Future Textiles

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Executive Summary

The textile industry is experiencing a substantial transformation due to its increasing dependence on synthetic fibres derived from fossil fuels. The shift from natural to synthetic fibres, primarily polyester, has led to severe environmental challenges, including greenhouse gas emissions, microplastic pollution and chemical contamination. It is estimated that fossil fuels will likely be completely depleted between 2050 and 2070, and almost definitely between 2070 and 2090. This raises concerns about the sustainability of current synthetic fibre production. Further, the rise of "fast fashion" has intensified textile waste, leading to overflowing landfills with non-degradable textiles that are causing environmental imbalance.

Moreover, not only synthetic fibre manufacturing and processing but also the production and handling of natural fibres to create yarn and fabrics, along with their wet treatments, pose significant environmental hazards. Consequently, pollution is present throughout the entire textile manufacturing process, from beginning to end. Taking immediate action is crucial to mitigate environmental degradation, climate change, resource depletion and health risks.

Before devising a solution, it is essential to identify the historical trends, properties, and chemistry of textile fibres, the extent and causes of hazards, and the alternatives that have already been proposed. Moreover, recognising the current global sustainability trends and technological advancements, such as Industry 4.0 technologies, is crucial. These technologies have significantly improved our quality of life and are continually evolving. This is wise to consider how their seamless integration with the textile industry over the next decades could drive sustainable modernisation. This integration could ensure a more efficient, transparent, and environmentally friendly production process, supporting effective and customisable circular garment production, potentially even at the domestic level.

An ideal approach forward involves examining likely near-future scenarios and identifying the research and innovation still required to achieve those goals, which is the emphasis of this paper. It appears that a new form of textile production has a significant opportunity in the future market, especially in clothing. This new development will hopefully address the environmental, energy, material, and waste issues currently prevalent in the most dominant processes for machinery, labour, spinning, weaving, cutting, and sewing. This would lead to a new era of technology, departing from age-old concepts in manufacturing. It would also pave the way for a dramatic shift in garment design and fashion.

This paper is structured into four chapters, each progressively focusing on Future Textiles. It begins by presenting key information on the historical development of textile fibres and manufacturing processes, as well as the extent and primary causes of environmental hazards. The discussion moves forward through sustainability and technological trends to forecast future directions. Lastly, it rationalises the theoretical foundations essential for designing the prerequisites of future advancements, envisioning a scenario where individuals can design and create their clothing at home with the simple press of a button, and deconstruct and reconstruct them as many times as needed.

If significant technological advancements for a waste-free textile process are not achieved by 2050, the reduction of non-biodegradable synthetics will create a substantial supply gap that natural fibres alone cannot fill. Therefore, developing textiles with specialised materials and construction techniques that allow for deconstruction and reconstruction is a clear solution to address this issue. This paper

has identified challenges in five major areas of textile manufacturing on its path to sustainability. These include— (1) *Sustainable Materials*: Transitioning from fossil-fuel-based fibres to bio-based alternatives at scale is complex. Bio-based materials like those from bacterial pathways, agricultural waste, and underutilised natural fibres need to be developed and integrated into mainstream production. (2) *Sustainable Colouration*: Traditional dyeing processes are resource-intensive and polluting. In contrast, bacterial colourants offer a sustainable alternative, but they require scaling and economic viability for widespread adoption. (3) *Green Chemical Processes*: Hazardous chemicals used in textile processes pose environmental and health risks. There is a need to develop and implement eco-friendly chemical alternatives and update industry standards to mandate greener practices. (4) *Separation and Reuse*: Current recycling of textiles, especially mixed fibre textiles, is complex and inefficient. Technologies like triboelectric separation show promise but need further development and infrastructure support. (5) *Circular Garment Production*: Implementing circular garment production at the domestic level is ambitious but achievable. Integrating Industry 4.0 technologies and overcoming limitations of nonwoven materials are essential for success.

In essence, human progress in textiles has only advanced marginally from the use of animal skins, as the fundamental techniques of spinning, weaving, cutting, and sewing, developed thousands of years ago, continue to dominate the industry today. This indicates a clear need for development and a significant business opportunity to evolve and address current and future challenges. The recommendations include investing in scalable bio-based materials, supporting bacterial dye technology, developing sustainable chemical alternatives, advancing recycling technologies, and leveraging modern technologies for circular systems, all while fostering collaboration among industry leaders, researchers, and governments.

Introduction

The textile industry, a foundation of modern civilisation, has been witnessing a paradigm shift in recent times. Historically anchored in natural fibres like cotton, wool, and silk, it has increasingly leaned towards synthetic fibres, particularly those derived from fossil fuels. Polyester, nylon, acrylic, and other synthetic textiles now dominate the market due to their durability, affordability, and versatility. However, this shift is accompanied by significant environmental concerns, driven by the escalating production rates of fossil fuel-based fibres and the consequent rise in textile pollution.

The advent of synthetic fibres in the mid-20th century revolutionised the textile industry. These man-made fibres offered a range of advantages over natural alternatives: they could be produced at a lower cost, exhibited superior strength and elasticity, and required less water and land resources compared to traditional agricultural methods. Polyester, the most prevalent synthetic fibre, exemplifies this transition. Now it accounts for over 60 % of global fibre production, with its demand projected to grow as the global population and consumerism expand. Within this time, mechanisms of preparing fibre were also developed through regeneration from natural resources, though their use is very limited till now. Figure 1 shows the rise of synthetic fibre production over the past 50 years when natural fibre production barely has increased. In 1975, natural fibre production was 63 % of global fibre production, which is now dramatically reversed by increasing production of synthetic fibres, mostly through polyester.

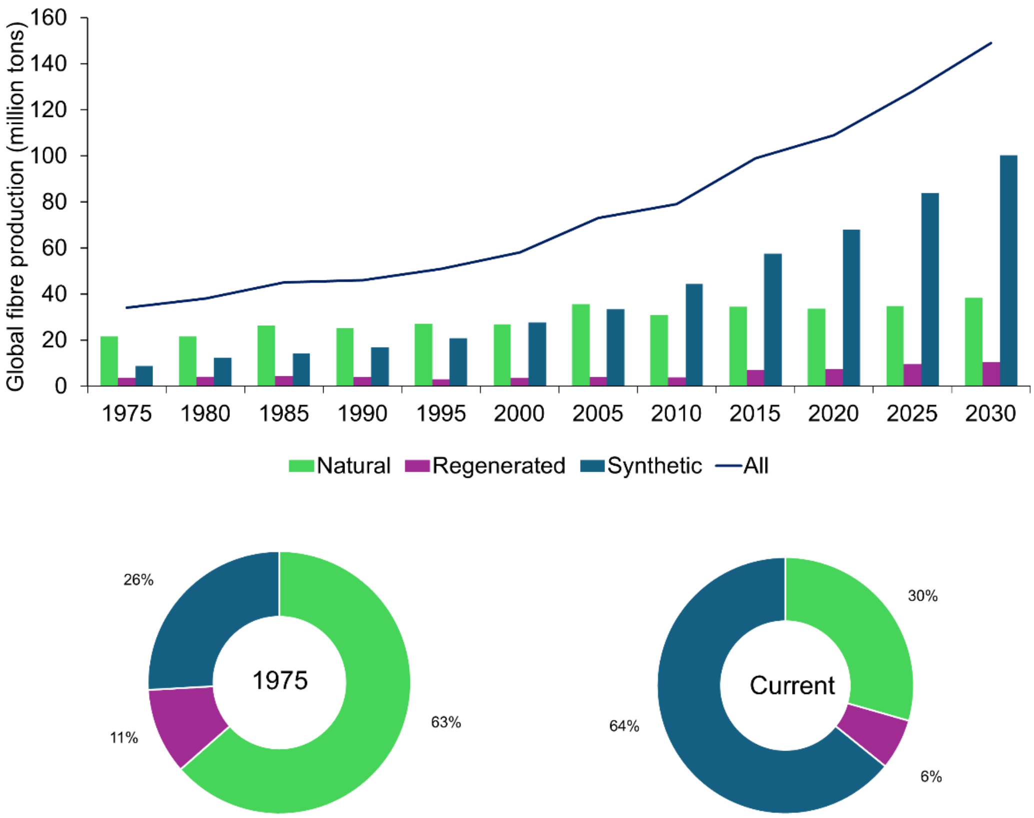

Figure 1: The gradual shift in textile fibre production over the past 50 years with the future projection [1].

