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Review

Recycling of Blended Fabrics for a Circular Economy of Textiles: Separation of Cotton, Polyester, and Elastane Fibers

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Abstract: The growing textile industry is polluting the environment and producing waste at an alarming rate. The wasteful consumption of fast fashion has made the problem worse. The waste management of textiles has been ineffective. Spurred by the urgency of reducing the environmental footprint of textiles, this review examines advances and challenges to separate important textile constituents such as cotton (which is mostly cellulose), polyester (polyethylene terephthalate), and elastane, also known as spandex (polyurethane), from blended textiles. Once separated, the individual fiber types can meet the demand for sustainable strategies in textile recycling. The concepts of mechanical, chemical, and biological recycling of textiles are introduced first. Blended or mixed textiles pose challenges for mechanical recycling which cannot separate fibers from the blend. However, the separation of fiber blends can be achieved by molecular recycling, i.e., selectively dissolving or depolymerizing specific polymers in the blend. Specifically, the separation of cotton and polyester through dissolution, acidic hydrolysis, acid-catalyzed hydrothermal treatment, and enzymatic hydrolysis is discussed here, followed by the separation of elastane from other fibers by selective degradation or dissolution of elastane. The information synthesized and analyzed in this review can assist stakeholders in the textile and waste management sectors in mapping out strategies for achieving sustainable practices and promoting the shift towards a circular economy.

Keywords: textile; cotton; cellulose; polyester; polyurethane; elastane; spandex; dissolution; molecular recycling; chemical recycling; advanced recycling

Citation: Choudhury, K.; Tsianou, M.; Alexandridis, P. Recycling of Blended Fabrics for a Circular Economy of Textiles: Separation of Cotton, Polyester, and Elastane Fibers. *Sustainability* **2024**, *16*, 6206. https://doi.org/10.3390/su16146206

Academic Editor: José Ignacio Alvarez

Received: 6 June 2024
Revised: 12 July 2024
Accepted: 17 July 2024
Published: 20 July 2024

1. Introduction

Environmental pollution and climate change present threats to life on our planet [1]. These threats are directly caused by industrialization and various activities of humans, including the fashion and textile industries [2,3]. According to the Textile Institute's Terms and Definitions Glossary [4], textile is "a general term applied to any manufacture from fibers, filaments or yarns characterized by flexibility, fineness and high ratio of Length to thickness". The root of the word textile is the Latin verb texere, which means to weave. The term "textile" was formerly limited to woven fabrics, but now it is typically used to refer to fibers, yarns, fabrics, or goods that are constructed of fibers, yarns, or fabrics [5]. The fashion and textile industries cause a lot of air, water, and solid waste pollution. The textile industry utilizes many non-renewable resources like petroleum, natural gas, and minerals that cannot be replenished. Numerous chemicals and industrial processes are involved, which can be both hazardous and harmful [6,7].

At present, the clothing industry operates in a straight line: resources are extracted and used, clothes are made, and people use them for a short period, and then they throw clothes away. This take-make-waste model creates huge environmental and societal problems. Fast fashion is a major culprit that is inciting this issue [8]. More than half of fast fashion

items are thrown away after just one year of use [6]. This extremely wasteful linear system squanders valuable resources, ignores economic opportunities, pollutes our planet, and negatively impacts society on multiple levels [6,9].

The textile industry has a significant environmental footprint. Synthetic fibers and polymers such as polyester, polypropylene, nylon (polyamide 6-6), and acrylic, which are derived from petroleum and petrochemicals, account for 63% of textile fibers, and their manufacturing and disposal result in significant carbon dioxide (CO_2) emissions. Moreover, 26% of clothing is made of cotton, which contributes to pollution from fertilizer and pesticide use and water depletion during its cultivation. For example, from 7000 to 29,000 L water is needed to produce 1.0 kg cotton. The excess pesticides not only affect the biodiversity of the land and surrounding environment but also change the quality of water and soil [10–12]. Solid and liquid forms of textile waste contaminate land and aquatic environments. The fibers from these materials take millennia to break down and release microplastics into the soil and ocean [13–16]. The various processes in the textile industry often use toxic chemicals that are harmful to workers, the environment, and aquatic life. Textile-producing plants can release wastewater into the environment, which affects aquatic life by lowering oxygen levels in water [3,11,17]. In the textile industry, wet treatments such as fiber preparation, dyeing, printing, finishing, etc., and the production of yarn and fabric rely significantly on fossil fuels and release pollutants and CO_2 into the atmosphere. Specifically, in 2015, the textile industry contributed 1.2 billion tons of CO_2 to global emissions, which are expected to increase by 26% by 2050 [6,11].

The production of fabrics and clothes has been steadily increasing worldwide, and this upward trend is likely to continue [18,19]. The amount of clothing sold has nearly doubled over 15 years as shown in Figure 1 [6]. Fifty years ago, back in 1975, the worldwide production of textile fibers was around 23.9 million metric tons. That number skyrocketed over the next few decades: by 2017, it climbed to fourfold to 98.5 million metric tons. Just two years later, in 2019, it had shot up further to 111 million metric tons of textile fiber production globally [20]. The demand for clothing is expected to continue growing quickly. The annual consumption of clothes worldwide was 62 million tons as of 2019 and predicted to reach 102 million tons by 2030 and 160 million tons by 2050 [11].

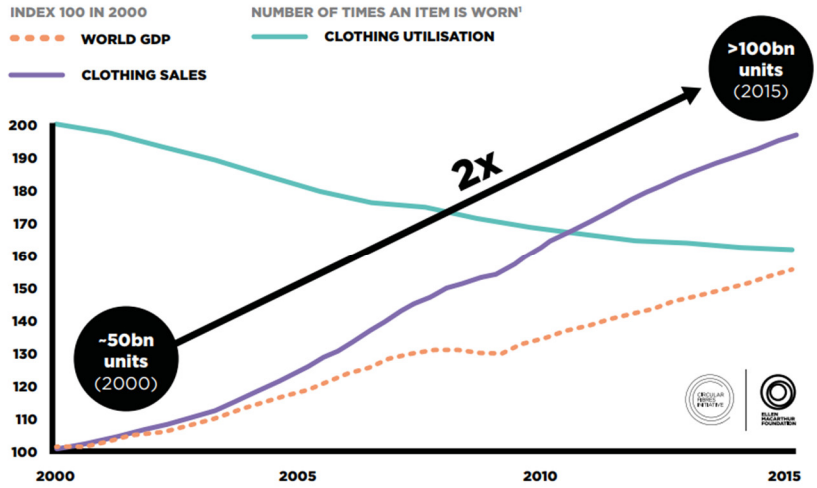


Figure 1. Growth of clothing sales and decline in the utilization of clothing between 2000 and 2015. Reproduced with permission from [6]. Copyright 2017 Ellen MacArthur Foundation. As of 2015, sales of clothing have approximately doubled, and the utilization of clothing (i.e., [1] the average number of times a garment is worn before it ceases to be used) has decreased by 36% since 2000. The index sets the initial value of the data series to 100 in 2000. The other index values in this data series are based on the difference of each data value to the initial value. GDP denotes gross domestic product. GDP is a measure of the size of an economy. It measures the value of the total final output of goods and services produced by that economy in a certain period of time.

The global fiber production in 2021 was approximately 113 million tons. These fibers were used in different sectors, such as apparel, home textiles, and other applications, including industrial products, medical products, footwear, etc., as shown in Figure 2.

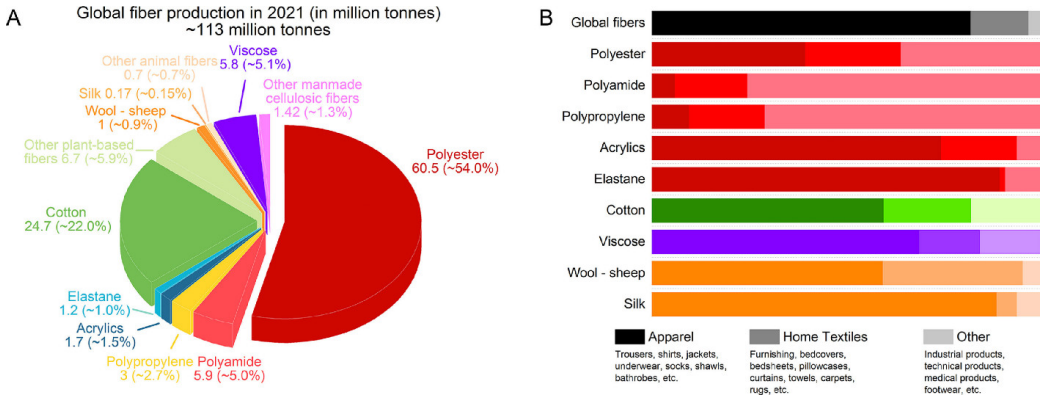


Figure 2. (**A**): Overview of the global fiber production in 2021 (in million tons) and (**B**) the amount of fiber used in various applications. Reproduced with permission from [21]. Copyright 2023, Elsevier.

Textile production is heavily based on petroleum-derived virgin polymers that currently constitute over half of the textile fiber market. Synthetic fibers are gaining market share in both the current and anticipated total fiber demand as depicted in Figure 3 [22].

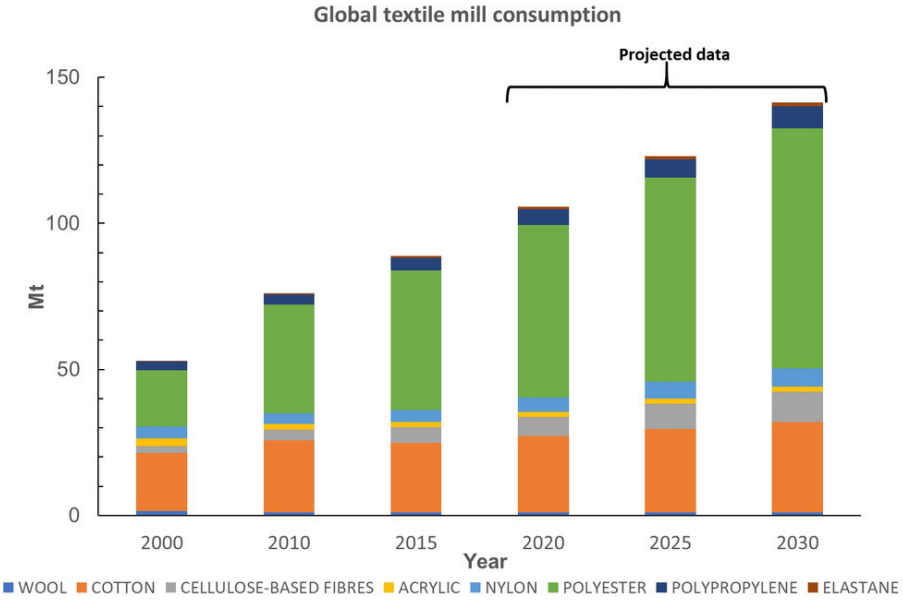


Figure 3. Current and predicted total fiber demand shows a growing market share for synthetic fibers. Reproduced from [22]. Copyright 2021, the authors.

The top four economies in terms of textile exports are China, the United States (US), the European Union (EU), and Canada. China generated approximately 20–26 million tons (MT) of textile waste annually in 2019. The EU textile industry generated about 16 MT of textile waste annually in 2018, and around 5.8 MT of textile waste was discarded annually by European consumers; of this, only 26% was recycled. In the US, only 15% of textiles are recycled or donated, with the remaining 85% ending up in landfills. An estimated 0.5 MT of clothing is disposed of each year in Canada [20].

After use, the large majority of textiles end up in landfill or incineration. In 2022 only about 25% of textile waste was recycled, and 75% of all textile waste around the world ended up in landfills or was incinerated [6,23]. According to [23], by incinerating 1 ton of textile waste, 15,800 MJ of energy can be recovered. However, incineration emits

greenhouse gases and toxic substances into the atmosphere, and it also generates 27 kg of ash per ton of waste textile. According to EU legislation, incineration is not recycling but recovery or disposal [24]. In the EU, it is estimated that 40% of discarded textiles are collected. Of these collected textiles, 10% are resold within the country where they were collected, another 10% are resold in other European countries, and the remainder is primarily exported to Africa and Asia. The remaining clothing, nearly 1.7 million tons per year, is incinerated [25]. In the US, 3.2 million tons of textiles were combusted in Municipal Solid Waste (MSW) for energy recovery in 2018, accounting for 9.3% of all MSW combusted. Landfills received 11.3 million tons of MSW textiles, making up 7.7% of all MSW landfilled. According to the most recent EPA data, the US generates just over 17 million tons of textile MSW annually, with 19% being burned [26,27].

Initiatives for recycling and upcycling can promote sustainability and a circular economy, which will lower the textile industry's carbon footprint. A circular economy involves reimagining the process of materials manufacturing and resource utilization to prioritize reusing and recycling over traditional methods of production, use, and disposal. By emphasizing the circular economy and extending product life and material reuse, recycling reduces waste production and maximizes the value of items [3].

The main classifications of recycling are:

- Closed-loop recycling: This involves recycling the material into a nearly identical product.
- Open-loop recycling: This involves recycling the material in a different product category. Figure 4 illustrates the closed-loop and open-loop recycling methods.
- Upcycling: Upcycling is the process of creating a product out of recycled resources that is more valuable than the original.
- Downcycling: In downcycling, the recycled material is less valuable than what was used to make the original item.

Recycling ensures that materials from products that are nearing the end of their useful lives remain in the economy. Further value can be created by repeatedly using these materials in a productive manner. Textile recycling, including closed-loop technologies like fiber-to-fiber recycling, aligns with the circular economy by preserving resources, reducing waste, and extending the lifespan of textile products [28]. Recycling eliminates waste, reduces its negative effects on the environment, stimulates innovation, creates economic opportunities, and promotes sensible consumption practices [29–31].

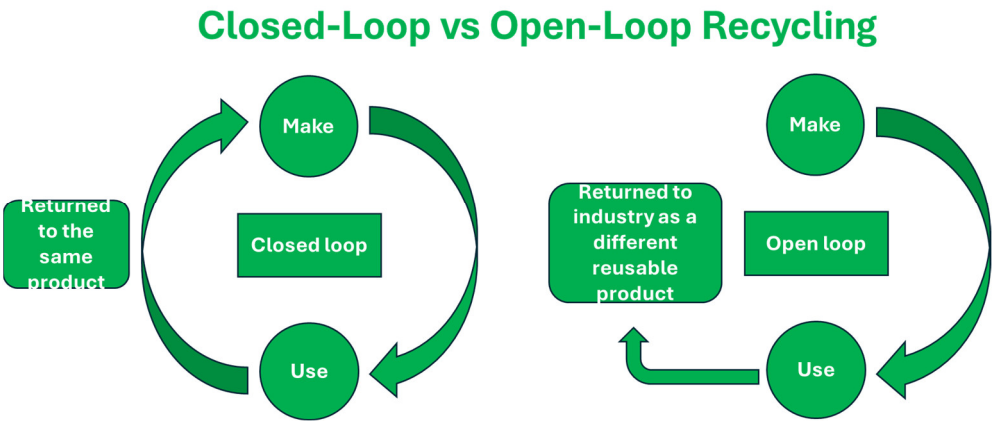


Figure 4. Closed-loop vs. open-loop recycling. Adapted from [32].

The fact that post-consumer textiles often consist of fiber blends is a major obstacle to their recycling, as the natural and synthetic polymer mixtures are so complex. Recycling is particularly difficult with fabric blends that have multi-material fiber compositions because the finely blended fibers must be separated before the individual components of the blends can be recycled; this cannot be done simply by mechanical separation [28,33]. Separating elastane or spandex (these are polyurethane (PU) elastomer fibers that are typically referred to as elastane in Europe and as spandex in the US), which gives fabrics elasticity and

comfort, is a key challenge. While it improves textile flexibility, elastane hinders recycling because it cannot be shredded like other materials. Elastane, even at low concentrations, clogs machinery and inhibits the efficient recycling of other polymers in clothes, leading to clumping. It is essential to remove elastane from textile blends to increase fiber recycling rates, as the leftover fibers can be recycled more effectively once elastane is removed from the blends [21,34].

Blended fabrics can be recycled with chemical, physical, and biological processes, utilizing dissolution, hydrothermal processes, and enzymatic processes [22,23,35]. The separation of blends guarantees that the distinctive qualities of every material can be preserved and successfully used in new products by recycling each one separately. The separation of cotton from polyester in blended fabrics can be achieved with various methods, including selective dissolution using solvents and ionic liquids, enzymatic hydrolysis, alkaline pretreatment, and hydrothermal treatment. The separation of elastane can be achieved by its selective dissolution or degradation. Ultimately, these processes offer promising pathways for recycling and repurposing blended textiles, which contributes to sustainable textile practices.

Research advancements in textile recycling are presented here. Following an overview of textile fibers, textile production, and main textile recycling methods, this review focuses on separating cotton from polyester and separating elastane from other fibers, so that each component material of a blend can be recycled, and resources can be utilized more effectively. The contents of this review are shown in Figure 5.

Figure 5. Overview of topics covered in this review.

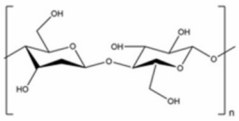
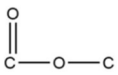
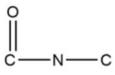
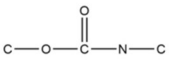
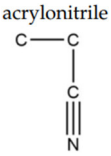
In the available literature, the review 'Recent advances in recycling technologies for waste textile fabrics: a review' [23] provided an overview of existing textile recycling technologies but did not report on the processes and reactions employed and the process/reaction conditions. The review 'Mechanical, chemical, biological: Moving towards closed-loop bio-based recycling in a circular economy of sustainable textiles' [28] focused on bio-based processes. 'Enzymatic textile recycling—best practices and outlook' [36] also focused on enzymatic hydrolysis for recycling textiles. 'Tackling critical challenges in textile circularity: A review on strategies for recycling cellulose and polyester from blended fabrics' [33] discussed developments in textile recycling, focusing on separating polycotton blends. The present review comprehensively organizes the molecular recycling technologies available to date to separate cotton, polyester, and elastane from blended fabrics. The latter topic has not been previously addressed in other review articles.

