and sorting these various mixes in subsequent recycling processes. However, various technological breakthroughs appeared in various parts of the world, although this is still a long way to go. On the other hand, chemical recycling of synthetic fibers or their mixtures based on textiles has yet to be in the mainstream. The third challenge is more future-oriented, as what will happen to the recycling of recycled textiles. In recent studies, it has been found that garments made of recycled fibers are more responsible for microplastic pollution than that of virgin fibers. The final challenge remains due to the nature of business, which, in many countries, is not straightforward and may be due to policy issues or the stakeholders involved in the waste supply chain. As a result, the transparency of these waste generation, collection, and subsequent business operations remained clandestine. It is expected that, with an increasing focus on the circular textile supply chain, these challenges could be overcome in a short period to build a sustainable textile sector.

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