Despite their economic benefits, the production and disposal of synthetic fibres pose severe environmental challenges. The manufacture of synthetic textiles is heavily reliant on petrochemicals, making it a substantial contributor to greenhouse gas (GHG) emissions. The entire lifecycle of these fibres—from raw materials to end-of-life disposal—saturates the environment with pollutants. The extraction and refinement of crude oil and natural gas to produce petrochemical precursors for synthetic fibres are energy-intensive processes. These operations release significant amounts of carbon dioxide (CO_2) and other GHG, worsening climate change. It is estimated that the textile industry is liable for around 10 % of global GHG emissions, a substantial portion of which originates from synthetic fibre production. One of the most dangerous consequences of synthetic fibre use is the release of microplastics. During laundering, synthetic textiles shed microfibres—tiny plastic particles that bypass filtration systems and enter aquatic ecosystems. These microplastics persist in the environment, posing threats to marine life and, ultimately, human health. Studies have found microplastics in the most remote parts of the oceans and inside human bodies, indicating the pervasive nature of this pollution.

The production of textiles requires the use of numerous chemicals, including dyes and finishing agents. These substances often contain hazardous compounds that can leach into soil and water systems during production, use, and disposal. The resulting contamination can harm wildlife, disrupt ecosystems, and pose health risks to humans. Figure 2 summarises the few key impacts of textile production in numbers.

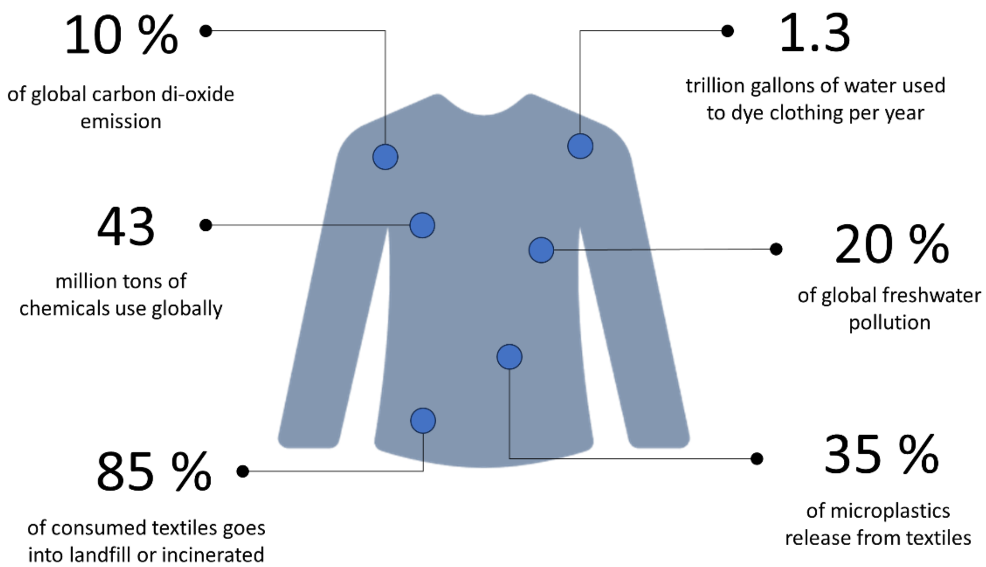

Figure 2: The environmental concerns for textile manufacturing.

The surge in synthetic fibre production has paralleled a rise in textile waste, compounding the issue of pollution. The "fast fashion" phenomenon—characterised by rapid production cycles and frequent turnover of fashion collections—has intensified this problem. Consumers are purchasing more clothing than ever, but they are also discarding garments at an unprecedented rate. These wastes predominantly end up in landfills or are incinerated, both of which have severe environmental consequences. Landfills, often ill-equipped to handle the volume and nature of synthetic textiles, become overburdened, leading to the release of methane, a potent GHG. Incineration, on the other hand, releases toxic emissions and contributes to air pollution, affecting public health and ecosystems.

The dependence of the textile industry on fossil fuels is not merely an environmental issue but a pressing concern for resource sustainability. The finite nature of fossil fuels means that their continued utilisation for textile production is unsustainable in the long term. As easily accessible reserves are exhausted, extraction becomes more complex, costly, and environmentally destructive.

The increasing rate of fossil-fuel-based fibre production as well as overall textile pollution present a dual-edged sword of environmental degradation and resource scarcity. Addressing these concerns requires a multifaceted approach involving governments, researchers, industry stakeholders, policymakers, and consumers. The textile industry stands at a crossroads, with the opportunity to redefine its relationship with the environment and resources.

This paper explores opportunities for future research in textile manufacturing by integrating sustainability, innovation, and responsible production methods. These approaches are forward-looking and technologically advanced, with significant potential for maturation in the coming years.

Chapter 1 provides background information on textile fibres, current manufacturing processes, and historical development trends. Chapter 2 evaluates the environmental costs associated with current processes. Chapter 3 highlights recent advancements, technological trends, and potential future directions in textile manufacturing. Chapter 4 discusses the theoretical foundations and design prerequisites necessary for the advancement of Future Textiles. Overall, this paper aims to provide a comprehensive overview of the current processes and advances and outline potential pathways to the sustainable and resilient Future Textiles.

Chapter 1

Textiles: A Brief History to Present

Preamble

This chapter gives an overview of the rise of textile manufacturing processes over thousands of years. This includes the historical development of textile fibres and mechanisms invented to produce different structures of textiles and their prerequisites. This also compares the growth rate in each of these segments and productivity.

1.1. Textile fibres

Textiles are made of fibres that are long, thin, and flexible structures resembling hair or thread. These fibres can be either natural or manmade. While the history of natural fibres, such as cotton, wool, and flax, is thousands of years old, manmade fibres like polyester and rayon have been emerging just from the last century. Fibres can also be either in a short staple form, i.e., short in length, or long filament form. Most of the natural fibres are short staple, whereas most of the manmade fibres are obtainable in a continuous filament form. Fibres are commonly spun into yarns, and then the yarns are organised into different textile structures or fabrics. Fabrics are then cut and sewed to produce garments.

1.1.1. Natural fibres

The oldest yarn remnants that have been discovered in the Caucasus region are made from flax (also known as linen), and date back to 36,000 BCE [2]. The first woven fabric sample found in ancient Egypt suggests the use of cotton fibres as early as 12,000 BCE across the Nile Valley region [3, 4]. Ancient Egypt is also known for founding flax cultivation as a textile crop and its use for funerary including mummy strips and funeral linen [5]. Cotton and flax are some examples of plant-based natural fibres, though some natural fibres, such as wool and silk are sourced from animals. Sheep are the source of wool and one of the four key animals managed in the Neolithic ages [6]. The demand for sheep wool must have emerged early, although the first conclusive evidence of wool production dates to the Mesopotamian region around 4,000 BCE [7]. The production of silk fibre through raising silkworms, known as sericulture, was first recorded in China near 2,700 BCE [8]. Silk is the only natural fibre that comes in a filament form and has been an inspiration among men to invent silk-like continuous fibres, which later led to the discovery of different manmade fibres. Figure 1.1 shows some key milestones throughout the historical advances in natural and manmade fibres.