2. Textile Fibers and Textile Production

Textiles mainly consist of fibers that are extremely long (2–5 cm) and extremely thin structures. Fiber is a unit of matter that has a diameter of 10–200 microns, a length that is at least 100 times its diameter, and is flexible. It is made up of long-chain molecules with a fixed preferred orientation [19]. A fiber that is used for the production of textiles is called textile fiber. Fiber is the main raw material of textiles, which are long and thin strands that are knitted into threads or fabrics with the help of spinning or extruding machines. Fabrics are made by weaving, felting, or pressing threads. Based on their sources, textile fibers are classified into natural and synthetic. Natural fibers come from plants, animals, and minerals. Flax, hemp, jute, cotton, wool, silk, and ramie are examples of natural fibers. Synthetic fibers are man-made from petroleum-based materials. Acrylic, polyester, and nylon are synthetic fibers [37]. Cotton accounts for 27% of the world's textile fiber production. The majority of textiles are created with synthetic fibers: polyester (55%), nylon (5%), acrylic (2%), and elastane (2%) (Figure 2). Less than 2% of all fibers are derived from animals, such as wool and silk, and are referred to as protein-based fibers [6].

For recycling reasons, different types of textile fibers can be divided into groups: polysaccharides, polyester, polyamide, polyurethane, polyolefin, and polyacrylic based on the main chemical linkages that connect the monomers. This is because fibers with identical chemical linkages usually possess equivalent chemical and physical characteristics. The classification of textile fibers according to monomer linkages is shown in Table 1 [19].

Table 1. Classification of textile fibers based on monomer linkages [19].

Polymer	Polysaccharides: Cellulose	Polyester	Polyamide	Polyurethane	Polyolefin	Polyacrylic
Linkage	β-glycosidic 	ester 	amide 	urethane 	alkane	acrylonitrile 
Fiber Example	Cotton, Linen, Viscose	PET	Wool, Silk, Nylon	Elastane	Polypropylene, Polyethylene	Acryl, Modacryl

The most popular natural fiber for clothing, cotton, grows around the seeds of cotton plants. Cotton has fair to good strength, is slightly elastic, less resilient and prone to wrinkling compared to silk or wool, soft and comfortable, and has good absorbency. Cotton conducts heat well, can withstand moderate heat, and decomposes after prolonged exposure to temperatures of 150 °C/320 °F or above. Cotton can be decomposed by insects, mildew, rot, and moths. Extended sunlight exposure can weaken cotton [38].

Polyester fiber consists of synthetic polymers that contain at least 85 wt% an ester of a substituted aromatic carboxylic acid—including but not limited to substituted terephthalate and para-substituted hydroxybenzoate units. Polyester is thermoplastic polymer, has good strength, is hydrophobic, has low moisture absorbency, and is very resistant to mildew. Polyester becomes sticky at 226 °C/440 °F to 243 °C/470 °F and melts and flames in the range 248 °C/480 °F to 290 °C/554 °F [38].

Blended fibers are created by mixing at least two different types of fibers. It is not uncommon for the final blend to have material properties that are different from those of the individual fibers. Blends of different fibers can be used to improve the performance of fabric, for example, adding elastane to polyester to make stretchy fabrics. Blended fabrics may sound novel, but in fact, blended fibers are the norm these days [34]. Classic examples of blends of natural and synthetic fibers include cotton-polyester [39], wool-nylon, and silk-rayon fabrics. Consider, for example, a polyester-cotton blend. This fabric might be wrinkle-resistant and long-wearing but, because polyester and cotton have different structures, the fabric feels soft and has some breathability. Excellent wearing comfort and

good breathability are ensured by the natural fabric cotton, while the synthetic polyester contributes to durability, flexibility, and shape retention [37].

The smallest component of a fabric is fiber. Fibers are spun into yarn; yarns are used to make fabrics and fabrics are used to produce clothes. Textile production consists of several steps as illustrated in Figure 6, spanning from sourcing different types of fibers such as cotton, wool, or synthetics, through spinning the fibers into yarn and weaving/knitting the yarn into fabric (discussed next), various pre-treatments (discussed next), to wet processes such as dyeing and finishing, to turning the produced fabric into clothes. Those clothes are manufactured in successive processes, involving the pattern making of the garment, cutting it to the specification of the pattern, sewing it together, attaching accessories such as zippers and buttons, inspecting the garment to make sure everything went according to the plan, and packing it, ready to be delivered to a customer [40].

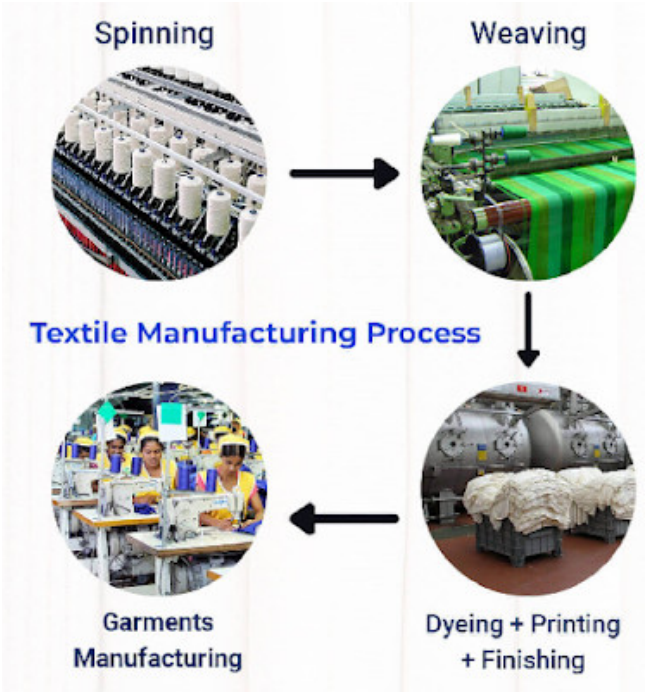


Figure 6. Overview of textile manufacturing process. Reproduced from [41].

Fabrics are produced using weaving, knitting, braiding, embroidery, felting, bonding, and spread towing processes that allow to produce a number of goods such as garments. Figure 7 shows different methods of making a fabric from yarn [40].

- Weaving: This is a technique for weaving cloth in which long strands are woven over and under one another in a herringbone pattern, parallel to each other.
- Knitting: Knitting is a traditional type of textile production completed by hand with a needle or crochet hook, but many industries today use large knitting machines.
- Braiding: This method of producing textiles involves taking two comparable materials and twisting them into knots according to a predetermined pattern [40].
- Embroidery: Embroidery is important in the textile industry for adding aesthetic value, texture, and customization to fabrics. It involves decorating materials with needle and thread or yarn, either by hand or with machines [40].

The processes below are pre-treatments necessary to prepare fibers, yarns, and fabrics to dye or accept functional chemicals that might be applied during other processing. The exact details will be different for different fibers, blends, or fibers-to-fabric, hence more steps can be involved [43].

- Washing: Everything to clean the fabric from the residues of the previous steps and steps of treatment, most of the time with water and detergents or solvents.

- De-sizing: Removing the sizing chemicals from the warp yarns in fabrics using enzymes, so that they are ready for finishing.
- Scouring: Fatty waxes and greases are removed from natural fibers such as cotton seed and husk using a detergent, base, or solvent.
- Bleaching: Usually done with bleaches; bleaching whitens fabrics to improve absorbency and make coloring easier.
- Mercerizing: Cellulosic fibers are treated to improve their strength, luster, and dyestuff affinity by causing them to swell (e.g., with bases); this can help lower the dyestuff level.
- Carbonizing: vegetable residues such as seed pods are removed from the wool fibers and the contents of the fiber are 'blackened' by the application of heat and chemicals (often based on acids) [43].

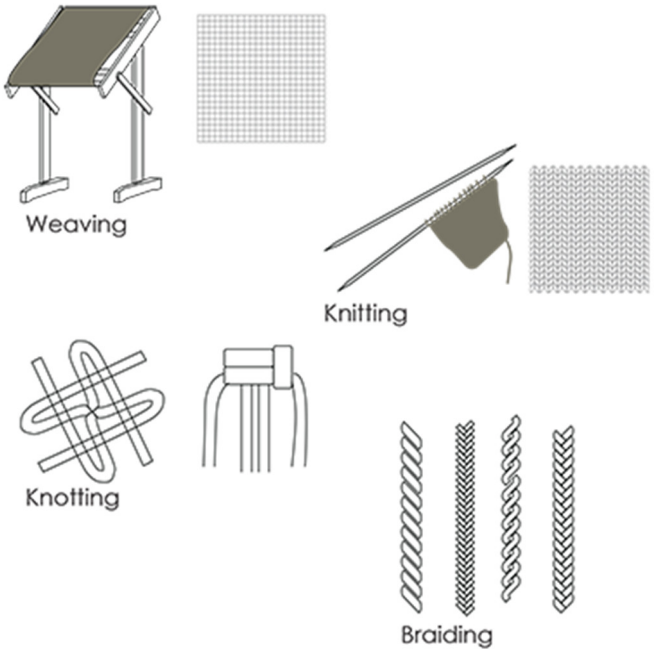


Figure 7. Different methods of making a fabric from yarn. Reproduced with permission from [42]. Copyright © NEXT.cc.

3. Textile Recycling Methods

The recycling of textiles is important because it helps protect the environment from textile waste, and it keeps resources utilized within the circular economy (less need for fibers and the associated pollution) [6,19,44]. Before textile recycling, clothing items are collected first. There are several systems in place now to gather used clothing. Municipal waste collection is used to collect garments. This method has the disadvantage that textiles need to be separated first from the other waste, and garments get dirty from other waste. Certain municipalities in the US, UK, and China collect discarded clothing through separate curbside collections. Additionally, neighborhood collection containers are available. Customers can also return clothing to the retailer for retailer drop-off. Numerous stores, such as H&M, Zara, and Patagonia, have already launched their own take-back programs [6]. The textiles need to be sorted after they are collected. Clothes that can be reused must be kept apart from non-reusable garments [45].

There are three main types of textile recycling technologies: mechanical, chemical, and biological [23]. Various levels of textile recycling are possible, including the recycling of fabric, fiber, polymer, oligomer, or monomer, which can be utilized in other applications (open-loop recycling) or in the same application (close-loop recycling) as shown in Figure 8 [33,46]. Recycling fibers refers to keeping the fibers intact after the cloth has been disintegrated by mechanical methods. Polymer recycling includes fiber disassembly with the polymers still intact through mechanical shredding followed by chemical or physical

dissolution methods. Recycling of monomers suggests that fibers and polymers are disassembled into their constituent chemical building blocks by chemical recycling methods [19].

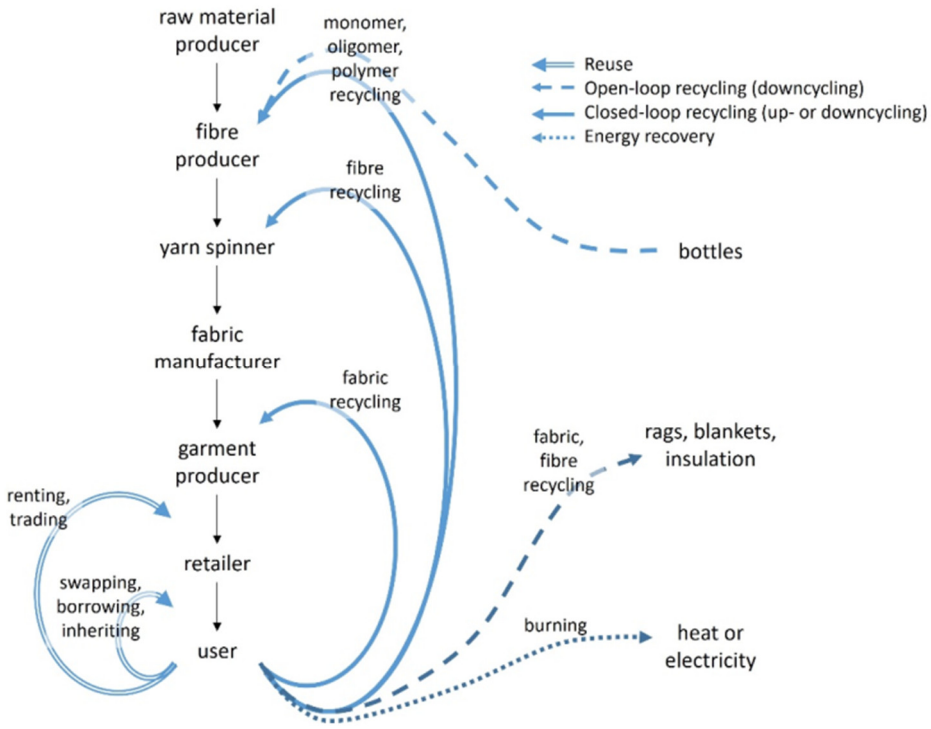


Figure 8. Textile reuse and recycling routes. Reproduced from [20]. Copyright 2022, the authors.

Now, we will present the mechanical, physical/chemical, and biological/enzyme-based technologies for textile recycling, as well as their advantages, drawbacks, and output.

3.1. Mechanical Recycling of Textiles

Mechanical textile recycling is the process of recycling textiles into fibers without using any chemicals. Mechanical recycling involves mechanical processes such as unraveling, garneting, ripping, cutting, grinding, etc. Mechanical recycling allows the material from textile waste to be reused and turned into new raw materials, without breaking down the polymer chains that make up the fibers. This differentiates it from chemical recycling methods [23,35,47]. Prior to shredding fabrics into smaller pieces, hardware components like zippers and buttons must be taken off. As the fabrics are made of fibers, mechanical recycling involves tearing and loosening the fabrics to break them down into fibers (the tearing machine comprises high-speed rotating cylinders or drums lined with saw wires or steel pins, which tear the textile apart, opening up its structure and releasing individual fibers) [48], combining those fibers with a certain amount of original fiber, re-spinning them into yarn, weaving or knitting recycled fabrics, and finally producing recycled apparel [49]. Figure 9 presents an overview of the mechanical recycling of textiles.

Natural fiber waste is frequently shredded and used in heat pressing or needle punching to create non-woven sheets for use in agricultural geotextiles, composite reinforcing materials, and noise and thermal insulation. Conversely, synthetic materials like polyester or nylon are melted and shredded to create flakes or pallets, which are then extruded to be re-spun into fibers [23].

Outputs from mechanical recycling of textiles include:

- Cut fabrics: Cut fabrics are pieces of fabric. If cut fabrics are present, the material needs to go through the tearing machine one or numerous times to produce single fibers. These fibers need blending with virgin fibers to re-spin into yarns because of the decline in fiber quality.

- Spinnable fibers: The output fraction consisting of long fibers of sufficient quality to be spun is known as the spinnable fiber fraction.
- Fluff: Although this product still comprises fiber, it cannot be utilized in a spinning process because the fibers are either too short or too twisted. Typically, fluff material is used to make filler items like insulation for the building sector or specialized non-wovens for the automotive sector.
- Filler materials: During certain procedures (such as milling), the fibers break down, resulting in tiny particles rather than fibers. These particles can be employed as reinforcements or fillers in plastics and composites, depending on their size, shape, and composition [48].

Figure 9. Overview of mechanical recycling of textiles. Reproduced with permission from: https://tortoisethelabel.com/blogs/journal/types-of-textile-recycling, accessed on 11 July 2024. Copyright: Tortoise the Label Private Limited.

Mechanical recycling is affordable and scalable. The energy requirement of this process is low, ranging from 0.3 to 0.5 kW per kilogram of input material [33]. The length of post-consumer textile waste garment fibers is decreased by the severe mechanical ripping or shredding process: recycled fibers can have up to a 40% shorter fiber length than virgin fibers. This degrades the fiber quality, and the recycled fibers may not weave or spin well enough to make yarn or fabric, which would reduce their potential for reuse. This makes closed-loop recycling more difficult [35]. To increase quality, the resulting short fibers are usually mixed with virgin fibers because they are weaker and of poorer quality than virgin cotton fibers [35].

Blended or mixed textiles, however, are not suitable for mechanical recycling as this cannot separate multi-material textiles which result in mixtures of different fiber materials [33,50]. Chemical recycling can address some of the drawbacks of mechanical recycling like no deterioration of the fiber length and separating fiber blends by selectively dissolving or depolymerizing a particular polymer, it could be a good replacement for recycling textile waste [23].

3.2. Chemical Processes for Textile Recycling

In a chemical recycling process, textile waste is reduced to fibers, polymers, oligomers, and/or monomers through melting or dissolution (these are physical processes but still fall under "chemical" recycling) or depolymerization (these are well-defined chemical reactions, to be distinguished from pyrolysis which is the main method of chemical recycling in plastics) [51]. The products of chemical recycling can then be re-processed to create new fibers or other goods [33]. Chemical recycling can thus help close the loop for textile materials. We note that chemical recycling is also called "advanced" or "molecular" recycling. "Advanced" recycling is a euphemism when it refers to pyrolysis which raises environmental concerns. Molecular recycling is a more appropriate term for the processes described here in Sections 4 and 5 because of the controlled generation of products and the ability to fully recycle the initial textile into other textiles.

There are two main chemical recycling routes—monomer recycling and polymer recycling. In monomer recycling, the polymer chain is depolymerized to obtain individual monomers. The monomers can subsequently be polymerized into virgin polymers [6,28]. For example, it is possible to recycle the monomers that are used to create polymers like polyester and polyamides by depolymerizing them. Depolymerization works well for recycling polyester. Polyester is depolymerized by solvolysis producing ethylene glycol (EG) and terephthalic acid (TPA). Technologies for monomer recycling are now limited to fibers derived from petrochemicals [52].

In polymer recycling, the fibers are initially separated mechanically by shredding and, once the garments have been shredded, unzipped, unbuttoned, and, in some cases, de-colored, the fibers are dissolved using selective solvents [53]. The fibers can then be spun and regenerated while the polymer chains are kept intact [28]. This technology can be used on fibers made of cellulose, polyester, or a combination of the two. Cellulose and polyester are isolated independently for additional processing. After that, cellulose pulp can be used to create new cellulose-based fibers and plastic polymers can be restored to their virgin quality by treating them differently [6]. For example, cotton, which is made up of cellulose, can be recycled by selectively dissolving the cellulose using an appropriate solvent [53–55]. The dissolved cellulose can be regenerated into fibers [19,52]. The polymers that make up the fibers are either modified or broken down in the chemical recycling process. Physical methods use physical processes such as melting or dissolution to make the fibers or polymers suitable for reprocessing. In these methods, the physical structure of the fibers is altered, but the polymer chemical structures remain intact. Melt spinning or solution spinning can be used to form new fibers following the melting or dissolution of the original fiber [19,33].