Most natural fibres are plant-based or cellulosic. Since these plants grow naturally, they are influenced by numerous factors, such as climate and weather conditions, cultivation practices, seed and soil quality, and fibre separation processes. For example, the genetic makeup of the plant seeds influences fibre attributes such as length, strength, and fineness [9]. Besides, the environment in which the plants grow, including the soil and climate affects fibre quality. Correct agronomic practices, such as appropriate irrigation, fertilisation, and pest control can optimise the quality of natural fibre. Harvesting practices, such as correct timing and harvesting mechanism are also important to ensure fibre quality. While harvesting at the correct time can gain mature fibres with maximum quality, some harvesting methods may lead to more impurities and fibre damage compared to other harvesting methods (such as higher impurities in stripper harvesting for cotton compared to spindle picking) [10].

Among plant fibres, cotton comes from the seed of the plant, while most other cellulosic natural fibres, such as jute, flax and hemp are collected from the fibrous layer in plant stems. Therefore, the collection and separation process of plant fibres plays a pivotal role towards the ultimate fibre quality.

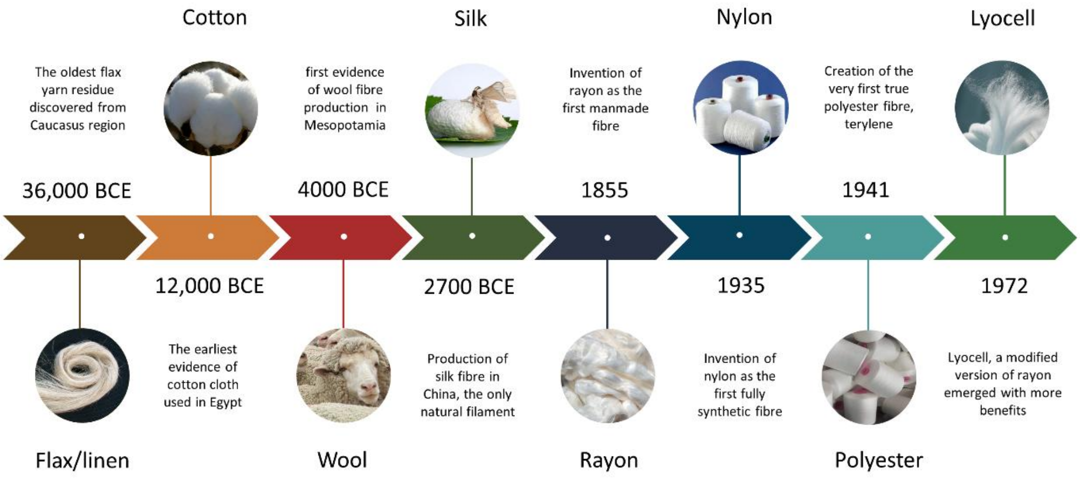

Figure 1.1: Key historical advances in the uses of natural fibres and the invention of manmade fibres.

Natural protein fibres are also dependent on climate conditions as well as farming practices. For example, the breed of sheep, grazing conditions, sheep health, shearing and sorting practices are key for wool fibre quality [11], whereas silkworm species, temperature, humidity, sericulture practices and silk reeling method are some of the key factors for achieving good quality fibre [12].

The quality assurance process of natural fibres has a major contribution to the properties of the final fibres that are used for spinning into yarn. Since cotton is the leading natural fibre and has superior demand worldwide, this is not surprising that this segment has a great technological advancement regarding quality assurance and control. However, there is still a huge barrier to overcome for other natural cellulosic fibres (such as flax, jute and hemp) regarding their modification, treatments, and quality control to integrate more of these fibres in today's fashion industries and marketplaces.

1.1.2. Manmade fibres

Though prior attempts have been made to prepare 'artificial silk', the first practical advancement for producing a man-made fibre was accidental. In 1846, from a treatment of cellulose with sulfuric acid and nitric acid, Christian Friedrich Schonbein proposed an explosive (gun cotton) and misnamed it as nitrocellulose, though it was indeed cellulose nitrate [13]. Later in 1855, George Audemars first demonstrated drawing out and reeling of cellulose nitrate threads that were sourced from cellulose of mulberry tree and patented as artificial silk [13]. Over the years, several types and derivatives of rayon have been developed, such as cuprammonium rayon and cellulose acetate, though the one known as viscose rayon (invented in 1891) now represents the majority of the regenerated cellulose fibres market worldwide. Viscose rayon is prepared from the treatment of cellulose alkali and carbon di-sulphide and was first commercialised in 1905 [13]. However, the most notable progress in the rayon segment is probably the introduction of lyocell in 1972 (commercialised as Tencel), which uses a sustainable and recoverable solvent for cellulose instead of hazardous carbon di-sulphide [14] and also results in a better fibre strength than that of viscose. These fibres are often called regenerated fibres or semi-synthetic since the raw material is sourced from natural plants. However, in the meanwhile, significant progress has been made in creating fully synthetic manmade fibres in the 1930s and 1940s.

Nylon was invented in 1935, as the first truly synthetic fibre. Soon after, polyester emerged in 1941 [15] and gradually exceeded all other fibre markets. These fibres are called fully synthetic as they are sourced from fossil fuels, not renewable resources of the planet. Synthetic fibres, like polyester are not as comfortable as the natural fibres during wear, but they are more durable, flexible and more importantly, cheap, which have stirred their high production over the past decades. Today, polyester has become the most dominating textile fibre in the world, having more than half share in the market (Figure 1.2).

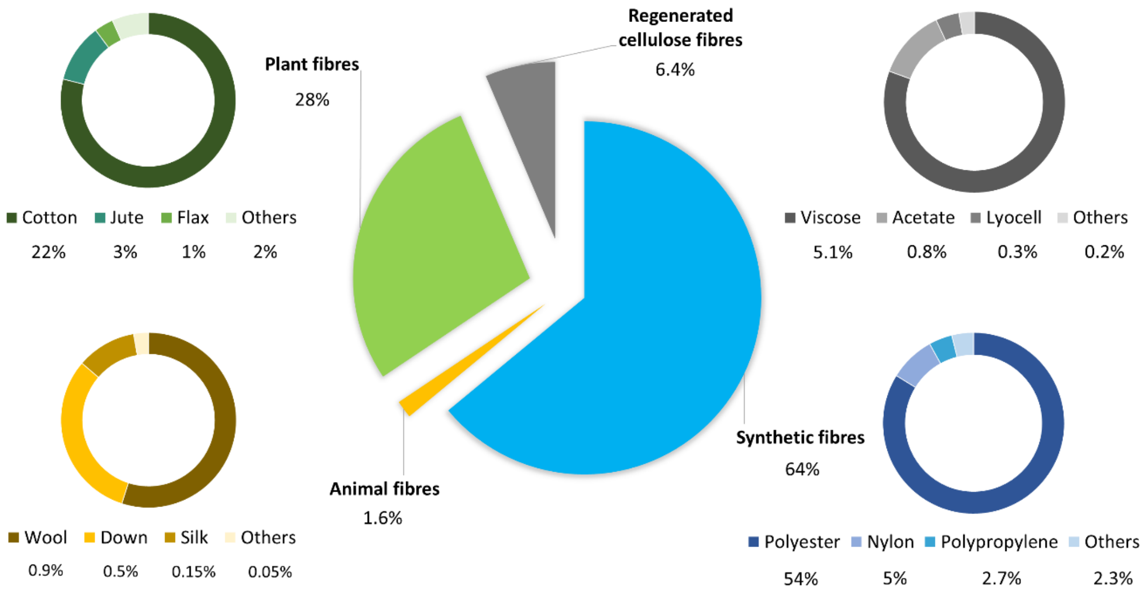

Figure 1.2: Current worldwide production of some major textile fibres, adapted from [1].