With polymer recycling, the existing approach has some limitations. The processes used, like shredding followed by dissolution with solvents, can degrade (break down) those long polymer chains. So, while the polymers are preserved to a large extent, the recycled fibers end up losing some quality. However, the monomer recycling process can essentially depolymerize those end-of-life textile materials into their molecular building blocks. Those raw monomer units can be repolymerized and spun to brand-new, virgin-quality fibers [28].

The advantages of chemical recycling are as follows. Blends of fibers can be treated with chemical recycling, can be applied to separate fiber blends by selectively dissolving or depolymerizing a particular polymer. The regeneration of used polymers to their virgin qualities are made possible via monomer recycling. The disadvantages of chemical recycling include the following. Degradation may cause the recovered polymers to have shorter chain length. There is an excessive use of chemicals (solvents, catalysts, acids, alkalis, etc.). The purity of the incoming material has a major impact on the efficiency of the recycling process [33].

3.3. Biological/Enzyme-Based Processes for Textile Recycling

Enzymatic depolymerization is a type of chemical recycling where an enzyme acts as a biological catalyst to catalyze a chemical reaction. Using appropriate enzymes, end-of-

life textiles can be depolymerized into their monomeric building blocks, which can then be repolymerized to produce virgin-quality polymers and fibers for brand-new textile products [33,45]. Biological processes have the advantage of usually using less energy (by operating at temperatures close to ambient) and safe chemicals and solvents. Enzymes are attractive for recycling blended textile waste because of their high level of selectivity: they can be used to selectively depolymerize a particular polymer to separate the blends. Additionally, the enzymes can be recycled and reused. However, there is an added expense for chemicals and special equipment because of the usage of enzymes. Moreover, compared to chemical recycling, reaction times are far slower (may take hours or even days to complete) [23,33]. Natural fibers, such as cotton (which is mainly cellulose) and wool, and synthetic fibers, such as polyester, can be recycled using biological processes with enzymes [22,28,56].

Next, we will highlight studies on separating cotton from polyester in a polycotton blend and on separating elastane from other fibers, which are the main focus of this review. These studies utilize processes such as dissolution, depolymerization, and enzymolysis. Mechanical processes (for example, shredding, milling, grinding) are sometimes used prior to dissolution or depolymerization.

4. Separating Cotton from Polyester in Blended Textiles

A fabric that is blended with polyester and cotton fibers is called a cotton-polyester blend or polycotton. Blended cotton and polyester fabrics possess the softness, breathability, and moisture-absorption properties of cotton, in addition to the durability and wrinkle-resistance properties of polyester. Each blend ratio is the result of the exact needs of the application and the balance that is sought between the desirable cotton and polyester qualities. A higher content of polyester would improve the wrinkling resistance and durability of the fabrics, but it also would decrease the softness and breathability of fabrics. On the other hand, a larger percentage of cotton would improve the breathability and softness of fabrics, but it also would eventually result in less durability and less wrinkle resistance of garments [57]. As of 2023, the market value for polycotton was USD 442 million. By 2033, the market for polycotton fabric is projected to grow at a compound annual growth rate (CAGR) of 3% and reach a valuation of USD 594 million [58].

Some of the most popular cotton-polyester blend ratios used in the textile industry are [57]:

- 50% polyester, 50% cotton: Commonly used to make T-shirts, sweatshirts, and bed linens.
- 60% polyester, 40% cotton: Used in sportswear, work uniforms, or casual fashion.
- 65% polyester, 35% cotton: Suitable for casual wear, workwear, or uniforms.
- 35% polyester, 65% cotton: Suitable for various applications from casual wear to home textiles.
- 20% polyester, 80% cotton: Used in sleepwear, casual wear, or summer clothing.

Solely employing mechanical techniques is often inadequate for unraveling and segregating the intricate intermingling between cotton and polyester fibers present within polycotton blends. The distinct chemical compositions of cotton (composed of about 95% cellulose) and polyester enable their efficient separation via either physical dissolution or depolymerization of one component through chemical recycling, while preserving the other as intact fibrous material as shown in Figure 10 [33].

In cellulose-removing technologies, the polyester component remains intact while cellulose is removed using the following strategies: (i) dissolution in solvents such as N-methylmorpholine-N-oxide (NMMO) and ionic liquids, (ii) hydrothermal treatment, (iii) acidic hydrolysis, and (iv) enzymatic hydrolysis [12,53–55,59].

Polyester can be removed from the polyester-cotton blended fabric by chemically or enzymatically degrading the polyester, while the cellulose component remains intact.

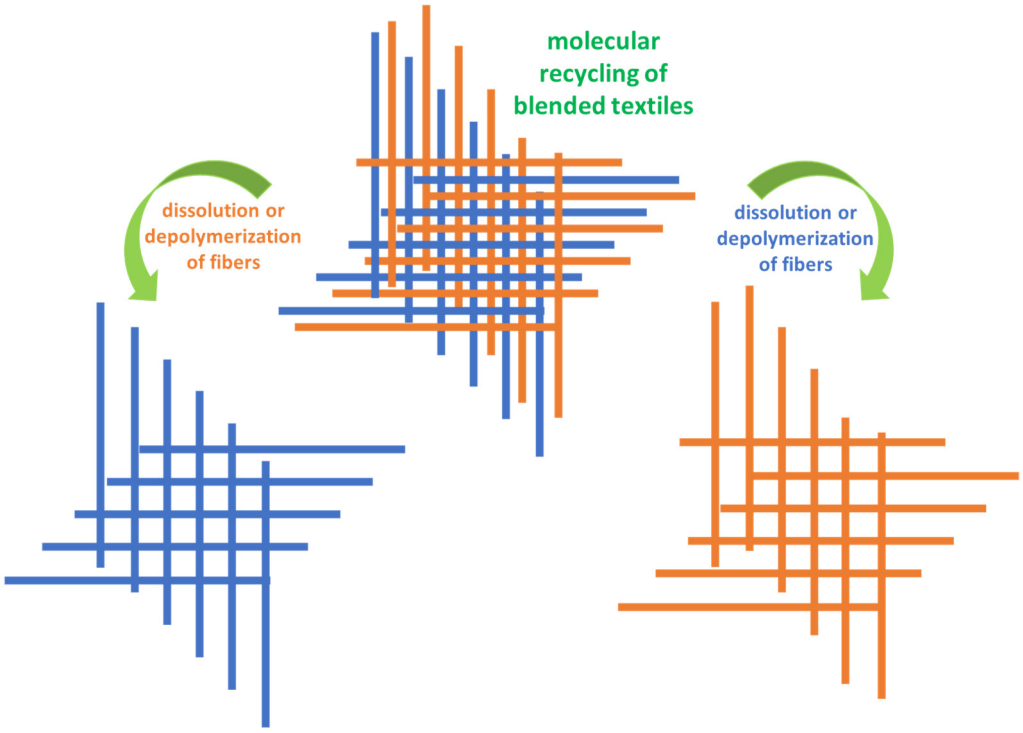


Figure 10. Molecular recycling of blended textiles. The different colors indicate different type fiber (e.g., cotton and polyester) in the blended textile. Selective treatment removes one type of fiber while leaving the other intact.

4.1. Dissolution of Cotton

Cotton is mostly cellulose. Cellulose consists of crystalline and amorphous regions. The crystalline regions contribute to cellulose's insolubility in water. Disassembling cellulose's supramolecular structure and separating the cellulose chains are required for cellulose to dissolve, either with or without the breaking of glycosidic bonds. Non-derivatizing solvents have the ability to disrupt the hydrogen-bonding network of native cellulose by creating new hydrogen bonds with the hydroxyl groups in cellulose, which would ultimately disrupt the crystalline structure of the material. Derivatizing solvents chemically change cellulose by reactions with hydroxyl groups, which disrupts the hydrogen-bonded network [53,60]. Non-derivatizing solvents for cellulose dissolution include NMMO, acidic aqueous solutions (e.g., H_2SO_4, HCl), alkaline aqueous solutions (e.g., NaOH, LiOH), ionic liquids, and deep eutectic solvents. Common ionic liquids utilized for cellulose dissolution include 1,5-diazabicyclo [4.3.0]non-5-enium acetate, [DBNH] [OAc], 1-allyl-3-methylimidazolium chloride (AMIMCl), and 1-butyl-3-methylimidazolium acetate (BMIMAc). Derivatizing solvents for cellulose include N_2O_4/DMF, HCOOH/H_2SO_4, etc. The extensive literature on biomass utilization that discusses the conversion of cellulose into valuable products offers significant insights and techniques that can be directly applied to the recycling of cotton [53,61,62].

On the topic of dissolution of cotton, our review of the literature identified the following studies:

1. To separate the cellulose (cotton and viscose) from blended-fiber waste textiles, NMMO was utilized [63]. Figure 11 depicts the dissolution of cellulose using NMMO. Textiles with 50/50 polyester/cotton and 40/60 polyester/viscose blends were tested. Textile pieces were mixed in 85% *w*/*w* NMMO solution in water at 120 °C for 2 h at atmospheric pressure. Following NMMO treatment, the polyester was recovered as fibers. Up to 95% of the cellulose fibers were removed from the textile sample as the cellulose dissolved in NMMO. The cellulose was then either hydrolyzed by cellulase enzymes, followed by fermentation to ethanol, or digested directly to produce biogas [63].

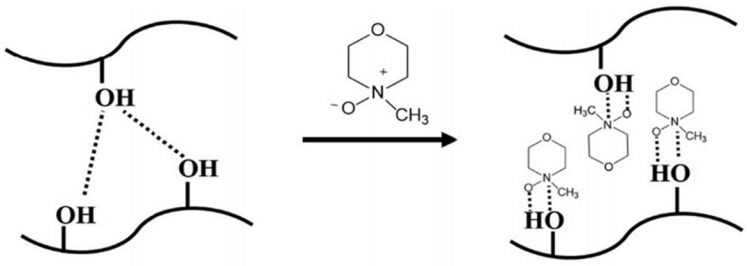


Figure 11. Proposed mechanism of dissolution of cellulose using NMMO. Reproduced from [64]. Copyright 2022, the authors.

2. 1,5-diazabicyclo[4.3.0]non-5-enium acetate, [DBNH] [OAc], an amidine-based ionic liquid, was used as selective cellulose solvent to separate cotton from polyester [65]. The textile was white post-consumer 50/50 wt% cotton polyester blend. The samples were shredded and blended to obtain a mixture. Using a vertical kneader system, the cotton polyester blend was combined with [DBNH] [OAc] (for 1 h, at 80 °C) to produce a 6.5 wt% cellulose solution. An extremely viscous spinning dope was produced when 13–15 wt% cellulose was dissolved in [DBNH] [OAc] at 80 °C. Hydraulic pressure filtering was used to separate the undissolved polyester fraction from the cellulose solution. After solidification by storing at 8 °C for a few days, the resultant solidified cellulose was used for dry-jet wet spinning. Lyocell-like characteristics were observed in the spun fibers, including linear densities ranging from 0.75 to 2.95 dtex (dtex or deci-tex is a unit of linear density, which is grams per 10,000 m of yarn) and elongations from 7 to 9%. The molar mass distributions (MMD) of the polyester and cellulose fractions were ascertained by size exclusion chromatography. PET degraded visibly as evidenced by a decline in its MMD (<51%) and tensile characteristics (<52%). To slow down the degradation of PET, process condition adjustment may be required, particularly concerning filtering and dissolving. The presence of other components (e.g., dyes) was not reported in this study [65].

3. 1-allyl-3-methylimidazolium chloride (AMIMCl) and 1-butyl-3-methylimidazolium acetate (BMIMAc) ionic liquids were used to selectively dissolve the cotton (cellulose) component from 50/50 wt% cotton-polyester blended yarn [66]. Before being dissolved, all yarn specimens were oven-dried to eliminate any moisture. Up to 10% yarn was added to AMIMCI at 80 °C. After six hours, the undissolved component was taken out, washed with water, and weighed. There was minimal variation in the amount of time needed to dissolve the cotton component in either BMIMAc or AMIMCI at 80 °C and 100 °C. At 120 °C, the cotton dissolved much faster for both ILs. Fibers and/or films could be made from the cotton/AMIMCI solution as illustrated in Figure 12.

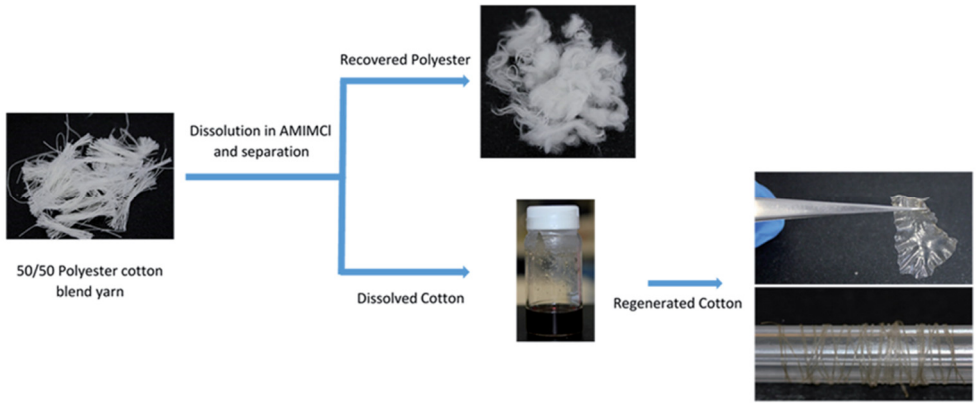


Figure 12. Separation of polyester/cotton blends using AMIMCI. Cotton was selectively dissolved in AMIMCI and regenerated into cellulose fiber or film. Polyester was recovered as solid fiber. Reproduced with permission from [66]. Copyright 2014, Royal Society of Chemistry.

The morphology of the materials was examined with scanning electron microscope (SEM). Before separation, both cotton and polyester fibers could be observed. After the separation, only polyester fibers were observed in the SEM images (Figure 13). Following the dissolution of cellulose, a small quantity (less than 2%) of cotton may have still been present in the recovered polyester, according to ^{13}C Nuclear Magnetic Resonance (NMR) and Fourier-transform infrared spectroscopy (FTIR) spectra. The treated sample underwent thermogravimetric analysis (TGA) to characterize the structure of the recovered polyester and cotton. The TGA curves showed little to no difference between the sample and recovered material for both cotton and polyester [66].

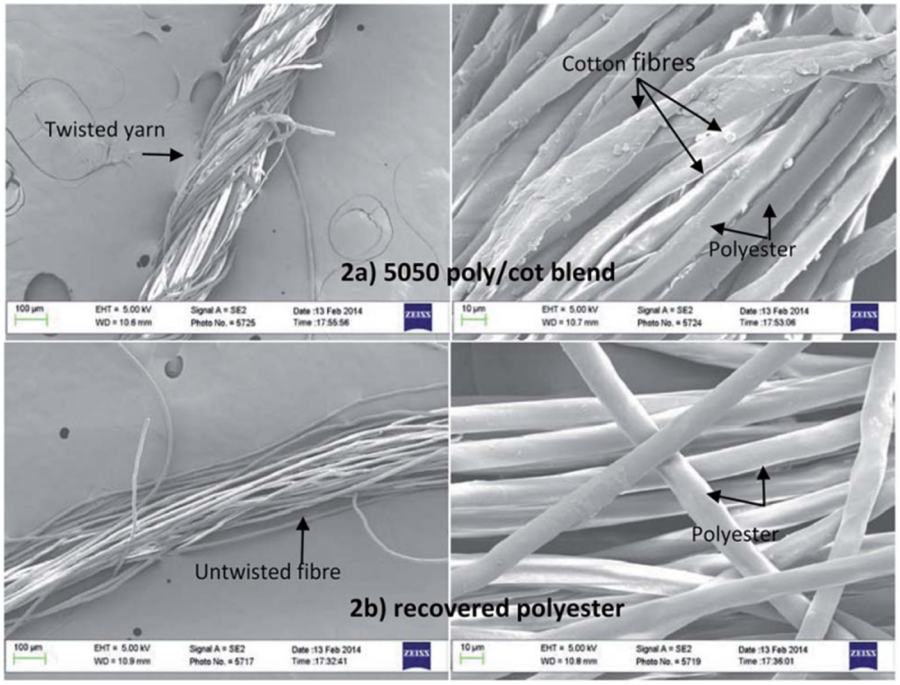


Figure 13. (top panels) SEM images of polyester/cotton blend; (bottom panels) SEM image of recovered polyester. Reproduced with permission from [66]. Copyright 2014, Royal Society of Chemistry.

4. 1-allyl-3-methylimidazole chloride ([Amim]Cl)/dimethyl sulfoxide (DMSO) and 1-ethyl-3-methylimidazolium diethyl phosphate ([Emim] DEP)/DMSO mixtures selectively dissolved cotton from waste poly-cotton fabrics: long-worn lab coats with 35% cotton/65% polyester fabric composition [67]. [Amim]Cl and [Emim]DEP acted as solvents and DMSO as the cosolvent to selectively dissolve cotton in the waste polycotton fabrics. It proved difficult to separate the polyester from the cotton-containing [Emim]DEP solution because of its high viscosity. Accordingly, DMSO was added to significantly lower the IL solution viscosity, which was great for mass transfer and fluid flow. Wet spinning was applied to the cellulose solution that was produced by the procedure. Melt-spinning was used to prepare the polyester into regenerated polyester fibers. The dissolution rate of cotton from the waste poly-cotton fabrics was 99.9% when the mass ratio of [Emim]DEP/DMSO was 5:5, the sample size was 1.0 × 1.0 cm, the cotton content was 1.4 wt%, the dissolution temperature was 80 °C, and the duration was 60 min.

The degree of polymerization DP of the sample fabric's cellulose portion was 1087. DP of the regenerated cellulose using [Amim]Cl/DMSO and [Emim]DEP/DMSO was decreased by 24.4% and 2.9%, respectively. A pneumatic single fiber strength machine was used to assess the regenerated fiber samples' strength and elongation at break. The breaking strength was 1.7 cN/dtex, and the elongation at break was 16.7%. The surface and cross-section of the regenerated cellulose fibers were captured with SEM micrographs, which showed that the regenerated cellulose fibers were cylindrical with a dense and smooth surface. FT-IR was used on the waste poly-cotton textiles, regenerated cellulose,

and regenerated cellulose fibers to confirm whether the functional group of cotton altered during the dissolution process. The FT-IR characteristic peaks of regenerated cellulose and regenerated cellulose fibers were essentially the same, indicating that no chemical reaction occurred during normal regeneration and wet spinning process. The dissolution of cotton from waste poly-cotton fabrics with [Emim]DEP/DMSO was further tested by XRD. The XRD patterns revealed that the waste poly-cotton fabrics initially exhibited diffraction peaks corresponding to both cellulose I-type structure and polyester crystal structure. After the cotton was dissolved and separated, the crystallization peak positions of the regenerated cellulose shifted, indicating a transformation from type I to type II structure [67].