In contrast to natural fibres, synthetic fibres (such as nylon and polyester) are independent of any weather conditions, though are largely dependent on fossil fuels (Figure 1.3). Polyethylene terephthalate (PET), the most common type of polyester, often called only ‘polyester’, is a synthetic polymer prepared from the chemical reaction of two chemicals, terephthalic acid and ethylene glycol, both are soured from fossil fuels, i.e., crude oil and its refining [16]. Fossil fuels are also used to obtain the precursors of nylon fibres. The synthetic polymers prepared by these processes are melted in a hopper and then are passed through a spinneret to draw fine filament (also known as the melt spinning technique). After melt spinning, these filaments can be readily twisted to get synthetic yarn or can be chopped into small fibres to be mixed with natural fibres. The ability of synthetic fibres to be produced directly into a yarn reduces a huge amount of time during textile production and hence has become a key promoter of today’s so-called fast fashion. However, with the fossil fuels current rate of decline from the world, the supply of truly synthetic fibres is likely to decrease soon.

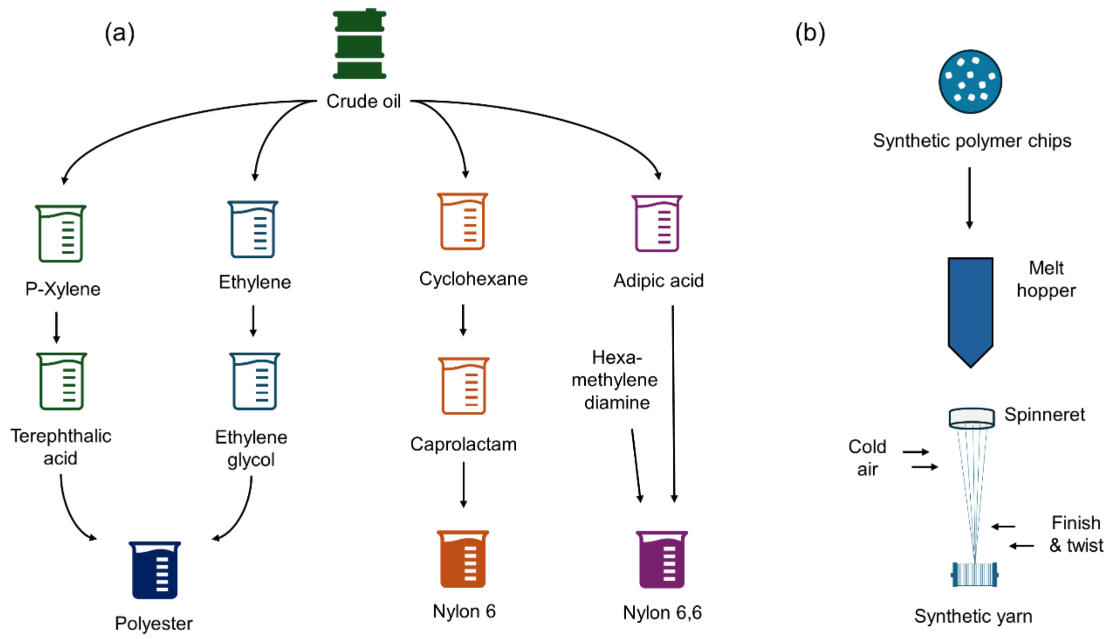

Figure 1.3: Production process of (a) polyester and nylon polymers and (b) their conversion into synthetic yarn by melt spinning.

Recently, polyester manufacturing has also been started from natural biomass, though they are currently just 0.02% of the global polyester production [1]. The polyester fibres prepared in such a way are known as bio-based polyester. The production of bio-based polyester involves sourcing ethylene glycol and terephthalic acid, from renewable biomass feedstocks such as sugarcane, corn, or other plant-based materials [17]. The resulting polyester has the same chemical structure as traditional polyester (and is not biodegradable) but is considered more environmentally friendly due to its renewable origin. There are also other kinds of bio-based synthetic fibres introduced in the recent past sourced from natural biomass, while some of them are claimed biodegradable in certain conditions [18]. These include bio-based polylactic acid (PLA), bio-based polybutylene succinate (PBS) and bio-based polyhydroxyalkanoates (PHA). However, their share in the current market is minor.

1.1.3. Global production of textile fibres

Figure 1.2 shows the distribution of current fibre consumption worldwide among fully synthetic, semi-synthetic (regenerated cellulose) and plant and animal-based natural fibres. According to a report published in October 2022 [1], the current production of synthetic fibres is 72 million tonnes (64 % of global fibre production), of which 60.5 million tonnes are polyester only. Nylon is the second highest synthetic fibre produced with a production of 5.9 million tonnes, while production of polypropylene and acrylic fibres are 3 million tonnes and 1.7 million tonnes, respectively. Despite regenerated cellulose fibres, i.e., different rayons, discovered before the fully synthetic fibres, the production of these fibres is still much lower and is more concentrated on the production of viscose only (5.8 million tonnes). The lyocell process is emerging, though now only plays a minor role in overall regenerated cellulose production (0.3 million tonnes). Among the natural fibres, the current share of plant-based fibres is 31.3 million tonnes, led by 24.7 million tonnes of cotton production. Other plant-based fibres as well as animal fibres have a marginal share in overall production, such as 3.4 million tonnes of Jute, 1.1 million tonnes of flax, and a total of 1.8 million tonnes from all the animal-based fibres, including wool, down and silk.

1.2. Textile manufacturing

There are four major sectors during the conversion of textile fibres into cloth. These are: (1) yarn manufacturing or spinning, (2) fabric manufacturing, (3) textile colouration and/or finishing, and (4) apparel manufacturing. Spinning is the conversion of fibres into yarn by aligning them lengthwise and twisting. For short-staple fibres, this is normally done by a series of machineries, involving multiple preparation stages, such as blowing, carding, drawing, and combing before the final spinning. However, manmade fibres can be directly spun into yarn from their filament form during the manufacturing process, such as by melt spinning or wet spinning. Spinning industries then supply these yarns to produce fabrics. The structures of textiles are made in the second stage, i.e., fabric manufacturing, where yarns are organised in a certain manner to produce fabrics. As per the designated structures, industries are different. When the fabrics are made by the fabric industry, they are transported to the apparel manufacturing industry to perform cutting, sewing and other requirements to make the garment and supply to the market. Within these steps, the colouration of textiles is also performed, though can be in between any stages. The most common practice is to colour textiles in their yarn or fabric form, though colouration of fibres at the very beginning or colouration of garments at the very end is also practised. Depending on the stage of colouration, as well as the structure of fabrics, separate machines and separate industries are involved to complete the whole process.

1.2.1. Textile structures

There are three basic structures of textiles; woven, knitted and nonwoven. For the first two, fibres first needed to be converted into yarn by spinning process. A woven structure is formed by interlacing two sets of yarn from perpendicular directions, known as weaving. The lengthwise yarns are known as the warp yarn and the widthwise yarns are known as the weft yarn. However, knitted fabrics are structured by forming loops in the width (weft knitting) or length direction (warp knitting) of the fabric with the help of needles. Nevertheless, the nonwoven structure is completely different from these two, as the fabric is made directly from fibres, without the need for any yarn. The structure is strengthened by bonding fibres together using different techniques, e.g., mechanical, chemical, or thermal bonding. Figure 1.4 shows the structural difference among woven, knitted, and nonwoven fabrics.

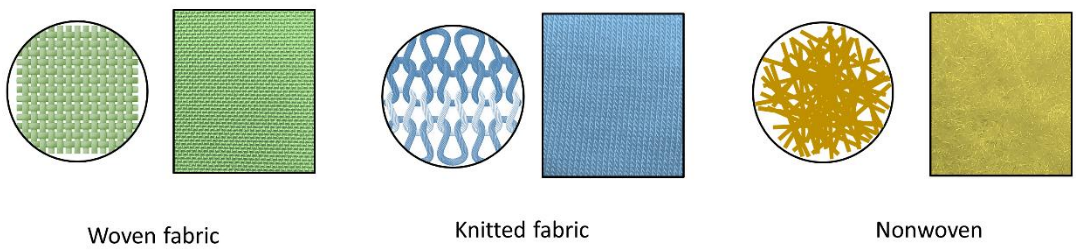

Figure 1.4: Structural difference in woven, knitted and nonwoven fabrics.