5. Polyester/cotton (65%/35%) blended fabric was effectively separated using a low-eutectic solvent/deep eutectic solvent (DES), which was based on the metal salt hydrates shown in Figure 14 [68]. Zinc chloride, water, and phosphoric acid were the three components used in a precise ratio to create DES. This solvent could dissolve the cotton fibers in blended fabrics in a selective manner without damaging the polyester fiber component. For the dissolution, the mixture was agitated at a speed of 600 rpm with a cellulose-to-solvent ratio of 5:100. The separated polyester fiber was used as the raw material for the melt-spinning process, which produced recycled polyester fiber. To create regenerated cellulose fibers, cellulose was recovered from the DES solution system via coagulation and then dissolved in a NaOH/urea/H_2O solvent for wet spinning. The FTIR spectrum of regenerated PET was very similar to that of original PET, indicating the stability of the PET structure before and after separation. The cotton fabric's XRD diffractogram displayed the standard cellulose I pattern. The regenerated cellulose that came from the DES showed peaks that correspond to cellulose II patterns. These results pointed to a conversion of cellulose I into cellulose II, which was accompanied by a fast dissociation and reformation of intra- and intermolecular hydrogen bonds between cellulose molecules [68].

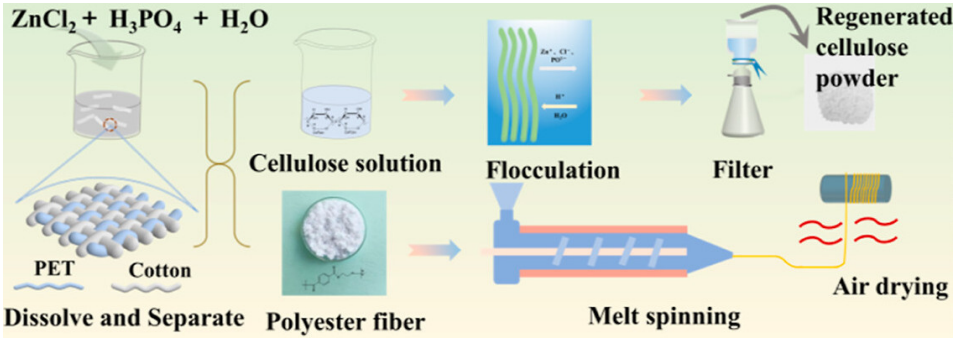


Figure 14. Schematic of the dissolution and separation process of polyester/cotton-blended textiles using DES. Reproduced with permission from [68]. Copyright 2024, American Chemical Society.

6. Acetylation of cellulose using as the heterogeneous catalyst [Hmim]HSO_4, an acidic IL N-methyl-imidazolium bisulfate, was used to separate a waste polyester/cotton (65/35 wt%) blended fabric (WBF) [69]. In the study, 4.63 g pulverized WBF, 20.42 g acetic anhydride, and 0.18–1.08 g [Hmim]HSO_4 were mixed and heated at 100 °C for 12 h under atmospheric pressure. The reaction mixture was then added to 100 mL ethanol. The cellulose acetate (CA) and PET-containing material were filtered, washed three times with ethanol, and then dried for 12 h at 60 °C in a vacuum oven. A portion of the sample was refluxed for 12 h using the Soxhlet extraction method and acetone as the solvent to extract the acetone-soluble CA. The acetone-soluble CA product was then obtained by vacuum-drying the filtrate for 12 h at 60 °C. Using dimethylformamide (DMF) as the solvent, the solid portion of the sample was refluxed for 12 h using the same procedure. This led to the extraction of DMF-soluble CA and the regeneration of PET. Comparison of FTIR spectra of the produced CA to that of commercial cellulose, demonstrated acetylation due to the existence of two significant ester bonds at 1752 cm^{-1}, due to C=O ester stretching, and 1235 cm^{-1}, which was assigned to the –CO– stretching of the acetyl group. Comparable

structural features were indicated by the similar XRD signals of the obtained CA and commercial CA. The XRD pattern of the obtained CA matched the crystalline cellulose I structure. The replacement of acetyl groups for hydroxyl groups during the acetylation process was considered the cause of this decrease in crystallinity [69].

7. Pre-consumer polycotton waste fabric (80%/20% and 50%/50% polyester/cotton) was processed with a mixed solvent of the ionic liquid 1-butyl-3-methylimidazolium acetate ([Bmim]OAc) and DMSO to dissolve cellulose [70]. Fabric samples were first treated with an aqueous solution containing 0.5 wt% sulfuric acid to reduce the degree of polymerization (DP) of the cotton component. The fabric concentration in the sulfuric acid solution was 5 wt% for the 80/20 polycotton blend and 2 wt% for the 50/50 blend. Subsequently, the samples were treated with a mixture of 20% ionic liquid and 80% DMSO. After 24 h, the solution was filtered using a syringe filter with a 15 mm metal mesh. The cellulose dope filtrate was collected for spinning, while the solid polyester material was washed, dried, and rinsed with DMSO to remove residual cellulose (shown in Figure 15) before being air-dried. The morphologies of the fabrics and recovered materials were examined by SEM, which confirmed the removal of cotton from the polycotton blend. The separated fibers retained the original color of the waste textile [70].

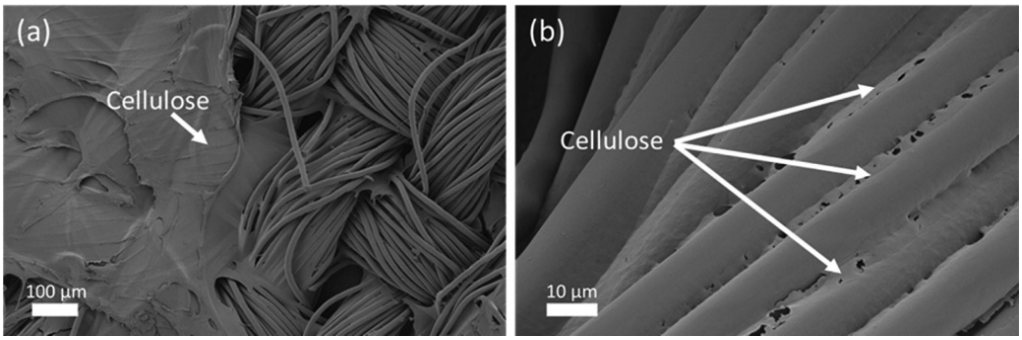


Figure 15. SEM images of recovered polyester fabric at low (**a**) and high (**b**) magnification showing the residual cellulose film remaining on the polyester fibers before the DMSO rinse step was introduced. The regenerated cellulose film is labeled as 'Cellulose'. Reproduced with permission from [70]. Copyright 2023, Textile Institute.

4.2. Dissolution of Polyester

Selectively dissolving the polyester component from a poly-cotton blend is a promising method to separate the poly-cotton blend. The dissolution of polyester involves two transport processes: solvent diffusion and polymer chain disentanglement. Solvent molecules initiate dissolution by penetrating and swelling the polymer. Chain disentanglement occurs when the polymer chains separate and self-diffuse in the presence of the solvent. The solvents used to dissolve PET include DMSO, DMF, acetone, trichloroacetic acid, etc. [71–73]. Our review of the literature identified the following studies:

1. A poly-cotton blend (80/20 cotton/polyester jeans) was separated by a three-step process as follows: leaching with nitric acid, dissolving with DMSO, and bleaching with a solution of sodium hypochlorite and diluted HCL [74]. These methods were used to rid of textile dyes, dissolve the polyester component and remaining organic part from textile dyes, and finally free the cotton fiber. Dyes from blue and black samples were dissolved using 1.0 M and 1.5 M HNO_3, with an average treatment duration of 20 min. 1 g samples of two different types of jeans were treated with 10–80 mL solvent at 50 °C. The black sample could be fully separated in 7 h with 40 mL solvent, while the blue sample needed 9 h and 60 mL solvent. Under soundwave treatment for 2 h at 40 °C, the cotton fibers were bleached with sodium hypochlorite and diluted hydrochloric acid to remove any leftover contaminants. FTIR showed that all dyes and contaminating elements were successfully removed by leaching, dissolving, and bleaching, and that the recovered fiber was made of highly pure cotton. Thermogravimetric/Derivative Thermogravimetric analysis (TGA-DTG) was used

to investigate the thermal degradation and stability trends of the precipitated polyester. The decomposition methods of the black and blue samples were similar and observed within the 80–365 °C range [74]. Figure 16 shows photos of untreated/treated black (A–D) and blue (E–H) samples at different periods during leaching and dissolution.

Figure 16. Waste denim fabric before and after being subjected to leaching and dissolution treatments: (**A**,**E**) untreated samples, (**B**,**F**) bare fabric after dyes leached, (**C**,**G**) treated fiber at the middle of the dissolution process, and (**D**,**H**) treated fiber at the end of the dissolution process. The scale was not reported in the article. Reproduced with permission from [74]. Copyright 2019, Elsevier.

2. From a colored 50/50 polyester/cotton blended fabric, dyes, polyester, and cotton were separated by dissolution and precipitation [75]. One part polyester/cotton and three parts DMSO were combined at 150 °C. Dissolution took place in about five minutes. After cooling down, the polyester precipitated. The dispersed dyes were extracted by washing the material with a small amount of heated DMSO. Following the separation of polyester and dispersion dyes, solvents containing varying ratios of DMSO to water were added to the remaining cotton fabric to swell the cellulose. The covalent bonds between the reactive dye and cellulose were broken by adding 0.07–0.6 wt% NaOH to the DMSO/water solvent. To completely separate the color from the cotton, the material was swollen three times. Every cycle lasted 10 min at 90 °C. Each cycle's weight ratios for the solution to cotton were 3. The dried polyester was wet spun at 270 °C into recycled polyester fibers. By stirring at 110 °C for two hours, a solution comprising 5% color-removed cellulose, 87 wt% NMMO, and 13 wt% water was created. Through dry-jet wet spinning, the cellulose solution was turned into fibers. The structures of fibers were determined by XRD and compared to virgin fibers. The recycled and virgin fibers had similar crystallization behavior. The FTIR spectra of the cellulose and the polyester were found identical both before and after the separation [75].

4.3. Hydrolysis of Cotton or Polyester

The chemical disintegration and deterioration of polymers brought on by prolonged contact to heat and humidity is known as hydrolysis. Simple esters are readily hydrolyzed by diluted acids or alkalis. Aqueous alkalis like NaOH can easily hydrolyze polyester at a concentration of 4–20 wt% at 210–250 °C, producing terephthalic acid (TPA) and ethylene glycol (EG) [76]. Our review of the literature identified the following studies:

1. Cotton polyester blended bed sheets comprised 48 wt% cotton and 52 wt% polyester was tested for PET hydrolysis at a temperature between 70 and 90 °C using 5–15 wt% aqueous NaOH. TPA and EG were produced during the process as shown in Figure 17 [77]. The technique produced three distinct product streams. First was the cotton; second, the TPA; and third, the filtrate containing EG and the process chemicals. Solid cotton residue

was separated by filtering, TPA was precipitated, and EG was in the filtrate. NMR revealed that the recovered TPA was free of any impurities. Following PET hydrolysis, the solid (cotton) residue's ATR FT-IR spectra were compared to a sample of pure cotton. This demonstrated that cellulose I had somewhat changed into cellulose II. Under the highly alkaline conditions used in the PET-removing procedure, undesired cellulose degradation reactions may also occur in the cellulose portion of a polycotton sample. These processes caused cellulose chains to break, which lowered the cellulose DP [77].

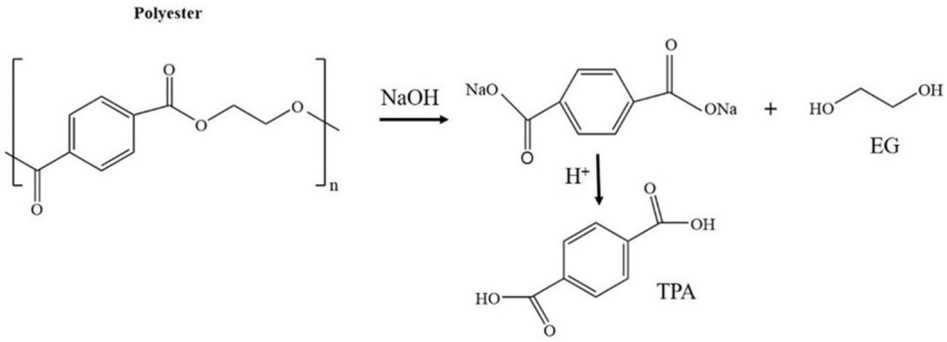


Figure 17. Alkaline hydrolysis reaction of polyester. Reproduced from [64]. Copyright 2022, the authors.

2. To separate polyester from cotton fiber, a waste polyester/cotton mixed fabric (composition not disclosed) was first cut into small pieces, treated with sulfuric acid (acidic hydrolysis of cotton), and then crushed in a grinder. After being treated, the blended polyester/cotton cloth was washed and dried. Using a grinder, the cotton fiber powder and the polyester fibrous mass were produced [78]. The separated cotton fibers' retention of their cellulose structure was validated by FTIR analysis, which also showed signs of lignin or hemicellulose removal post treatment. XRD indicated that the crystallinity of the separated cellulose fiber was very high, and it was the structure of cellulose type I. The morphology of the separated polyester and cotton fibers was investigated using SEM. Following acid hydrolysis and mechanical agitation, the cotton fiber had surface damage, fractures, and a marked reduction in length. The surface of the treated polyester fiber remained intact, and it contained a small amount of cotton fiber [78].

3. Alkaline hydrolysis of polyester has been shown effective in separating viscose:polyester (70:30) blended textiles. Oven-dried textile sample was added to heated (90 °C) aqueous NaOH (5 wt%), and hydrolysis was performed for a selected time (60–1440 min). Depolymerization of polyester produced TPA, whereas viscose was recovered as a solid residue via filtration from the reaction solution. The purity of the TPA obtained from PET depolymerization was established with NMR. The alkaline treatment reduced the intrinsic viscosity of the recovered cellulose by up to 35% [79,80].

4.4. Hydrothermal Treatment

Hydrothermal treatment utilizes high-temperature and pressure water as the solvent for the hydrolysis reaction, typically carried out in high-pressure reactors at 5–25 MPa with an acid catalyst present, at temperatures between 110 and 180 °C from 0.5 to 3 h. Cotton fibers break down throughout the reaction as a result of the breaking of the 1,4-β glycoside bond within cellulose [33].

Our review of the literature identified the following studies:

1. A hydrothermal method for removing cotton and PET from waste cotton/polyester (65/35) blended fabrics (WBFs) used diluted hydrochloric acid as a catalyst for cellulose hydrolysis. While the PET component of the WBF maintained its fibrous structure, the cotton component hydrolyzed and turns into cellulose powder or oligosaccharide [81]. This made the combined fabric ingredients separate effectively. Before hydrolysis, the sample was divided into tiny fragments (5 × 2 cm^2), washed with water, dried, and stored for later use in a desiccator. Cotton fiber started to hydrolyze at 120 °C under acid catalysis conditions, whereas polyester hydrolyzed at 180 °C. The components could be separated

under hydrothermal conditions because of the difference in the hydrolysis temperatures of the cotton and polyester in the mixed fabric. The cotton/polyester blended fabric hydrothermal degradation studies were conducted in a high-pressure batch stainless steel reactor fitted with a polytetrafluoroethylene liner. In a closed reactor, each dry sample (2.0 g) was combined with 0.5–2.5 wt% hydrochloric acid and heated to the required temperature (110–170 °C) at 60% consistency. After the reaction was complete, the solid residues were collected by filtration, cleaned, and oven-dried for six hours at 80 °C in a vacuum oven. The powdered cellulose made up the majority of the hydrolysis result, and some of it broke down into oligosaccharides that dissolve in water. Simultaneously, the polyester in the blended cotton/polyester fabric was stable, did not hydrolyze, and the end products continued to be polyester fiber. After 3 h at 150 °C, almost all of cotton had hydrolyzed. Using techniques such as SEM, FTIR, XRD, and high-performance liquid chromatography, the morphology and structure of the hydrothermal products—both solid and liquid—were characterized and compared to untreated polyester and cotton. The results indicated that after three hours of hydrolysis at 150 °C with 1.5 wt% diluted HCL, the polyester fiber preserved its fiber properties while the cotton fiber entirely degraded. The hydrolysis did not alter the crystalline structure of cellulose, as seen by the essentially similar XRD patterns of cotton and cellulose powder. The fabric in this investigation was blue; however, the fate of the blue dye was not reported in this study [81].

2. Hydrothermal treatment was used to treat white shirts of 66% cotton and 34% polyester [82]. After being cut into pieces measuring around 5 by 5 cm^2, the sample cloth was added to a reactor that held 300 mL pure water. The cloth was treated for 10–180 min at 180–250 °C. The reactor was then allowed to naturally cool to 40 °C. After the reactant fabric was taken out, filtering was used to recover the solid residue in the water. While cotton remained in its cloth state, the heat treatment at 230 °C for 10 min eliminated practically all polyester from the fabric sample. After the treatment, the fabric was removed, and a membrane filter was used to recover the solid residue in the water. The fabric (cotton) and solid residue (polyester) were then dried in an oven. Using SEM, the surface conditions of the treated mesh fabric were compared to those of the raw material. Following treatment, SEM images demonstrated that the cotton fiber condition was preserved. It was also evident that the fibers had suffered some little damage from the 230 °C treatment. It was hypothesized that the cotton fibers gradually deteriorated due to the subcritical water treatment. FTIR examination verified the minute fragments and powdery material obtained after treatment to be PET and the mesh fabric to be cotton [82].

4.5. Enzymatic Hydrolysis of Cotton or Polyester

Enzymatic hydrolysis is a suitable process for recycling textiles made of cotton and polyester. Enzymes are available that can selectively degrade cellulose or polyester [36,83–85]. Our review of the literature identified the following studies:

1. In the study, 60/40 cotton/polyester (PET) blend textile was hydrolyzed enzymatically using cellulase and β-glucosidase to extract glucose and recover polyester fiber. The maximum glucose recovery yield was 98.3%, obtained with 20 FPU/g cellulase (FPU means filter paper units, the quantity of enzyme needed to catalyze the release of one μmol of glucose equivalent per minute is define as 1 FPU) and 10 U/g β-glucosidase at 3% (*w*/*v*) substrate loading, at 50 °C and pH 5 [86]. The recovered PET could be reused by melt spinning to new PET fiber. SEM comparison of the textile surface morphology before and after enzymatic hydrolysis revealed notable alterations. Before hydrolysis, polyester and cotton fibers were firmly bonded together to form a compact structure. Small holes were created, and fewer fibers were left behind during hydrolysis. This happened because non-biodegradable polyester fibers remained intact while cellulose fibers were broken down into soluble sugars. No structural alterations in the recovered polyester fibers were discerned [86].

2. In 65% PET/35% cotton and 80% PET/20% cotton mixed textiles, PET could be directly and selectively depolymerized to TPA using a commercial cutinase from *Humicola*

insolens under moist-solid reaction conditions [56]. This process was easily combined with cotton depolymerization through simultaneous or sequential application of Cellic CTec2 cellulases blend, yielding glucose. After cutting the textile samples into squares measuring 0.7 cm × 0.7 cm, they were ball milled for 5 or 30 min (30 Hz) in 15 mL stainless-steel milling jars with HiC (0.65% *w*/*w*) and/or CTec2 (0.7% *w*/*w*) enzymes present. This was followed by seven days of static incubation at 55 °C. TPA (with a maximum yield of 30 ± 2%) and glucose (with a maximum yield of 83 ± 4%) were obtained through the mechanoenzymatic hydrolysis of the PET/cotton blended textile. Additionally, ethylene glycol (yield unknown) and a small reaction product, up to 0.5% yield of mono(2-hydroxyethyl) terephthalate (MHET), were produced by the hydrolysis of PET [56].

3. Alkali pretreatment was assessed to enhance polyester recovery and ethanol production from the cellulose portion of a white 40/60 polyester/cotton blended fabric [87]. Several alkali solutions of NaOH (12 wt%), NaOH/urea (7/12 wt%), NaOH/thiourea (9.5/4.5 wt%), and NaOH/urea/thiourea (8/8/6.4 wt%) were used for the pretreatment, which lasted 1 h at −20 °C, 0 °C, 23 °C, and 100 °C. The yield of enzymatic hydrolysis using cellulase and β-glucosidase improved to over 88% because of all pretreatments, compared to 46.3% for the untreated textiles. After pretreating the textile with NaOH/urea at 20 °C, the maximal yield of ethanol production from the textile by simultaneous saccharification and fermentation was 70%, compared to only 36% for the untreated material. Following the hydrolysis of the cellulose portion of the material, the remaining solid polyester portion was recovered. In addition, 98% of the polyester was recovered after the alkaline pretreatment and hydrolysis, and its characteristics remained mostly unchanged. FTIR revealed that, after the polyester was treated with NaOH, the trans/gauche ratio dropped, indicating a reduction in the crystalline area. Compared to untreated PET, the polyester's crystallinity was somewhat reduced as a result of the alkaline pre-treatment [87].

4. Different cotton/polyester blended textiles were subjected to pretreatment with autoclaving, freezing alkali/urea soaking, and alkali for textile recycling. A 60/40 cotton/PET textile with 15% NaOH pretreatment at 121 °C for 15 min proved ideal for enzymatic hydrolysis of cellulose [88]. Moreover, 7% substrate loading and 30 FPU/g enzyme loading produced a maximum hydrolysis yield of 90%. The products were liquid glucose and solid PET. After processing with NaOH, SEM showed notable changes in the surface morphology of textile sample. At first, the fabric had a surface that was a little uneven and harsh. However, after treatment, the cotton/PET digestion by NaOH caused a partial breakdown of the textile's structure into rough fibers. The textile samples were examined using FTIR both before and after processing. PET and cellulose polymer-corresponding absorption bands were visible in the FTIR spectra. Significant alterations in the cellulose polymer bands were found upon analysis of the pretreated textile waste, demonstrating the pretreatment process efficacy in changing the polymer structure [88].

5. Phosphoric acid pretreatment and subsequent enzymatic hydrolysis was used to separate a sample of poly-cotton blend (used jeans, composition not reported). Two enzymes were used for cellulose hydrolysis: cellulase from *Trichoderma reesei* and cellobiase from *Aspergillus niger* [89]. Phosphoric acid pretreatment was performed with 85% phosphoric acid, at 50 °C, for 7 h, and a ratio of fabric and acid of 1:15. In 150 mL flasks with a 50 mL work volume, the regenerated cellulose was enzymatically hydrolyzed in 50 mM sodium citrate buffer (pH 4.8). With a cellulase loading of 7.5 FPU/g regenerated cellulose and a cellobiase loading of 15 CBU/g regenerated cellulose, the substrate consistency for enzymatic hydrolysis was maintained at 1.0% (*w*/*v*). The hydrolysis was carried out for 96 h at 50 °C in an air-bath shaker at 130 rpm. Polyester was recovered in solid form. At the optimized conditions 100% polyester recovery with a maximum sugar recovery of 79% was accomplished. Surface morphology was analyzed using SEM. Distinct cotton and polyester fibers were visible in the original waste textiles sample. The cellulose fibers changed significantly and became rougher after pretreatment. The majority of cotton fibers remained intact after enzymatic hydrolysis without pretreatment, underscoring the necessity of pretreatment for effective sugar recovery. Cotton was effectively extracted

from polyester using phosphoric acid pretreatment, resulting in 100% polyester recovery without changing the surface of the polyester as seen on SEM images [89].

6. Cotton and polyester can be separated from a blended textile (with a composition of 65% polyester, 35% cotton) with alkaline pretreatment (NaOH/urea) followed by cellulase-based enzymatic hydrolysis of cellulose [90]. In the study, 4 g textile was pretreated in 400 mL NaOH/urea solution. Using 50 mM citric acid buffer at pH 5.0 and sodium azide (0.02%), hydrolysis was carried out in a 1 L flask. In a 500 mL buffer, the textile substrate was added with a solid load of 0.8% (w/v). The activity of the enzyme dose was adjusted to 0.68 FPU per g of cellulose. For 24 h, hydrolysis was carried out in a heating incubator at 50 °C and 70 rpm orbital shaking. Cellulose could be completely recovered as glucose while preserving the quality of the polyester. FTIR analysis compared untreated textile blend, pure polyester, and regenerated polyester fibers. It revealed decreased peaks characteristic of cellulose and increased peaks characteristic of PET [90].

All studies published since 2010 that have discussed the separation of cotton from polyester are summarized in Table 2, which reports the type of method used, starting material and composition, process or reaction taking place, process or reaction conditions, products obtained, analysis and findings, and any issues or problems. These studies are organized according to the method used.

Table 2. Summary of studies regarding the separation of poly-cotton.

#	Method	Starting Material and Composition	Process/Reaction	Process/Reaction Conditions	Products	Analysis	Any Other Component Present	Issue/ Problem	Reference
1	Dissolution of Cotton	Textiles blended with 40/60 polyester and viscose and 50/50 polyester and cotton.	N-methylmorpholine-N-oxide (NMMO), was utilized in this procedure to separate cellulose (cotton and viscose) from blended textiles.	85% *w*/*w* NMMO solution in water was mixed with 15 g of the textile pieces at 120 °C in an oil bath for 2 h under atmospheric conditions.	The products were cellulose solution and undissolved polyester. The cellulose was then either hydrolyzed by cellulase enzymes followed by fermentation to ethanol, or digested directly to produce biogas.	Gas chromatography was used to measure the amount of methane produced during anaerobic digestion. Within 6 days of digestion, 53–62% of the theoretical yield of methane was obtained.	After 2 h treatment, non-cellulosic fibers, and other impurities, e.g., buttons and zippers remained as the solid phase while cellulose is dissolved in the liquid phase.		[63]
2	Dissolution of Cotton	White post-consumer textiles. The composition of the poly-cotton blend was 50:50.	[DBNH] [OAc], (1,5-diazabicyclo[4.3.0]non-5-enium acetate) an amidine-based Ionic Liquid, was used as a selective cellulose solvent to separate cotton from polyester.	Using a vertical kneader system, the cotton polyester blend was combined with [DBNH] [OAc] (for 1 h, at 80 °C).	The products were cellulose solution and undissolved polyester. Hydraulic pressure filtering separated the undissolved polyester fraction from the cellulose solution. After solidification, by storing at 8 °C for a couple of days, the resultant cellulose was spun through dry-jet wet spinning.	The molar mass distributions (MMD) of the polyester and cellulose fractions were ascertained using size exclusion chromatography.PET degrades visibly in this method as evidenced by a decline in its MMD (<51%). The linear density, elongation at break, and tenacity of every spun fiber were measured. Linear densities ranging from 0.75 to 2.95 dtex, (dtex or deci-tex is a unit of linear density, which is grams per 10,000 m of yarn) and elongations of 7 to 9%.		PET degraded visibly in this method once it was dispersed in [DBNH] [OAc], as evidenced by a decline in its MMD (<51%) and tensile characteristics (<52%).	[65]
3	Dissolution of Cotton	The cotton polyester blended yarn consisted of 50 wt% cotton and 50 wt% polyester.	To recover cotton from the cotton-polyester blend, cellulose-dissolving ionic liquid 1-allyl-3-methylimidazolium chloride (AMIMCl) and 1-butyl-3-methylimidazolium acetate (BMIMAc) was used to selectively dissolve the cotton component.	Dissolution in AMIMCl at 80 °C for 6 h.	The products were cellulose solution and undissolved polyester. 100% of the cotton from the blend dissolved. Undissolved polyester was removed by filtering. Fibers and/or films can be made from the cotton/AMIMCI solution.	SEM was used to examine the morphology of the materials. Before separation, both cotton and polyester fibers can be observed. After the separation, only polyester fibers are observed in the SEM image. Following the cellulose's dissolution, a small quantity (less than 2%) of cotton may still be present in the recovered polyester, according to the 13 C Nuclear magnetic resonance NMR spectra and FTIR spectroscopy. On a thermogravimetric analyzer, the treated sample underwent thermogravimetric analyses (TGA) to characterize the structure of the recovered polyester and cotton. The TGA curves showed little to no difference between the sample and recovered material for both cotton and polyester.		The ^{13}C NMR spectrum and FTIR indicated that a small amount (less than 2%) of cotton may remain with the recovered polyester.	[66]

Table 2. *Cont.*

#	Method	Starting Material and Composition	Process/Reaction	Process/Reaction Conditions	Products	Analysis	Any Other Component Present	Issue/ Problem	Reference
4	Dissolution of Cotton	Experiments were conducted using the long-worn lab suits as raw materials consisting of 35% cotton and 65% polyester.	Cotton can be selectively dissolved from waste poly-cotton fabrics using 1-allyl-3-methylimidazole chloride ([Amim]Cl)/Dimethyl sulfoxide (DMSO) and 1-ethyl-3-methylimidazolium diethyl phosphate ([Emim] DEP)/DMSO system as solvents.	([Amim]Cl) and ([Emim] DEP) as solvent, DMSO as a cosolvent. 0.4 g of waste poly-cotton fabrics combined with solvent (10 g ILs, 10 g DMSO) and dissolved for 5 h at 80 °C. To eliminate the cotton that remained on the regenerated polyester, it was treated for one hour at 50 °C with diluted sulfuric acid. After washing with water, it was dried for 48 h at 105 °C. It was put in a melt-spinning machine.	Wet spinning was used to immediately use the cellulose solution that was produced by the procedure. Melt-spinning was used to prepare the polyester into regenerated polyester fibers.	The cellulose's relative viscosity was determined, and the degree of polymerization DP of the material was calculated. DP of the sample fabric's cellulose portion was 1087. DP of the regenerated cellulose using [Amim]Cl/DMSO and [Emim]DEP/DMSO was decreased by 24.4% and 2.9%, respectively. The breaking strength of the regenerated fiber was found to be 1.7 cN/dtex, and the elongation at break was 16.7%. The surface and cross-section of the regenerated cellulose fibers were captured with SEM which showed that the regenerated cellulose fibers were cylindrical with a dense and smooth surface. The FT-IR characteristic peaks of regenerated cellulose and regenerated cellulose fibers were basically similar, indicating that no chemical reaction occurred during normal regeneration and wet spinning process. The dissolution of cotton from waste poly-cotton fabrics utilizing the [Emim]DEP/DMSO system as the solvent was further validated by XRD analysis. The XRD patterns revealed that the waste poly-cotton fabrics initially exhibited diffraction peaks corresponding to both cellulose I-type structure and polyester crystal structure. After the cotton was dissolved and separated, the crystallization peak positions of the regenerated cellulose shifted, indicating a transformation from type I to type II cellulose structure.		The degree of Polymerization of the regenerated cellulose decreased by 25.5% while using [Amim]Cl/ DMSO and 5.0% while using [Emim]DEP/DMSO.	[67]

Table 2. *Cont.*

#	Method	Starting Material and Composition	Process/Reaction	Process/Reaction Conditions	Products	Analysis	Any Other Component Present	Issue/ Problem	Reference
5	Dissolution of Cotton	Polyester-cotton blended fabric with a composition of 65% polyester, 35% cotton.	Selective dissolution of cotton from a poly-cotton blend using a deep eutectic solvent (DES) based on metal salt hydrates.	Synthesis of the metal-salt-hydrate-based DES: For 30 min, $ZnCl_2$, H_2O, and H_3PO_4 in the molar ratio of 1:3:0.5 were magnetically agitated to create a homogeneous ternary solvent. Dissolution: The combined fabric was put into DES. To begin the dissolving separation, the mixture was agitated at a speed of 600 rpm with a cellulose-to-solvent ratio of 5:100. The separated polyester fiber was used as the raw material for the melt-spinning process, which produced the recycled polyester fiber. To create regenerated cellulose fibers, cellulose was extracted from the DES solution system using the coagulation process and then dissolved in a NaOH/urea/H_2O solvent for wet spinning.	Cellulose fiber, Polyester fiber	The FTIR spectra of the blended fabric as well as separated polyester were obtained. The FTIR spectra of regenerated PET is very similar to that of original PET indicating the stability of the PET structure before and after separation. The cotton fabric's XRD diffractogram displayed the standard cellulose I pattern. The regenerated cellulose that came from the DES showed peaks that corresponded to cellulose II patterns. These results pointed to a conversion of cellulose I into cellulose II, which was accompanied by a fast dissociation and reformation of intra- and intermolecular hydrogen bonds between cellulose molecules.			[68]
6	Dissolution of Cotton	Waste polyester/cotton blended fabrics (WBF), with a composition of 65/35 wt%.	Acetylation of cellulose using a Bronsted acidic ionic liquid (IL) N-methyl-imidazolium bisulfate, [Hmim]HSO_4, as a novel catalyst.	Using [Hmim]HSO_4, an acidic IL N-methyl-imidazolium bisulfate, as the heterogeneous catalyst, acetylation of cellulose was performed at atmospheric pressure. 4.63 g of the pulverized WBFs powders, 20.42 g of acetic anhydride, and 0.18–1.08 g of the [Hmim]HSO_4 were mixed and heated at 100 °C for 12 h. The reaction mixture was then added to 100 milliliters of ethanol. The cellulose acetate (CA) and PET-containing material were filtered, washed three times with ethanol, and then dried for 12 h at 60 °C in a vacuum oven. A portion of the sample was refluxed for 12 h using the Soxhlet extraction method and acetone as the solvent to extract the acetone-soluble CA. The acetone-soluble CA product was then obtained by drying the filtrate for 12 h at 60 °C in a vacuum oven. Using DMF as the solvent, the solid portion of the sample was refluxed for 12 h using the same procedure. This led to the extraction of DMF-soluble CA and regeneration of PET.	Acetone-soluble CA and PET. With 84.5% of the cellulose in the WBFs converted, the highest yield of acetone-soluble CA was 49.3%; in the meantime, almost 96% of the PET was recovered.	The degrees of substitution (DS) values of the cellulose acetate (CA) products were determined by 1 H NMR spectroscopy. The acquired CA and the commercial CA sample's FTIR spectra were gathered. When the spectra of the produced CA were compared to the spectrum of commercial cellulose, they clearly demonstrated acetylation due to the existence of two significant ester bonds at 1752 cm^{-1}, which were given to C=O ester stretching, and 1235 cm^{-1}, which was assigned to the –CO– stretching of the acetyl group. XRD patterns were collected for obtained CA and commercial CA. Comparable structural features were indicated by the similar XRD signals of the obtained CA and commercial CA. The obtained CA's XRD pattern demonstrated a drop in peak intensities that matched to the crystalline cellulose I structure. The replacement of acetyl groups for hydroxyl groups during the acetylation process was the cause of this decrease in crystallinity.			[69]

Table 2. *Cont.*

#	Method	Starting Material and Composition	Process/Reaction	Process/Reaction Conditions	Products	Analysis	Any Other Component Present	Issue/ Problem	Reference
7	Dissolution of Cotton	Polycotton fabric (polyester cotton ratio was 80:20 and 50:50)	The separation was done by dissolution of cotton using a co-solvent system of ionic liquid and dimethyl sulfoxide	Fabric samples were treated with an aqueous solution containing 0.5 wt% sulfuric acid to reduce the degree of polymerization (DP) of the cotton component. Subsequently, the samples were treated with a solvent system of 80% DMSO and 20% ionic liquid. After 24 h, the solution was filtered. The cellulose dope filtrate was collected for spinning, while the solid polyester material was washed, dried, and rinsed with DMSO to remove residual cellulose solution before being air-dried.	Regenerated cellulose fiber and intact polyester.	The morphologies of the fabrics and recovered materials were examined by SEM. Which confirmed the removal of cotton from the polycotton blend.			[70]
8	Dissolution of Polyester	Black 100% cotton jeans and blue 80/20 cotton/polyester jeans.	Three-step process: (a) Textile dye leaching using Nitric Acid. (b) Dissolution process using Dimethyl Sulfoxide (DMSO) to dissolve the polyester and remaining organic part from textile dyes. (c) Bleaching using sodium hypochlorite and diluted hydrochloric acid for recovered cotton purification.	Dyes from blue and black samples were dissolved using 1.0 M and 1.5 M HNO_3, with an average treatment duration of 20 min. 1 g samples of two different types of jeans were treated with 10–80 milliliters of solvent at a constant temperature of 50 °C. The black sample could be fully separated optimally in 7 h with 40 mL solvent, while the blue sample needed 9 h and 60 mL solvent. Under soundwave treatment for 2 h at 40 °C, the cotton fibers were bleached with sodium hypochlorite and diluted HCl to remove any leftover contaminants.	Dissolved polyester in the spent solvent, cotton fiber.	FTIR spectroscopy was used to examine the chemical structure of the fiber samples both before and after the treatment. It showed that all dyes and contaminating elements were successfully removed by leaching, dissolving, and bleaching and that the recovered fiber was made of highly pure cotton. Thermogravimetric/Derivative Thermogravimetric analysis (TGA-DTG) was used to investigate the thermal degradation and stability trends of the precipitated polyester. The decomposition methods of the black and blue samples were similar and observed within the 80–365 °C range.			[74]