1.2.2. Preparation of woven structure

The machine used to prepare a woven fabric is known as a loom. In a loom, warp yarns are inserted lengthwise parallel to each other, and as per a desired pattern, a selection of yarns are lifted to create a tunnel in which weft yarn is inserted sideways. Then that set of warps is lowered, and another set is lifted to pass through another weft yarn. Therefore, warp yarns need to be aligned parallelly in a beam beforehand to supply continuous yarns to the loom. This process of aligning the spun yarn parallelly into a beam is called warping. Further, to withstand the constant tension and friction applied on warp yarns (by lifting and lowering) during weaving, they need a prior coating or lubrication. Applying this coating or lubrication on warp yarns is known as sizing. After warping and sizing, warp yarns become ready to be used in a loom. However, those additional steps are not required for weft yarn, and they can be directly used in the loom. Woven fabrics are commonly less stretchable and have poor crease resistance, but are dimensionally more stable [19]. Their conversion cost from yarn is higher than knitted fabrics, as several preparation stages are required. Figure 1.5 shows a comparative schematic of the processes involved in preparing woven fabric, compared to knitted and nonwoven fabrics.

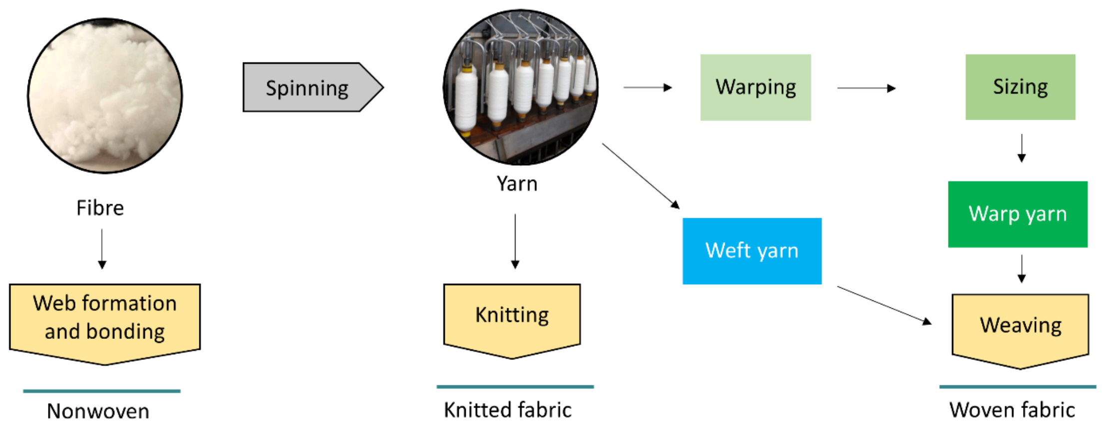

Figure 1.5: Major processes involved in the preparation of woven, knitted, and nonwoven fabrics.

1.2.3. Preparation of knitted structure

There are two fundamental types of knitted structures, i.e., weft-knitted and warp-knitted. In the weft-knitted type, one yarn is used for creating one horizontal line of loops, whereas for the warp-knitted structure, each loop in one horizontal line is made from different yarns and supplied separately. Contrasting the preparation process for weaving, the preparation of a weft-knitted structure is rather simple. For weft knitting, there is no such preparation process required and the spun yarns can be directly fed into the knitting machine. For warp knitting, since the yarns need to be supplied from a warp beam, a warping process is needed (resembles the warp yarn supply process in weaving), though no sizing is involved. Knitted fabrics are known for their stretchability and comfort, though are commonly less durable than woven fabrics. The transformation from yarn to knitted fabric requires almost no preparation, which lowers its production cost [19].

1.2.4. Preparation of nonwoven structure

The preparation nonwoven, is comparatively straightforward compared to either weaving or knitting methods. This is because there is no yarn required and the structure can be made directly from the fibres. For this process, at first, a sheet or web of fibres is formed followed by a bonding process that unites the fibres together. The bonding can be performed through mechanical, chemical, or thermal methods. For instance, in mechanical bonding, the fibres are bonded together by needle punching, stitching or by liquid or air jets. For chemical bonding, chemicals or binders are sprayed on the web to bind the fibres chemically. For thermal bonding, a thermoplastic component should be present in fibre form which can glue all other fibres when heat is applied. Nonwoven fabrics are cheap and quick to produce compared to woven and knitted fabrics due to their significantly reduced number of process steps (Figure 1.5). The current machines for producing nonwovens also have a significantly higher production rate than most contemporary knitting or weaving machines, which can be perceived from Figure 1.6.

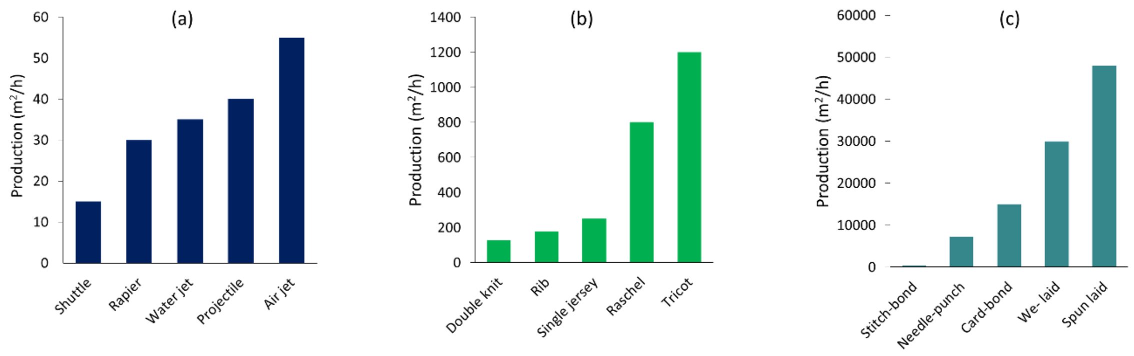

Figure 1.6: Production speed of some modern woven (a), knitted (b) and nonwoven (c) fabrics producing machines, adapted from [19].

1.3. Historical development of textile manufacturing

The development of weaving technology is probably linked to the rise of human civilisation since the dawn of history. Wearing clothes was found to be a notable feature of ancient artefacts and mural paintings [20]. The oldest examples of clothing are mainly in woven structures. Flax yarn specimens from 36,000 BCE [2], cotton woven fabric from 12,000 BCE [4], and linen woven fabrics from Ancient Egypt (2140-1295 BCE) [5], together suggest a wide time span when the art of weaving was well progressed.

However, early looms had a very low production due to the need for alternative lifting of warp yarns and insertion of weft yarn manually. For weft insertion, Egyptians used a simple skein, which was later done employing a shuttle, containing a yarn spool inside. The shuttle was manually operated by throwing from one end to the other end of the loom [21]. Evidence of such handlooms is found in artworks, such as paintings in the tombs in Egypt (Chemhòtpe at Beni Hasan) [21]. Only around 333 CE, pedal-operated looms (to lift the warp yarns) were found in Egypt.

Compared to the primitive history of weaving, knitting is relatively a recent technology. The oldest evidence of a knitted fabric, a pair of wool socks, was dated from only 400-500 CE from Egypt (Victoria and Albert Museum, London) [19]. From the beginning, the technique of knitting involves using two sticks, i.e., hand knitting [22], which is still done at home in many parts of the world. Though woven fabric was used for almost all clothing purposes of humans, any previous use of knitting (except for socks) is unknown. Going forward, by the 9th century, weft-knitted stockings were being worn in the Arab world, and by the 10th century, two-colour stockings were prevalent in Egypt [23]. Later, knitted gloves (11th Century) and caps (12th century) were also appeared [22].