Table 2. *Cont.*

#	Method	Starting Material and Composition	Process/Reaction	Process/Reaction Conditions	Products	Analysis	Any Other Component Present	Issue/ Problem	Reference
9	Dissolution of Polyester	Colored 50/50 polyester/cotton blended fabric.	Using dimethyl sulfoxide (DMSO), the polyester component and dispersion dyes were extracted from blends of polyester and cotton. Following the breakdown of dye-cellulose linkages, the remaining colored cotton was swollen to remove its dyes. Regenerated fibers were created from colorless polyester and cotton.	One part polyester/cotton and three parts DMSO were combined at 150 °C. In about five minutes, the dissolution took place. After cooling down recycled polyester and dispersed dyes in DMSO, the polyester precipitated. The dispersed dyes were extracted by washing the material with a small amount of heated dimethyl sulfoxide. Following the separation of polyester and dispersion dyes, cellulose molecules were swelled by adding solvents containing varying ratios of DMSO to water to the cotton fibers that retained their color. Since reactive dyes and cellulose had covalent connections, the covalent bindings between the dye and cellulose were broken by adding 0.07–0.6 weight percent of NaOH to the DMSO/water solvent. To completely separate the color from the cotton, the material was swollen three times. Every cycle lasted 10 min at 90 °C. Each cycle's weight ratios for the solution to cotton were 3. At 270 °C, the dried polyester was wet spun into recycled polyester fibers. By stirring at 110 °C for two hours, a solution comprising 5% color-removed cellulose, 87 wt% NMMO and 13 wt% water was created. Through dry-jet wet spinning, the cellulose solution was extruded into fibers.	Colorless polyester and cotton which were regenerated into fibers.	Morphologies of the regenerated polyester and cellulose fibers were characterized by a field-emission scanning electron microscope. The structures of fibers were determined by X-ray diffraction. The recycled and virgin fibers had similar crystallization behavior. The cellulose's FTIR spectra were determined to be identical both before and after the separating procedure. The polyester's FTIRs before and after the separation procedure were identical.	Dyes were extracted as a dye solution.		[75]

Table 2. *Cont.*

#	Method	Starting Material and Composition	Process/Reaction	Process/Reaction Conditions	Products	Analysis	Any Other Component Present	Issue/ Problem	Reference
10	Hydrolysis	The cotton polyester blended bed sheets comprised 48 wt% cotton and 52 wt% polyester.	PET was degraded to terephthalic acid (TPA) and ethylene glycol (EG) using NaOH	5–15 wt% NaOH in water and temperature in the range between 70 and 90 °C for the hydrolysis of PET, for 40 min.	Three product streams were generated from the process. First is the cotton; second, the TPA; and third, the filtrate containing EG and the process chemicals. Solid Cotton residue (Separated by filtering), TPA was precipitated, and EG was in the filtrate.	NMR spectroscopy was used to characterize the polycotton bed sheets prior to separation. The degraded PET was analyzed using NMR spectroscopy, which revealed that the recovered TPA was free of any impurities. Following PET hydrolysis, the solid (cotton) residue's ATR FT-IR spectra were compared to a sample of pure cotton. This demonstrated that cellulose I had somewhat changed into cellulose II.		Under the highly alkaline conditions used in the PET-removing procedure, undesired cellulose degradation reactions may also occur in the cellulose portion of a polycotton sample. These processes cause cellulose chains to break, which lowers the cellulose's DP.	[77]
11	Hydrolysis	Polyester-cotton blended fabric. Composition is not mentioned in the study.	Acid treatment with Sulfuric acid then a grinder was used to crush it to separate the polyester from cotton fiber.	The waste polyester/cotton mixed fabric was split into 2 × 2 cm pieces and subjected to varying sulfuric acid concentrations over varying periods of time. After being treated, the blended polyester/cotton cloth was washed and dried. Using a grinder, the cotton fiber powder and the polyester fiber ball stained with the powder were produced. Subsequently, a certain volume of powdered cotton fiber was weighed and swelled using a NaOH solution. The pH was then brought to a neutral level. After using 64% sulfuric acid for a predetermined amount of time, the reaction was completed by adding 10 times as much deionized water. After being diluted, the mixture was dialyzed to neutrality and centrifuged. After a specific number of homogenizations using a high-pressure homogenizer, the treated solution's concentration was blended to 0.5% and freeze-dried.	The separated products were polyester as a fibrous mass and cotton powder. Nanocellulose from the cotton was obtained by further processing.	The separated cotton fibers' retention of their cellulose structure was validated by the FTIR analysis, which also showed signs of lignin or hemicellulose removal post treatment. XRD was used to examine the crystallinity of the separated cotton fiber which indicated that the crystallinity of cellulose fiber was very high, and it was the structure of cellulose type I. The morphology of the separated polyester and cotton fibers was investigated using SEM. Following acid hydrolysis and mechanical agitation, the cotton fiber had surface damage, fractures, and a marked reduction in length. The surface of the treated polyester fiber remained intact, and it was stained with a little amount of powdered cotton fiber.			[78]

Table 2. *Cont.*

#	Method	Starting Material and Composition	Process/Reaction	Process/Reaction Conditions	Products	Analysis	Any Other Component Present	Issue/ Problem	Reference
12	Hydrolysis	Garments with a blended fabric containing 70% viscose and 30% polyester	Alkaline hydrolysis of viscose/PET	The aqueous NaOH (5 wt%) was heated to 90 °C before adding the oven-dried (2 h at 105 °C) sample to the reaction vessel. Hydrolysis was performed for a selected time (60–1440 min). After the reaction, the solid residue was separated from the reaction solution via filtration.	The reaction yielded a solid cellulose residue, and the PET monomers terephthalic acid (TPA) and ethylene glycol (EG).	NMR was utilized to ascertain the purity of TPA derived from PET depolymerization, using a commercial TPA as the reference standard. The spectrum of the precipitate showed a distinct singlet at 7.58 ppm which was assigned to pure TPA.		The alkaline treatment reduces cellulose's intrinsic viscosity by up to 35%, hence it would not be appropriate for traditional fiber-to-fiber recycling.	[79,80]
13	Hydrothermal Treatment	A blue 65/35 cotton/polyester blend fabric served as the waste textile sample.	To recover cotton from the cotton-polyester blend, the cotton component was hydrolyzed and turned into cellulose powder or oligosaccharide using diluted hydrochloric acid as a novel hydrothermal treatment catalyst for cellulose.	1.5 wt% dilute hydrochloric acid at 150 °C, 3 h of reaction time.	Cellulose powder, polyester fiber.	Using techniques such as SEM, FTIE, XRD, and high-performance liquid chromatography, the morphology and structure of the hydrothermal products—both solid and liquid—were characterized and compared to untreated polyester and cotton. The results indicate that after three hours of hydrolysis, the polyester fiber preserved its fiber properties while the cotton fiber entirely degraded. The hydrolysis did not alter the crystalline structure of cellulose, as seen by the essentially similar XRD patterns of cotton and cellulose powder.	The fate of the blue dye was not reported in this study.		[81]
14	Hydrothermal Treatment	White shirts with a composition of 66% cotton and 34% polyester.	Hydrothermal treatment which separated polyester and cotton from the blend.	After being cut into pieces measuring around 5 by 5 cm^2, the sample cloth was added to a reactor that held 300 mL of pure water. The cloth was treated for 10–180 min after being heated to the appropriate temperature (180–250 °C). The reactor was then allowed to naturally cool to 40 °C. After the reactant fabric was taken out, filtering was used to recover the solid residue in the water.	Cotton as mesh fabric. Polyester as a solid powder.	Using SEM, the surface conditions of the treated mesh fabric were compared to those of the raw material. Following treatment, SEM images demonstrate that the cotton fiber condition is preserved. It is also evident that the fibers have suffered some little damage from the 230 °C treatment. It wass hypothesized that the cotton fibers have gradually deteriorated due to the subcritical water treatment. FTIR examination verified the minute fragments and powdery material obtained after treatment to be PET, and the mesh fabric to be cotton.			[82]

Table 2. *Cont.*

#	Method	Starting Material and Composition	Process/Reaction	Process/Reaction Conditions	Products	Analysis	Any Other Component Present	Issue/ Problem	Reference
15	Enzymatic Hydrolysis	Textile waste of cotton and polyester (PET) blend by 60/40.	Using cellulase and β-glucosidase, textile waste was hydrolyzed enzymatically to extract glucose and polyester.	Textile fabrics were enzymatically hydrolyzed at 50 °C for 96 h. The maximum glucose recovery of 98.3% was obtained with 20 FPU/g of cellulase dosage and 10 U/g of β-glucosidase dosage at 3% (*w*/*v*) substrate loading, temperature of 50 °C and pH 5	Glucose, Glucose yield was 98.3%. The recovered PET fiber can be reused by melt-spinning to new PET fiber.	Glucose concentration was determined by HPLC. SEM analysis before and after enzymatic hydrolysis showed significant changes in textile morphology. Prior to hydrolysis, cotton and polyester fibers formed a compact structure. After hydrolysis, the structure loosened with fewer fibers, and small holes appeared due to the digestion of cellulose fibers. PET fibers remained intact.			[86]
16	Enzymatic Hydrolysis	Clothing: with a composition of 65% PET, 35% Cotton. And 80% PET, 20% Cotton.	Using a commercial cutinase from Humicola insolens (HiC) under moist-solid reaction conditions, PET in mixed PET/cotton textiles could be directly and selectively depolymerized to terephthalic acid (TPA). This process was easily combined with cotton depolymerization through simultaneous or sequential application of the Cellic CTec2 cellulases blend, yielding glucose.	After cutting the textile samples into squares measuring 0.7 × 0.7 cm, they were ball milled for 5 or 30 min (30 Hz) in 15 mL stainless-steel milling jars with HiC (0.65% *w*/*w*) and/or CTec2 (0.7% *w*/*w*) enzymes present. This was followed by seven days of static incubation at 55 °C.	TPA (with a maximum yield of 30 ± 2%) and glucose (with a maximum yield of 83 ± 4%) were obtained through the mechanoenzymatic hydrolysis of the PET/cotton blended textile. Additionally, ethylene glycol (yield unknown) and a small reaction product, up to 0.5% yield of MHET were produced by the hydrolysis of PET.	Cotton hydrolysis products were assessed using a commercially available glucose test, while PET hydrolysis products were quantified by HPLC.			[56]
17	Enzymatic Hydrolysis	A white 40/60 polyester/cotton blended fabric.	Alkali pretreatment and enzymatic hydrolysis followed by saccharification and fermentation.	Waste textiles were pretreated using aqueous alkaline mixes of NaOH (12 wt%), NaOH/urea (7/12 wt%), NaOH/thiourea (9.5/4.5 wt%), and NaOH/urea/thiourea (8/8/6.5). 5 g of waste textile and 95 g of an alkaline solution were combined for the pretreatments, which lasted one hour at various temperatures of 20 °C, 0 °C, 23 °C, and 100 °C. Using 30 FPU cellulase and 60 IU b-glucosidase per gram of cellulose, waste textiles were treated to a 72 h enzymatic hydrolysis at 45 °C and pH 4.8 (in 50 mM sodium citrate buffer supplemented with 0.5 g/L sodium azide) with 3% (*w*/*v*) solid (substrates) loading.	Polyester and Ethanol. When saccharification and fermentation were carried out simultaneously on the textile, the greatest yield of ethanol production was 70%. The recovered polyester accounted for 98%.	The characteristics of recovered polyester were evaluated by FTIR, DSC, and viscosity analyses. The FTIR result revealed that after the polyester was treated with NaOH, the trans/gauche ratio dropped, indicating a reduction in the crystalline area.			[87]

Table 2. *Cont.*

#	Method	Starting Material and Composition	Process/Reaction	Process/Reaction Conditions	Products	Analysis	Any Other Component Present	Issue/ Problem	Reference
18	Enzymatic Hydrolysis	Textile waste blends of cotton and PET, with compositions of 35/65 and 60/40.	Sample waste fabrics were cut into little pieces (about 0.5 × 0.5 cm^2) and soaked in freezing alkali/urea for three separate modification methods: autoclaving, freezing, and alkaline pretreatment. Then the sample was subsequently exposed to enzymatic hydrolysis.	After adding the mineral solution to achieve the appropriate initial moisture level, the textile waste was autoclaved for 15 min at 121 °C as part of the autoclave pretreatment. Textile waste was mixed with urea (12% *w*/*v*) and NaOH (7% *w*/*v*) for the freezing alkali/urea soaking process. The mixture was then frozen at −20 °C for six hours. The textile waste was autoclaved for 15 min at 121 °C or soaked for 3 h at 80 °C in a 15% NaOH solution for alkaline pretreatment. Enzymatic hydrolysis was used to regenerate cellulose from cotton/PET textile waste mixtures. In this study, commercial cellulase (Cellic CTec2, 185 FPU/mL) was employed. Two grams of regenerated cellulose were added, at a substrate-enzyme dose of 25 FPU/g, to a citric buffer (100 mL, 50 mM, pH 4.8). For 96 h, hydrolysis was carried out at 50 °C and 200 rpm.	Glucose and PET as a solid mass.	Utilizing a high-performance liquid chromatography column (HPLC), the amount of glucose was determined. After processing with NaOH, SEM analysis showed notable changes in the surface morphology of textile sample. At first, the fabric had a surface that was a little uneven and harsh. However, after treatment, the cotton/PET digestion by NaOH caused a partial breakdown of the textile's structure into rough fibers. The textile samples were examined using FTIR both before and after processing. PET and cellulose polymer-corresponding absorption bands were visible in the spectra. Significant alterations in the cellulose polymer bands were found upon analysis of the pretreated textile waste, demonstrating the pretreatment process's efficacy in changing the polymer structure.			[88]
19	Enzymatic Hydrolysis	Used jeans, composition not mentioned in the study.	Phosphoric acid pretreatment and subsequent enzymatic hydrolysis of cotton-based waste textiles to recover sugar and polyester. Two enzymes were used for enzymatic hydrolysis: cellulase from Trichoderma reesei and cellobiase from Aspergillus niger.	Phosphoric acid pretreatment: 85% phosphoric acid, at 50 °C, for 7 h, and a ratio of fabric and acid of 1:15. Enzymatic hydrolysis In 150 mL flasks with a 50 mL work volume, the regenerated cellulose was enzymatically hydrolyzed in 50 mM sodium citrate buffer (pH 4.8). With a cellulose loading of 7.5 FPU/g regenerated cellulose and a cellobiase loading of 15 CBU/g regenerated cellulose, the substrate consistency for enzymatic hydrolysis was maintained at 1.0% (*w*/*v*). For 96 h, the hydrolysis was carried out at 50 °C in an air-bath shaker at 130 rpm.	Polyester in solid form. At the optimized conditions (85% phosphoric acid, 50 °C, 7 h, and a ratio of 1:15), 100% polyester recovery with a maximum sugar recovery of 79.2% was accomplished.	The glucose content was determined by HPLC. Surface morphology was analyzed using SEM. Distinct cotton and polyester fibers were visible in the original waste textiles sample. The cellulose fibers changed significantly and became rougher after pretreatment. The majority of cotton fibers remained intact after enzymatic hydrolysis without pretreatment, underscoring the necessity of pretreatment for effective sugar recovery. Cotton fibers were effectively extracted from polyester using phosphoric acid pretreatment, resulting in 100% polyester recovery without changing the surface of the polyester as seen on the SEM images.			[89]

Table 2. *Cont.*

#	Method	Starting Material and Composition	Process/Reaction	Process/Reaction Conditions	Products	Analysis	Any Other Component Present	Issue/ Problem	Reference
20	Enzymatic Hydrolysis	Blended textiles (65% polyester, 35% cotton)	NaOH/urea solution pretreatment is followed by cellulase-based enzymatic hydrolysis. It was found that using concentrations of NaOH varying from 20.7% to 26.6% with either 0% urea or a mixture of 13.9% NaOH and 12% urea was efficient and almost entirely eliminated the cellulose in the blended textile.	400 mL of NaOH/urea solution was used for pretreatment and 4 g of textile substrate were weighed in a beaker for every experiment. Using sodium azide (0.02%) and a 50 mM citric acid buffer at pH 5.0, hydrolysis was carried out in a 1-L flask. In a 500 mL buffer, the textile substrate was added with a solid load of 0.8% (w/v). The activity of the enzyme dose was adjusted to 0.68 filter paper units (FPU) per g of cellulose. For 24 h, hydrolysis was carried out in a heating incubator at 50 °C and 70 rpm orbital shaking.	Polyester as solid residue, and Glucose	To find the released glucose, high performance anion exchange chromatography (HPAEC) was employed. After being hydrolyzed by enzymes, the quality of the recovered synthetic fibers was assessed using Fourier transformed infrared spectroscopy (FTIR). FTIR analysis compared untreated textile blend, pure polyester, and regenerated polyester fibers. It revealed decreased peaks characteristic of cellulose and increased peaks characteristic of PET.			[90]

5. Separating Elastane from Other Fibers

Polyurethane (PU) elastomer fibers are widely referred to as elastane in Europe and as spandex in the United States. Elastane is used in clothing whenever stretchiness is needed. For example, practically all types of form-fitting underwear for both men and women contain this fabric. Elastane is often utilized in motion capture suits, bras, leggings, shorts, yoga pants, competitive sporting wear, cycling apparel, tights, and socks. Elastane blended fabric has high breathability, high moisture-wicking abilities, and low heat retention abilities. Elastane content in blended fabrics ranges from 5% to 85%. The more elastane there is in the blend, the stretchier the fabric is [34].

The separation of elastane is a key challenge in the recycling of fibers from clothes. Elastane is typically present in small amounts, but even at these low concentrations, it prevents the other polymer types present in clothing from being recycled. Since elastane is so elastic, it cannot be shredded by the shredders that are often used to shred textiles before recycling. Elastane causes clumping, clogs, and soiling in the machinery. To increase the rates of fiber recycling, elastane must be removed from textile blends [91].

Elastane can be removed from a blend by the selective dissolution of elastane from a blended textile or the selective degradation of elastane by aminolysis or solvolysis.

5.1. Selective Dissolution of Elastane

The selective dissolution of elastane can be done using appropriate solvent or solvent blend that can dissolve elastane while sparing other fibers like cotton, polyester, or nylon. Our review of the literature identified the following studies:

1. Selective dissolution of elastane from blended textiles (PET/elastane: 85/15 and polyamide/elastane: 88/12) was achieved using tetrahydrofurfuryl alcohol (THFA) and γ-valerolactone (GVL) as solvents for 4 h at 100 °C [21]. The products were elastane solution, PET fiber, and polyamide fiber in solid form. TGA-FTIR was used to determine the maximal solubilities: 4.9 mg/g THFA and 4.3 mg/g GVL (Figure 18). Before solvent treatment, ^{1}H-NMR of the pure elastane fiber revealed that it exclusively included methylene diisocyanate derived carbamates. THFA solvent treatment, however, caused the carbamate bond to break, which indicates the elastane fibers partially depolymerized [21].

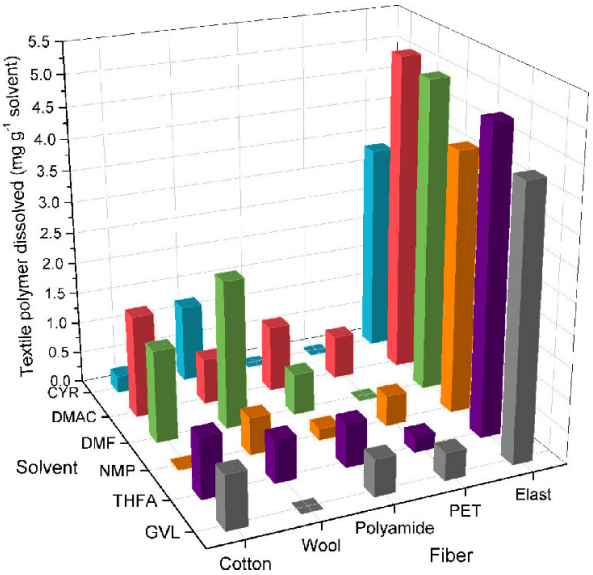


Figure 18. The maximal solubilities of cotton, wool, polyamide, polyester, and elastane in five elastane-dissolving solvents. CYR: cyrene, DMAC: dimethylacetamide, DMF: dimethylformamide, NMP: n-methylpyrrolidone, THFA: tetrahydrofurfuryl alcohol, and GVL: γ-valerolactone. Reproduced with permission from [21]. Copyright 2023, Elsevier.

Pictures and SEM images of case study materials (sportshirt and panties) before and after solvent treatment with DMF and THFA are shown in Figure 19. The color removal in both cases indicates that the solvent treatment also coextracted dyes and maybe other additives like finishing chemicals, UV stabilizers, antioxidants, and other auxiliaries [21].

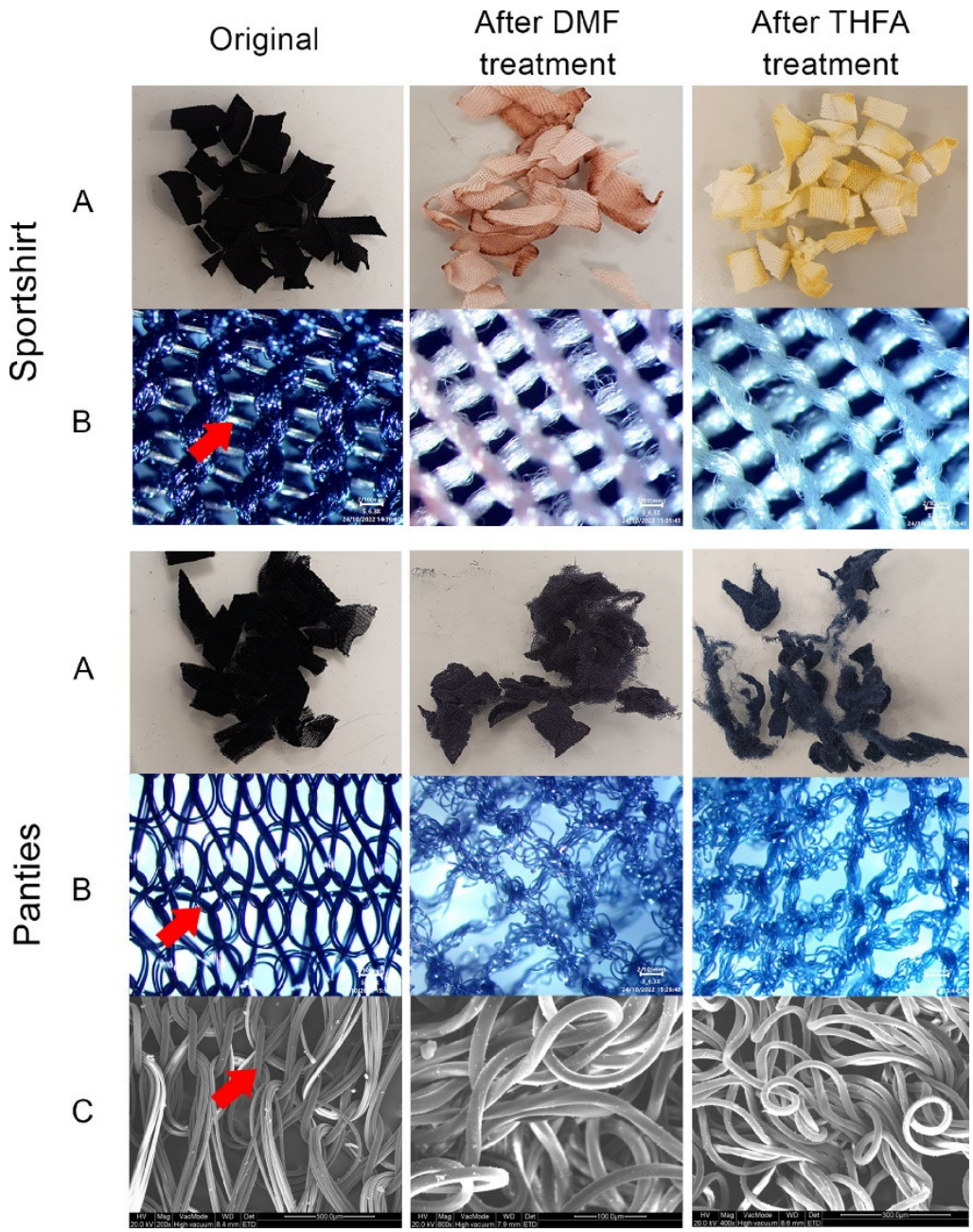


Figure 19. Photographic (**A**), microscopic (**B**), and SEM images (**C**) of case study materials (sportshirt and panties) before and after solvent treatment with DMF and THFA. The red arrows on the images indicate elastane. Reproduced with permission from [21]. Copyright 2023, Elsevier.

2. Green-colored polyester/elastane (82% PET/18% EL) and black-colored polyamide/elastane (92% PA/8% EL) post-industrial textile waste samples were dissolved using six different organic solvents (Cyrene, DMAc, DMF, DMSO, GVL, NMP), with DMSO shown the most favorable for elastane dissolution [92]. Figure 20 depicts the separation of elastane using DMSO. Then, 1 g sample was dissolved in 200 mL DMSO at 120 °C for 30 min. The product of dissolution was an elastane solution. By filtering the solution, washing, and drying the filtride, polyester or polyamide components were recovered. Poly-

mer degradation behavior was analyzed using TGA. In textiles that have not been treated, elastane degradation peaks could be seen at approximately 300 °C. Because of the high elastane content in the PET/EL textile, an earlier degradation started (412 °C) was seen. The successful separation of elastane was confirmed by this comparison. There appeared to be no deterioration in the polymer matrix since the degradation peak associated with the PET reference (442 °C) coincided with that of the recovered material. Comparably, limited variation between degradation peaks (around 423 °C) for the black PA/EL textile indicates that the polymer matrix had not changed. The morphology of the samples was analyzed using SEM. The collocation of polyester and elastane fibers in the PET/EL fabric was apparent in the SEM images. Following the elastane separation, recovered PET showed no signs of elastane-related residues being adhered to the fibers as shown in Figure 21. Up to 18 g/L elastane could dissolve in DMSO. DMSO could not be reused as solvent anymore beyond this point because elastane particles and colorant collected in the treated solvent [92].

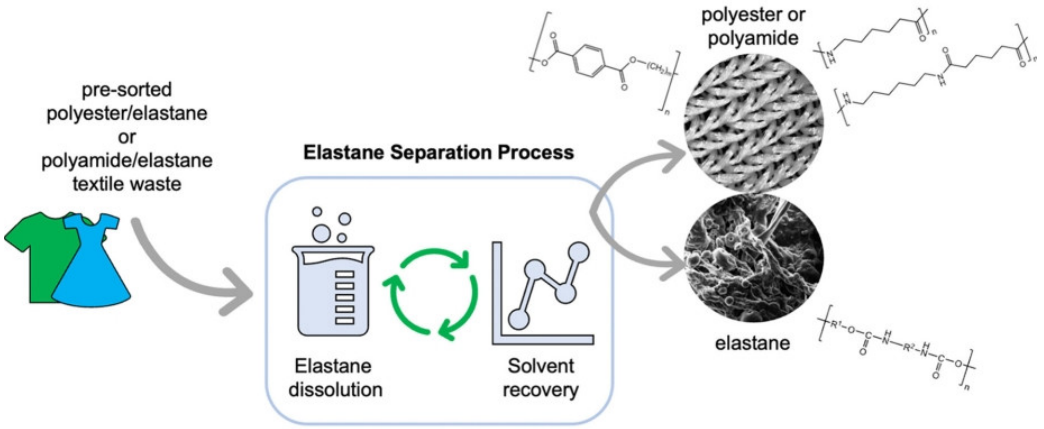


Figure 20. Selective dissolution of elastane in DMSO from blended textile such as polyester/elastane and polyamide/elastane. The solvent was recovered, and polyester/polyamide was recovered as solid fiber, whereas elastane was regenerated into fiber. Reproduced from [92]. Copyright 2023, the authors.

3. Elastane in mixed polyamide fabrics was selectively dissolved using a 70 vol%:30 vol% THF:DMSO solvent mixture. PA6/elastane blend with 6.3% elastane and PA66/elastane blends (with 23% and 32% elastane) were tested [91]. In this study, 20 mL solvent was added to 1 g previously dried fabric cuts, which were then stirred for an hour at room temperature. After that, the sample was washed for 30 min in each of 20 mL ethanol and 40 mL water. The elastane was recovered after the low-boiling solvent was evaporated under decreased pressure and as the elastane precipitated. SEM micrographs of the untreated and solvent treated sample showed that most of the elastane was dissolved in a first cycle, and the washing process in non-solvent precipitated the elastane left on the fabric surface. DSC and FTIR analysis also indicated that elastane was removed from the sample [91].

5.2. Elastane Degradation by Aminolysis or Solvolysis

The breakage of chemical bonds in the presence of a solvent is known as solvolysis. Aminolysis is any chemical reaction in which a molecule is split into two parts by reacting with ammonia or an amine. Elastane can be removed from a blended textile by aminolysis or solvolysis of the polyurethane [93,94]. Our review of the literature identified the following studies:

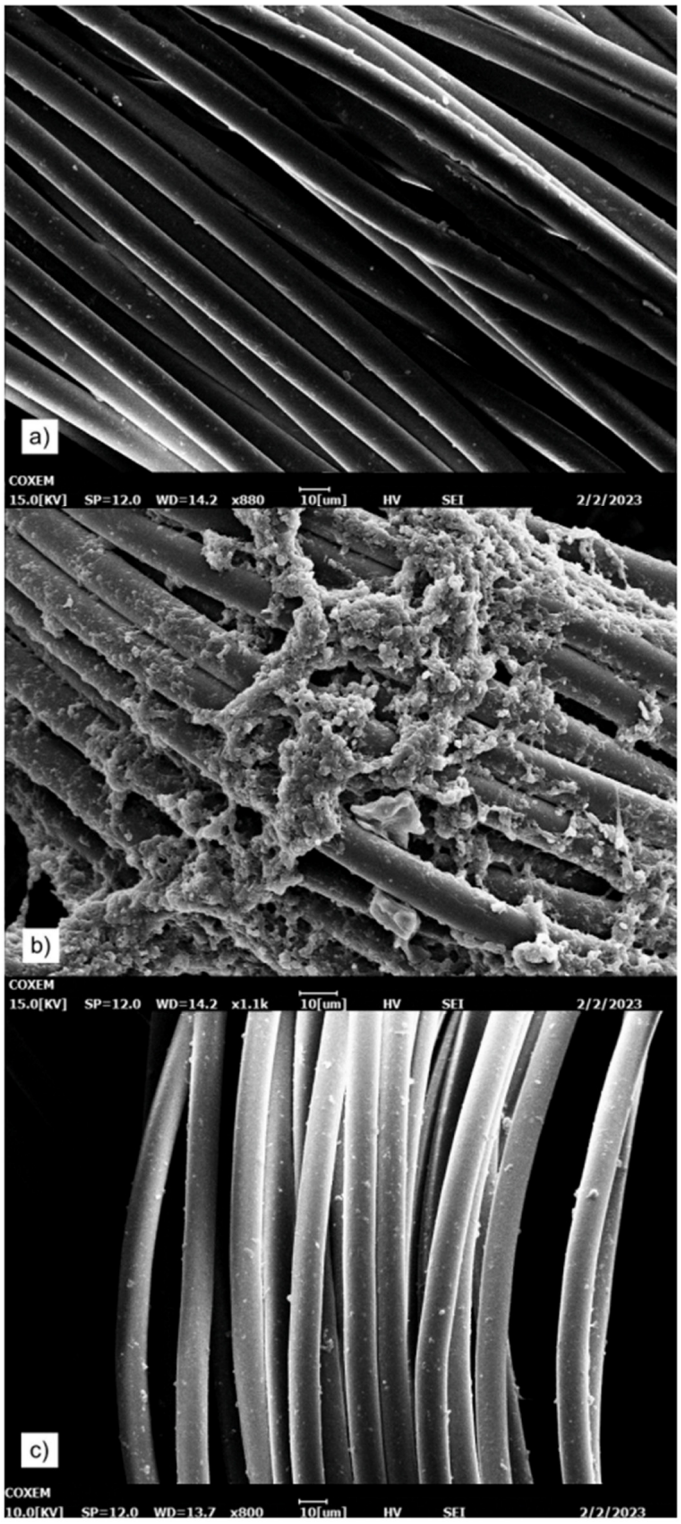


Figure 21. SEM images: (**a**) The initial PET/EL fabric with dust particles attached to the fibers. (**b**) Inadequate elastane dissolution of the PET/EL fabric. Strong EL contamination is visible. (**c**) Recovered PET. No EL-related residues attached to the fibers are visible. Reproduced from [92]. Copyright 2023, the authors.

1. Aminolysis was used to selectively remove elastane from cellulose in white preconsumer textile blend composed of 95 wt% cotton and 5 wt% elastane. An amine attacks the urethane bonds during the aminolysis of elastane by nucleophilic addition, which is

followed by the removal of the alkoxy group. The end products of the depolymerization process are substituted amines and polyols (Figure 22) [95]. In this study, 8 g ground fabric was added to 160 mL solvent mixture containing a cleaving agent: diethylenetriamine (DETA) and an elastane solvent: DMF or DMSO in a 1:1 volume ratio. The process was carried out at 80 °C for 4 h. The solid and liquid phases were separated by filtration. The liquid phase contained the solvent mixture and the degraded elastane products. The elastane products were precipitated by adding water to the liquid phase. Cellulosic material was dissolved in [DBNH] [OAc] and turned into new fibers for textile applications via dry-jet wet spinning. Both the recovered elastane and pure elastane showed similar thermal behavior assessed by TGA. The recovered elastane was tested with FTIR and NMR to understand more about its chemical composition. The distinctive polyurethane peaks were visible in the FTIR spectra of the sample elastane and the recovered elastane [95].

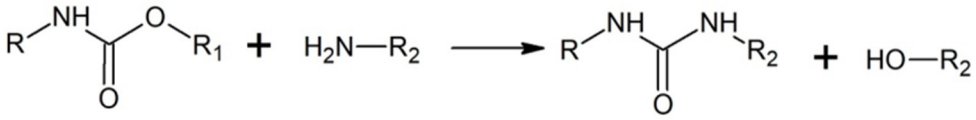


Figure 22. Aminolysis of polyurethane. Reproduced from [93]. Copyright 2020, the authors.

2. The PU coating of a polyester (PET) fabric was selectively solvolyzed by cleavage of C–O and C–N bonds in 70% $ZnCl_2$ aqueous solution [96]. This catalyst-assisted solvolysis did not degrade the polyether bonds, and PU was converted to the amine form of the used isocyanate and the original polyether polyol. 10 g PU-coated polyester was added to 250 g $ZnCl_2$ solution (70 wt% in water), heated to 140 °C for 2 h. The degradation products were cooled to room temperature and then agitated for five minutes in 250 mL of water following the reaction. After the mixture was filtered, an insoluble residue (fabric and insoluble degradation products of PU) and a water mixture were obtained. The fabric was filtered off after the residue was added to 200 mL of ethyl acetate. The ethyl acetate mixture was washed three times with brine, then the organic phase was evaporated with a rotary evaporator. The water mixture was evaporated, and diethyl ether was added. The precipitated product was separated via filtration and dried overnight at 70 °C under atmospheric pressure. The thermal, chemical, and mechanical characteristics of the virgin PET and recycled PET were analyzed through tensile strength tests, IR, TGA, and GPC. The virgin polyester fabric's tensile force and elongation were 360 N and 33.5%, respectively. The tensile strength of recycled polyester fabric was 350 N, and its elongation was 34%. Therefore, the mechanical characteristics of the polyester fabric were unaffected by the heat treatment in the presence of $ZnCl_2$. The IR spectra of virgin polyester and recycled polyester showed significant similarities, which indicates that the PET recovered after the degradation of polyurethane in $ZnCl_2$ solution was not degraded. TGA showed that the polyester did not degrade during solvolysis, while the PU was converted into polyol and amine. As analyzed in GPC, when compared to virgin PET, the recycled PET's molecular weight did not decrease, indicating that it did not break down during solvolysis [96].