Despite that nonwoven is considered a new technology (the first commercial journey in 1942), reports suggest that the first finding of nonwoven felt is from 3500-3000 BCE, made by pressing hairs of different animals together. Those were mainly used to create tents for shelter as well as protective clothes [24], and nowadays this form of felting has been largely practised in home furnishing, such as floor carpets. Further, some nonwoven felt caps aged 3500 years have been found in Scandinavia, while a few other nonwoven items belonging to 1400-1200 BCE were found in Germany and Siberia [25] as well. Interestingly, unlike woven and knitted structures, nonwoven has many prototypes available in nature. These include the nests of birds and mammals, membranes in eggshells, plant roots and so on. The invention of paper is also correlated to nonwoven as paper is indeed a form of nonwoven structure. There are also evidences of using silk cocoons and hemp in paper preparation in China (around 200 BCE).

Within the past few centuries, particularly around the time of the Industrial Revolution, radical technological progress was made in the segments of textile manufacturing. The inclusion of machines (rather than hand) in textile manufacturing, has drastically altered the way textiles were made before and are manufactured now. The major inventions made in this period are discussed in the following subsections.

1.3.1. Key progress in weaving

From the existence of looms before the common era and gradual updates in its mechanism, this is obvious that weaving technology was in a more advanced stage compared to knitting and nonwoven technology. For instance, in 1466, Giovanni il Calabrese constructed the earliest instance of a precursor of a programmed loom, when there was no machine available for either knitting or preparing nonwoven. This was known as the draw loom, which could lift some heddles designated to some of the warp yarns and could be operated by pulling some buttons that have designated numbers. The weaver used to pull the button as per a pre-noted sequence and insert weft yarns accordingly [21]. Later, major progress in weaving occurred with the invention of the flying shuttle by John Kay in 1733, which is a mechanism of throwing shuttles from one end to another mechanically rather than by hand. Even with its primary versions, it allowed a four-fold boost in output and the ability to produce larger fabrics with just one weaver. In 1760, his son Robert Kay produced a drop box that allowed the use of more than one shuttle and permitted different coloured weft yarn. A few years later in 1787, steam-powered mechanical loom was introduced by Edmund Cartwright and was employed in weaving mills. However, stronger warp yarn was required by power looms, which coincided with the invention of the first sizing machine in 1803 [26]. Soon after, a significant development in the weaving segment came through Joseph Marie Jacquard in 1804, which was the invention of the Jacquard mechanism. This was the first automatic version of a programmable loom able to produce complex designs. In this method, a punched cardboard system was used with more versatility in lifting warp yarns. It is sometimes credited as the precursor of modern computers since it employed a binary method to store data so that it could be read by the loom and repeatedly replicated [27]. With further advancement in this segment, shuttle-less looms appeared in the 1950s (commercial journey since the 1960s) as the most upgraded versions; replacing 'shuttle' in the loom, which was a key component in past weaving history [28]. Now technology has permitted further high production speed and a more economical way of weaving by means of other methods to carry weft yarn rather than shuttle, such as air, water, projectile, rapier and so on. Table 1.1 summarises the major milestones in the weaving segments in the past few centuries.

Table 1.1: Some major technological advances in weaving segments in the past few centuries.

Year	Event
1466	First use of draw loom, lifting warp by pulling buttons
1733	Invention of the flying shuttle, the first mechanical movement of the shuttle
1760	Invention of a dropbox to use multiple shuttles at once
1787	Development of the first steam-powered loom
1803	Invention of the sizing machine to strengthen warp yarn
1804	Invention of the jacquard system, the first programmable automatic loom
1950s	Invention of shuttle-less looms
1960s	Commercial journey of today's shuttle-less looms

1.3.2. Key progress in knitting

Knitted fabrics were not as popular as woven fabrics and were not significantly produced before. Knitting only became a profession in the 15^{th} century when males first got involved [22]. Knitting socks became prevalent around the 17^{th} century [19], and not many other types of knitted clothes were available like nowadays. The first major movement in the mechanisation of knitting happened in 1589 when William Lee invented the very first knitting machine (known as a stocking hand frame). This invention is considered at least 150 years ahead of its time, though it needed two persons to operate and was able to knit only poor-quality stockings. This is thought to be the foundation of today's industrial knitting machines, despite further technical advances and refinements in succeeding centuries [29]. In 1758, J. Strott introduced a double-knit structure, i.e., a pattern that uses two sets of needles, producing fabric that is two times thicker than regular knitted fabric [22]. In 1769, rotary drive was adopted in knitting machines. In 1847, the latch needle, which is still now the most used needle in knitting, was invented by Matthew Townsend [22, 29]. A few years later in 1850, the first power-driven circular knitting frame was invented [22]. In 1863, the first V-bed flat knitting machines were developed. Earlier developments were mainly on weft knitting, while the warp knitting technique was first developed by Crane and Porter in 1769 [29]. Further progress in warp knitting occurred in 1915 and 1953 when tricot and raschel machines were built, respectively [22]. Circular knitting machines (single and double jersey), V-bed, tricot and raschel knitting machines are some of the common examples of knitting machines that are widely used in industries. Table 1.2 shows some key advances in knitting machines since its beginning. Nowadays knitting technology can produce a wide range of apparel including, t-shirts, trousers, sweaters, active wear, home furnishing and accessories. Knitted fabrics are gaining increasing popularity as they are more flexible and crease-resistant than woven fabric and can be well-suited in varied environments. A recent advance in the knitting segment is the inclusion of seamless garment knitting in 1995. This is a technique where knitting machines are designed in such a way that garments can directly be produced by knitting, without the need cutting and stitching [30]. With the aid of this technology, seamless, perfectly fitted, three-dimensional tubular ready-to-wear garments are made. This has added a greater advantage for knitting over weaving, in terms of further savings of cost and time and increase overall productivity.

Table 1.2: Some fundamental advances in knitting technology.

Year	Event
1589	Invention of the Stocking hand frame, the first knitting machine
1758	Introduction of double rib knit frame

1769	First adoption of rotary drive in a knitting frame
	Invention of the first warp knitting machine
1847	Invention of the latch needle, today's most used needle in knitting
1850	First power-driven circular knitting machine
1863	First development of V-bed flat knitting machines
1915	First Tricot warp knitting machine
1953	First Raschel warp knitting machine
1995	Inclusion of seamless garment knitting, direct garments by knitting

1.3.3. Development of nonwoven technology

There were some thick jute-sisal needle-punched nonwoven felt available in the UK and USA around 1890s [25]. However, any industrial progress on nonwoven technology was not identified till the 1930s, when the first laboratory and pilot-scale run was performed. The first commercial production of nonwoven in large quantities (some thousand pounds) occurred only in 1942. After that, by the end of the 20th century, several commercially feasible nonwoven manufacturing techniques had been developed and the engineered products are now competing with woven and knitted fabrics. For example, the first disposable diaper using nonwoven was made by George Schroder in 1947. Later, dry-laid (1948), spun-laid (1950s) and wet-laid nonwoven (1971) were developed by Freudenberg [31]. Table 1.3 summarises some key progress in the nonwoven technologies. Currently, the use of nonwoven is expanding in many applications including filters, wipes, carpets [25], automotive and medical purposes, apparel and so on [19]. In 2003, a new technique of nonwoven preparation, i.e., spray-on fabric technology was patented where the fabric was made by spraying a solution on a supporting substrate [32]. The solution consists of very short fibres, a binder and a diluent. The supporting substrate can be even a human body [33], which points to the possibility of making garments in a completely new way.

Table 1.3: Some milestones in the advance of the nonwoven sector.