3. Elastane from a fabric blend (consisting of 27% Elastane and 73% Nylon) could be depolymerized by a solvolysis process with tert-amyl alcohol and catalytic KOH [94]. Solvolysis was performed on 250 mg of pure elastane fiber using tert-amyl alcohol (5 mL) and KOH (1.9 mg) at 225 °C for 4.5 h, resulting in the formation of 4,4′-methylenedianiline (4,4′-MDA) and poly-tetrahydrofuran (polyTHF) with yields of 33.3 mg and 186 mg. The overall mass recovery was 86 wt%. In this study, 1.02 g fabric sample was added to tert-amyl alcohol (5 mL) and KOH (0.19 wt%) at 225 °C for 4.5 h as illustrated in Figure 23. The products were 50.9 mg 4,4′-MDA, 266 mg polyTHF in the liquid phase, and 698 mg leftover fabric. FTIR suggested that the elastane had been effectively removed from the polyamide matrix, while polyamide remained unaltered. For pure elastane, DSC showed a crystalline peak at 20 °C. Both a wide crystalline phase for the polyamide at 225 °C and a crystalline peak for the elastane at 20 °C were seen in the untreated sample. At 255 °C, the polyamide could form a crystalline phase, and there was no evidence of elastane in the

remaining treated fabric. This suggested that elastane was successfully removed, and that the polyamide fiber was intact with no symptoms of contamination or deterioration [94].

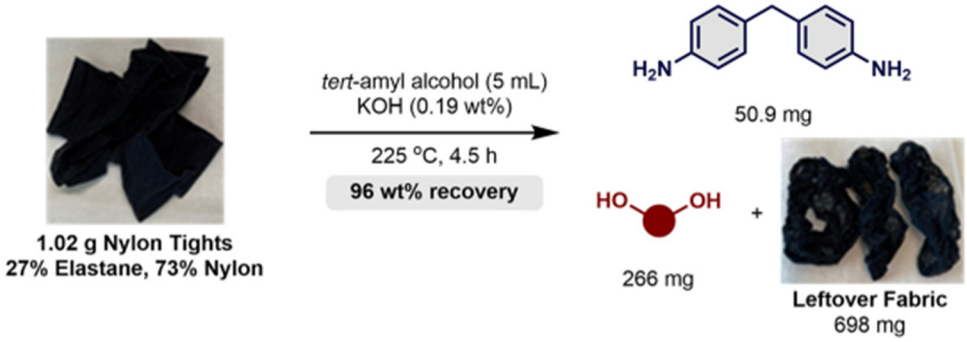


Figure 23. Solvolysis of elastane blended fabric (nylon tights) with tert-amyl alcohol and catalytic KOH. Reproduced with permission from [94]. Copyright 2023 Royal Society of Chemistry.

All studies on the separation of elastane from blended fabrics are summarized in Table 3. The articles we report here are very recent, as we were not able to find articles on elastane separation published before 2022. The table includes the type of method used, starting material and composition, process or reaction, process or reaction conditions, products obtained, analysis and findings, and any issues or problems. These studies are organized according to the method used.

Table 3. Summary of studies regarding the separation of elastane from blended fabrics.

#	Method	Starting Material and Composition	Process/Reaction	Process/Reaction Conditions	Products	Analysis	Any Other Component Present	Issue/Problem	Reference
1	Selective dissolution of elastane	Polyester-elastane blend and Polyamaide-elastane blend. (PET/elastane: 85/15), (Polyamide/ elastane: 88/12)	The selective dissolution of elastane from blended textile can be done using tetrahydrofurfuryl alcohol THFA and γ-valerolactone. (GVL).	4 h and 100 °C, tetrahydrofurfuryl alcohol THFA and γ-valerolactone (GVL) as solvents.	Elastane solution. PET fiber and polyamide fiber in the solid form.	Thermogravimetric analysis with Fourier transform infrared spectroscopy (TGA-FTIR) was used to determine the maximal solubilities (4.9 mg/g THFA and 4.3 mg/g γ-valerolactone). The quality of the extracted elastane fibers was assessed by liquid 1H-NMR. Before solvent treatment, liquid 1H-NMR of the pure elastane fiber revealed that it exclusively included methylene diisocyanate derived carbamates. THFA solvent treatment, however, caused the carbamate bond to break, which indicated elastane fiber partially depolymerized.			[21]
2	Selective dissolution of elastane	Polyester/elastane, and polyamide/elastane textile waste samples Green-colored polyester/elastane and black-colored polyamide/elastane post-industrial textile waste samples. The textile compositions were 82% PET/18% EL and 92% PA/8% EL.	Dissolution of elastane.	1 g sample in 200 mL solvent, dimethyl sulfoxide (DMSO), at 120 °C for 30 min	Elastane solution. By filtering the solution, washing, and drying the filtride, polyester or polyamide components are recovered.	Polymer degradation behavior was analyzed using TGA. In textiles that have not been treated, elastane (EL) degradation peaks could be seen at approximately 300 °C. Because of the high elastane content in the PET/EL textile, an earlier degradation start (412 °C) was seen. The successful separation of elastane was confirmed by this comparison. There appeared to be no deterioration in the polymer matrix since the degradation peak associated with the PET reference (442 °C) coincided with that of the recovered material. Comparably, limited variation between degradation peaks (around 423 °C) for the black PA/EL textile indicated that the polymer matrix had not changed. Morphology of the samples was analyzed using scanning electron microscopy (SEM). The PET/EL fabric's rich collocation of polyester and elastane fibers was apparent in the SEM images. Following the elastane separation, recovered PET showed no signs of elastane-related residues being adhered to the fibers.		The solvent enriched with colorant and elastane particles during the treatment; therefore it could not be used indefinitely. Elastane could dissolve in DMSO up to an 18 g/L concentration. DMSO could not be used any more beyond this point because elastane particles collected in the treated solvent.	[92]

Table 3. *Cont.*

#	Method	Starting Material and Composition	Process/Reaction	Process/Reaction Conditions	Products	Analysis	Any Other Component Present	Issue/Problem	Reference
3	Selective dissolution of elastane	Pre-consumer-waste fibers and fabrics. One PA6/elastane blend with 6.3% elastane. Two PA66/elastane blends (with 23% and 32% elastane).	Using a solvent blend (THF: DMSO in a 70%:30% by volume ratio), elastane in a mixed polyamide fabrics can be selectively dissolved.	1 g fabric in 20 mL solvent, dissolution at 25 °C for 1 h, THF:DMSO in a 70%:30% by volume ratio.	Precipitated Elastane, solid polyamide in the spent solvent.	SEM micrographs of the untreated and solvent treated sample show that, most of the elastane was dissolved in a first cycle, and the washing process in non-solvent precipitated the elastane left on the fabric surface. DSC and FTIR analysis also indicated that elastane was removed from the sample.			[91]
4	Elastane degradation	A white pre-consumer textile blend, composed of 95% (*w*/*w*) of cotton and 5% (*w*/*w*) of elastane.	Selective Elastane Degradation by Aminolysis.	4 h at 80 °C. 8 g of the ground fabric was added to 160 mL of a solvent mixture containing a cleaving agent (DETA) and an elastane solvent (DMF or DMSO) in a 1:1 volume ratio.	The solid and liquid phases were separated by filtration. The liquid phase contained the solvent mixture and the degraded elastane products, by adding water to the liquid phase, the elastane products were precipitated. Cellulosic material was dissolved in [DBNH][OAc] and turned into new fibers via dry-jet wet spinning.	TGA was used to study thermal behavior. Both the recovered elastane and pure elastane showed similar thermal behavior. The recovered elastane underwent FTIR and NMR tests to understand more about its chemical composition. The distinctive polyurethane peaks were visible in the FTIR spectra of the sample elastane and the recovered elastane.			[95]

Table 3. *Cont.*

#	Method	Starting Material and Composition	Process/Reaction	Process/Reaction Conditions	Products	Analysis	Any Other Component Present	Issue/Problem	Reference
5	Elastane degradation	Polyester fabric coated with polyurethane.	Selective degradation of PU elastomers by cleavage of C–O and C–N bonds in 70% $ZnCl_2$ aqueous solution. This catalyst-assisted solvolysis did not degrade the polyether bonds and PU was converted to the amine form of the used isocyanate and the original polyether polyol.	10 g PU coated polyester was added to $ZnCl_2$ solution (70 wt% in water, 250 g), heated to 140 °C and for 2 h. The degradation products were cooled to room temperature and then agitated for five minutes in 250 mL water following the reaction. After the mixture was filtered, an insoluble residue (fabric and insoluble degradation products of PU) and a water mixture were obtained. The fabric was filtered off after the residue was added to 200 mL ethyl acetate. The ethyl acetate mixture was washed three times with brine, then the organic phase was evaporated with a rotary evaporator. The water mixture was evaporated and diethyl ether was added. The precipitated product was separated via filtration and dried overnight at 70 °C at atmospheric pressure.	Polyester fabric, polyol, and amine	The thermal, chemical, and mechanical characteristics of the virgin PET and recycled PET were analyzed through tensile strength tests, IR, TGA, and GPC. The virgin polyester fabric's tensile force and elongation were 360 N and 33.5%, respectively. The tensile strength of recycled polyester fabric was 350 N, and its elongation was 34%. Therefore, the mechanical characteristics of the polyester fabric were unaffected by the heat treatment in the presence of $ZnCl_2$. The IR spectra of virgin polyester and recycled polyester showed significant similarities which indicates that the PET recovered after the degradation of polyurethane in $ZnCl_2$ solution was not degraded. TGA Analysis showed that the polyester did not degrade during solvolysis, while the PU was converted into polyol and amine. As analyzed in GPC, when compared to virgin PET, the recycled PET's molecular weight did not decrease, indicating that it did not break down during solvolysis.			[96]

Table 3. *Cont.*

#	Method	Starting Material and Composition	Process/Reaction	Process/Reaction Conditions	Products	Analysis	Any Other Component Present	Issue/Problem	Reference
6	Elastane degradation	Fabric sample consisting of 27% Elastane and 73% Nylon.	Solvolysis using tert-amyl alcohol in the presence of KOH.	1.02 g fabric sample consisting of 27% elastane and 73% Nylon was added to tert-amyl alcohol (5 mL) and KOH (0.19 wt%) at 225 °C for 4.5 h.	The products were 50.9 mg 4,4′-MDA, 266 mg polyTHF in the liquid phase and 698 mg leftover fabric.	FTIR analysis was performed on sample and treated fabric sample. The results suggested that the elastane had been effectively removed from the polyamide matrix. The polyamide remained unaltered, while the elastane fibers in the fabric were depolymerized. For pure elastane, DSC showed a crystalline peak at 20 °C. Both a wide crystalline phase for the polyamide at 225 °C and a crystalline peak for the elastane at 20 °C were seen in the untreated sample. For the treated fabric at 255 °C, the polyamide could form a crystalline peak, and there was no evidence of elastane. This suggests that the elastane has been successfully removed and that the polyamide fiber was intact with no symptoms of contamination or deterioration.			[94]

6. Recycling of Blended Textiles in Industry

Several companies are advancing molecular recycling technologies for processing blended textiles (Table 4). Note that several of the companies highlighted below are relatively new and relatively small (start-ups).

Table 4. Information on companies that process blended textiles.

#	Company	Founded	Location	Process	Output	Scale
1	Ambercycle	2015	Los Angeles, CA, USA	Biological recycling process	PET pellets and fiber	Pilot plant
2	BlockTexx	2018	Loganholme, Australia	Chemical Process	PET and Cellulose	Commercial scale plant
3	Circ	2011	Danville, Virginia	Hydrothermal process	Cellulose, terephthalic acid TPA, and ethylene glycol EG.	Commercial scale plant
4	Worn Again Technologies	2005	Nottingham, England	Solvent-based dissolution	PET and Cellulose	Pilot plant
5	Purfi	2018	Waregem, Belgium	D'Elastane™ technology	PET fiber	Not mentioned
6	Textile Change	2019	Vejle, Denmark	Chemical Process	PET and Cellulose	Pilot plant
7	Sodra (OnceMore®)	2022	Växjö, Sweden	Chemical Process	Cotton fiber	Commercial scale plant
8	Phoenxt	2018	Blomberg, Germany	Solvent-based process	PET, Cellulose	Not mentioned
9	Eeden	2022	Münster, Germany	Chemical Process	Cotton fiber, terephthalic acid TPA, and ethylene glycol EG.	Not mentioned

1. Ambercycle (Founded in 2015, Los Angeles, GA, USA) is testing a pilot plant to separate polyester from mixed textile waste, producing PET pellets and polyester fiber. The Ambercycle system uses a biological recycling process to separate fibers within garments at a molecular level and reprocess the materials. No information on the actual process is provided on the company website, and no patents have been identified [97,98].

2. BlockTexx (founded in 2018, based in Loganholme, Australia) has developed the so-called S.O.F.T. (Separation of Fiber Technology) process to chemically separate textile fibers, reclaiming PET from polyester and cellulose from cotton fibers. No information on the actual process is provided on the company website, and no patents have been identified [97,99].

3. Circ (founded in 2011, based in Danville, VA, USA) uses a hydrothermal process to recover materials from polycotton blends, extracting cellulose and depolymerizing polyester with supercritical water. In this method, the waste textile blend is treated in a subcritical water reactor at a temperature of about 105 to 190 °C, and a pressure of about 40 to 300 psi for about 90 min. Dissolved cellulose, terephthalic acid, and ethylene glycol are produced [97,100,101].

4. Worn Again Technologies (founded in 2005, based in Nottingham, England) separates, decontaminates, and extracts PET and cellulose from blended polyester and cotton waste. This company opened a pilot plant in 2020 and plans to build a full-scale plant. They use solvents to selectively dissolve PET and cellulose. No information on the actual process is provided on the company website, and no patents are available [97,102].

5. Purfi (founded in 2018, based in Waregem, Belgium) specializes in "rejuvenating" textile waste and creating new fibers, including elastane removal, through the so-called D'Elastane™ technology. No information on the actual process is provided on the company website, and no patents have been identified [35,103].

6. Textile Change (founded in 2019, based in Denmark) develops textile chemical recycling technology that converts blended textile waste into high-quality raw materials for new fiber production, aimed at transforming discarded textiles into cellulose and polyester for new clothes. According to the company, their technology has been proven on a pilot plant scale and has shown the capability of scaling. However, no information on the actual process is provided on the company website, and no patents are provided [104].

7. Sodra (Sweden) developed OnceMore® which, according to the company, is the world's first large-scale process for recycling blended fabrics, specifically polycotton blends, which are widely used textiles. The cotton is separated from the polyester, and the cotton fibers are revived by combining them with renewable wood cellulose from sustainably managed forests, turning waste into high-quality material. The polyester is incinerated to generate energy, which powers the OnceMore® process. No information on the actual process is provided on the company website, and no patents are available [105].

8. Phoenxt (founded in 2018 in Germany) is a blend recycler specializing in circular recycling technology for polyester and other plant-based natural cellulosic fibers. According to the company, their unique approach includes environmentally friendly recyclable solvent technology, maintaining fiber quality, and targeting the largest waste markets. They use an innovative proprietary chemical process to separate, purify, dissolve, and reformulate textile waste into base polymer materials. However, no information on the actual process is provided on the company website, and no patents are available [106].

9. Eeden (founded in 2022 in Germany) has developed a novel chemical process to recover both cotton and polyester from cotton-PET blends, commonly used in modern clothing. This upcycling technology recovers cellulose from cotton and breaks down polyester into its basic building blocks. The recovered materials are then spun into new, high-quality fibers suitable for various applications. No information on the actual process is provided on the company website, and no patents have been identified [107].

7. Conclusions

The textile sector is under pressure because of its high energy and water consumption, environmental pollution, and the emission of greenhouse gases. Textile reuse and recycling can be a sustainable solution for the reduction of textile waste, the reduction of virgin materials required for textile production, and the corresponding reduction of environmental impact.

Mechanical recycling of textiles works best with mono-material fabrics of cotton, linen wool, and acrylics. However, most textile fabrics are made from blended natural and synthetic fibers. For example, blends of cotton and polyester offer comfort and durability, while elastane or spandex confers stretch to textiles. The complex intermixing of cotton and polyester, as well as the rubbery behavior of elastane, make their separation by current mechanical recycling methods infeasible. To overcome this roadblock, the separation of fiber blends can be accomplished by the selective dissolution of or depolymerization of specific polymers. These processes fall under chemical or molecular recycling.

This review focuses on the separation of cotton, polyester, and elastane from other fibers in blended fabrics. Cotton and polyester can be separated from blends through their selective dissolution in solvents, hydrolysis, hydrothermal treatment, and enzymatic hydrolysis. For example, a deep eutectic solvent selective for cellulose can leave polyester fibers intact, while 5–15 wt% NaOH in water at temperatures between 70 and 90 °C can hydrolyze PET into its monomers TPA and EG and preserve the cotton fibers. Elastane can be selectively removed from textile blends through dissolution (e.g., using a 70:30 vol% THF:DMSO solvent mixture), aminolysis, or solvolysis, while preserving the integrity of the other fibers in the blend.

Several companies are advancing molecular recycling technologies for processing blended textiles. The actual practice in industry emphasizes the importance of the research that we reviewed here and the need for further research.

The methods highlighted here address the challenge of fiber separation from blended textiles and enhance the sustainability of textile recycling processes. The effectiveness, scalability, and environmental impact of emerging techniques for recycling textiles merit further research. Enzymes are very specific for individual textile polymer types, making them useful to this end. The melting or dissolution properties of the polymer are critical for physical polymer recycling. To achieve quality of the recycled product on par with that of virgin materials, depolymerization of the polymer into its monomeric building blocks followed by the monomer purification and re-polymerization is preferable. However, high cost and large-scale production for economic viability are drawbacks. The insights provided in this review inform the development of recycling methods that can achieve separation of blends with high efficiency on a large scale.

Author Contributions: Conceptualization, P.A. and M.T.; methodology, P.A. and K.C.; formal analysis, K.C.; investigation, P.A. and K.C.; resources, P.A.; data curation, K.C.; writing—original draft preparation, K.C.; writing—review and editing, K.C., M.T. and P.A.; supervision, P.A.; project administration, P.A.; funding acquisition, P.A. and M.T. All authors have read and agreed to the published version of the manuscript.

Funding: This material is based upon work supported by the U.S. National Science Foundation (NSF) under Grant No. EFMA-2029375.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflicts of interest.

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