Year	Event
1890s	Evidence of thick needle-punched felt from jute and sisal
1930s	First laboratory and small-scale run for nonwoven production
1942	First-ever production of nonwoven on a commercial scale
1947	First disposable diaper made from nonwoven
1948	Production of dry-laid resin bonding system for nonwoven
1950s	Development of spun-laid nonwoven mechanism
1965	First production of the spun-laid nonwoven from nylon
1970	Commercial journey of the spun-laid nonwoven from polyester
1971	First ever wet-laid nonwoven
2003	Nonwoven fabric from spray-on technology

1.3.4. Key progress in other sectors of textile manufacturing

Development in weaving technology was closely connected to the development of spinning, as yarn is a prerequisite for weaving. The oldest method for yarn preparation was hand spinning, resulting in only a few hectograms of yarn a day [21]. A major improvement in the spinning segment was the use of the spinning wheel, which first emerged in the 13th Century [21]. However, there was only one flyer attached to collect yarn from it, thus was slow and was not feasible when the population was radically growing by the Industrial Revolution. Besides, the invention of the flying shuttle (1733) in weaving enhanced the production of fabric, which demanded more yarns. Thereby, James Hargreaves brought a timely invention (1754) known as spinning Jenny which was a revival in spinning. This machine could deliver a much higher yarn production than ever before. In the beginning, the developed machine had 8 spindles to collect yarn and later upgraded to up to 80 spindles [21]. In 1768, Richard Arkwright devised the first spinning frame. This was a water-powdered machine and was able to produce thin yarns. Within a few years in 1779, a new machine 'Mule-jenny' was invented by Samuel Crompton which combines the spinning jenny and the spinning frame in a single machine. The ring frame, which is nowadays a common machine for industrial spinning was invented back in 1828, by John Thorp [21].

While the spinning techniques were rising, men also attempted as early as 1750 to create a machine that would sow fabrics for them to prepare garments [34], before that hand sewing was the only option for sewing which was a laborious and slow process. Finally, a practical sewing machine appeared 100 years later in the 1850s. Soon after, commercial sewing machines were developed by the 1860s [35].

Another important segment in textiles is colouration as the use of dyes has been a key part throughout the development of textile manufacturing. Nature contains an infinite number of colouring agents including dyes and pigments in living and non-living elements. Since time immemorial, humans have become experts at extracting and using them in textiles. Using natural dyes has been a tradition for thousands of years. However, this scenario dramatically changed after the appearance of synthetic dyes in 1856. Nowadays only small businesses, hobbyists, and artists have managed to keep alive the practice of utilising natural dyes [36]. Despite some earlier attempts from scientists (1743 to 1834) to prepare synthetic dyes, William Perkin's invention of "Mauveine" in 1856, as the first synthetic dye, marked the beginning of commercial development. Later, some other dyes were developed in quick intervals until around the end of the 19th century [37]. This includes the invention of different acid and basic dyes (1856-1876), azo and direct dyes (1876-1893) and sulphur dyes (1893-1902) [38]. Further, disperse dyes (1920s) and reactive dyes (1950s) were developed, which are the two most common dyes currently used to dye polyester and cotton, respectively [39]. With the immense growth of synthetic dyes over the years, industries also have embraced a wide range of machinery to perform dyeing operations [40]. However, synthetic dyes are made of non-renewable fossil fuels and hence are now continuously contributing towards the shortfall of these natural resources. Figure 1.7 summarises a schematic of some major progress made in weaving, knitting, nonwoven and other sectors in textile manufacturing from ancient times to the present.

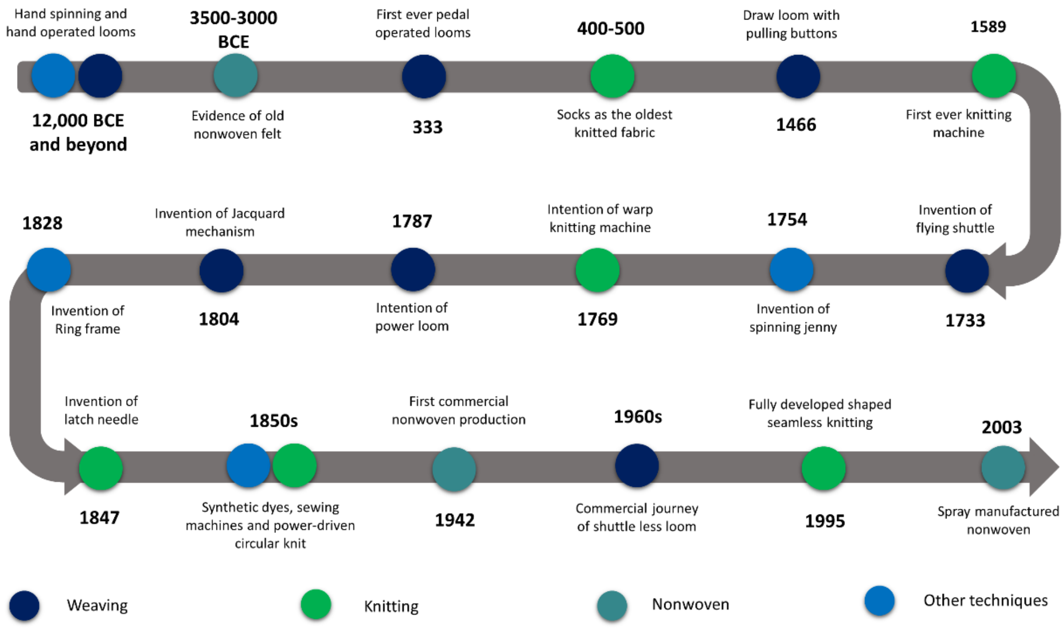

Figure 1.7: Chronology of major technological progress in different sectors of textile manufacturing.

1.4. Trend of development

Though human beings have been using cloths since the dawn of civilisation, this is obvious that most of the scientific developments in the textile sectors, including fibre production and machine invention, have occurred just recently, i.e., in past centuries. Overall, the historical trend of textile development has been triggered by two main correlating factors: population growth and industrial revolution. On one hand, the increasing rate of population has asked for more textiles, which motivated the invention or adoption of new techniques to achieve future faster production more economically. On the other hand, the Industrial Revolution influenced the growth of the population through industrialisation, migration, and the spread of urbanisation. From 10,000 BCE to 1700, in a time span of 11,700 years, the growth rate of the worldwide population was only 0.04%, from 1700 to now, the population increased from 600 million to 8 billion in just about 200 years [41]. This growth rate had already peaked at 2.2% in 1962-63. This is the time span when revolutionary inventions took place internationally and changed the human lifestyle. For instance, the invention of steam and power, later electricity, electronics, and information technology enforced more automation, which is reflected in textile machinery development. Moreover, inventors not only were keen on developing modern machinery to manufacture the fabrics, but they were also keen to create new textile fibres offering further low-cost production and in a quicker time, i.e., the discovery of the manmade fibres. Figure 1.8 represents this relationship between the Industrial Revolution and population rise, which could be justified by the major timeframe of textile fibres and machinery development discussed in previous sections.

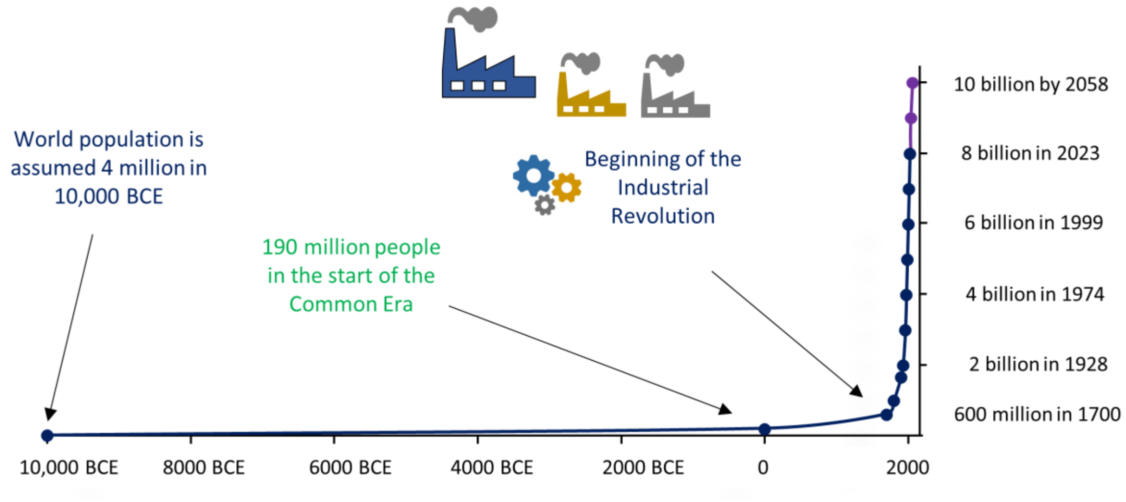

Figure 1.8: A schematic relation between the Industrial Revolution and the population rise, adapted from [41].

A second observation is the increasing domination of processes that are faster and more economical. For example, the higher growth speed of the knitted fabric market compared to the woven fabric market. Woven fabrics have been used since prehistoric times, and there is no wonder that woven fabric still has the highest market size among all kinds. Knitted fabrics only gained popularity in the 17th century through socks use, but in a relatively quicker time has gained wide appeal in today's regular garments. Since the knitting technique has reduced the number of processes, its production of knitted fabric is faster and cheaper than woven fabrics, and the sector is growing more rapidly than the woven sector. This is also reflected in the current compound annual growth rate (CAGR) of the knitted fabric market (5.1%) [42], which is only 1.4% for the woven market [43]. This scenario has become even more dramatic when the nonwoven market is considered in the equation. Currently, the nonwoven sector is the highest-growing sector in textiles, with a CAGR of 6.1% [44]. Despite newer technology, the market size of nonwoven (47.7 billion USD) [44] is already more than that of knitted fabric (28 billion USD) [42]. The ability to create materials with unique qualities quickly and affordably, compared to other manufacturing methods, is crucial for the rapid development and commercial acceptance of nonwovens [23]. Figure 1.9 shows the current proportion of woven, knitted and nonwoven markets and their projected growth rate in the next 10 years. This is true that the nonwoven market is still more concentrated on non-clothing applications and has drawbacks like poor strength and durability compared to woven and knitted fabrics. However, history suggests more technological advancements are coming in near future to recover the current shortcomings of nonwovens, to be accommodated more in regular textiles that we wear every day.

This observation is also true when considering the domination of manmade fibre production over natural fibre production in the last decades. The production process of natural fibres is slow due to dependency on climate, geography, and cultivation processes, whereas manmade fibres are free from these provisions. Further, most natural fibres to date need a comprehensive spinning process to produce yarns. In contrast, yarns can directly be produced from filaments of synthetic fibres during their manufacturing. Both these factors influence the time and cost consumption for the production and stir the use of synthetic fibres over natural fibres. Not only synthetic fibres but also synthetic dyes are gaining many advantages and capturing commercial uses over natural dyes for the same reason.

Nevertheless, synthetic fibres and dyes require polluting processes in their manufacturing and also are non-biodegradable. They are also made from fossil fuels which are limited and with the current consumption rate, the resources will be phased out possibly in the next 50 to 100 years. Since textile manufacturing has already become highly dependent on these, balancing the shortfall of fossil fuels will be critical. Early steps should be the utmost priority in finding solutions to all these factors to avoid the evolving scenario.

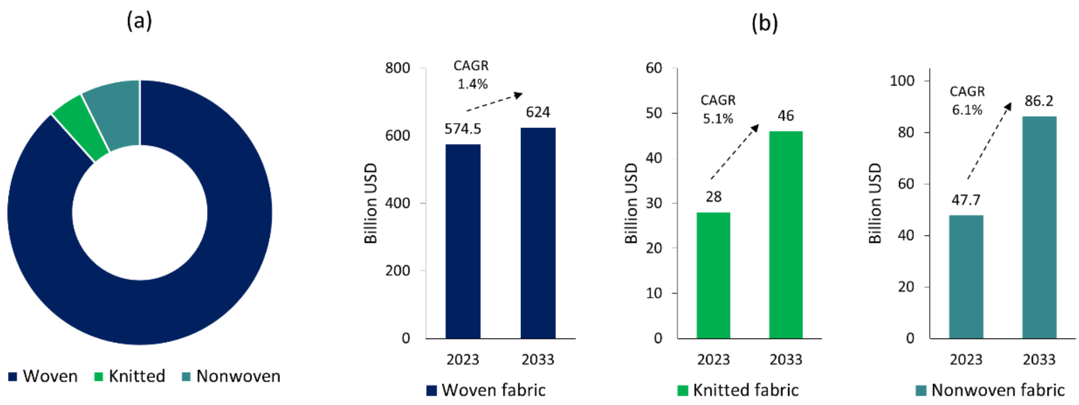

Figure 1.9: Current fraction of woven, knitted and nonwoven market (a) and their likely growth rate from 2023 to 2033, adapted from [42-44].

1.5. Summary

Overall, the historical trend suggests some likely movement in textile manufacturing in the near future through nonwoven technology. Since nonwoven is made from fibres and essentially does not need yarns, this technique is also suitable to utilise the huge waste fibres (often short fibres that are not spinnable and therefore become low-value or waste) that are generated throughout the textile manufacturing processes. Moreover, the structure of nonwoven is such, that it is easier to disintegrate and rearrange again, compared to the more ordered orientation of woven and knitted fabrics. Therefore, the circular use of textiles and their waste is more logical with the nonwoven technique which could be a future era of textile fabrication.

To this end, it is important to know the economic benefits and environmental costs related to the preparation of nonwoven, compared to woven and knitted structures and connected processes. Consideration of the impact of the consumed textiles and any current practices to offset the limitations are also relevant. Chapter 2 will thereby explore the advantages and disadvantages of the current processes to get an overall depiction.

Chapter 2

Hazards in Current Textile Processes

Preamble

This chapter provides an outline of the environmental concerns related to the textile manufacturing processes starting from the fibre manufacturing processes to their end of life. These include parameters such as carbon footprint, water consumption and pollution, microplastic shedding, biodegradation profile and current status of any remediation. This chapter summarises the critical truth in textile processes that need consideration towards advancing the technology for a sustainable future.

2.1. Overview: Properties of key textile fibres

One of the major features of textile fibres that has separated them from any other materials is their length-to-diameter ratio. Fibres are defined to have a very high length-to-diameter ratio, which is often more than 1000 to 1. The diameter of textile fibres commonly lies in the lower range of microscale, such as 8-20 µm for cotton and 16-40 µm for wool. [45, 46]. This is much finer than the diameter of average human hair (53-83 µm) [47]. These features along with their flexible nature have provided textile fibres the advantage to be spun and weaved into textile structures with excellent drape ability that is suitable to wear. Since cotton and polyester are the highest consumed textile fibres in natural and manmade segments, respectively (having a total world share of 76 %) properties of these two key fibres provide practical insights [1].

Apart from their physical structures that are greatly suitable for manufacturing products, textile fibres of natural origin (such as cotton) have breathability [48]. This means they transport moisture from one side to the other (e.g., from the human body to the air) and provide comfort to the skin. Cotton has some unique advantages over all the other fibres. The quality of cellulose in cotton (in terms of orientation and degree of polymerisation) is much superior to cellulose sourced from wood or other agricultural resources. Besides, the strength of cotton increases when it becomes wet [49]. This gives cotton the capacity to survive efficiently in extensive wet processes in the manufacturing stages. Cotton can absorb moisture more than 24 times its weight, which helps easily soak up sweat from human skin in hot seasons and then ventilate to the other side. Cotton has a low thermal conductivity [50] which helps retain the body warmth in winter, making it a wearable option in all seasons. Cotton can be made into fabrics of varied thicknesses with wide-ranging strengths, warmth, and texture. Therefore, cotton is used in almost every purpose possible from textiles, such as casual, formal, or long shirts, t-shirts, and pants including denim, socks and undergarments, and different fabrics such as flannel, poplin, chambray, jersey, home textiles and absorbent pads.

Despite numerous advantages, cotton also has some limitations. The colour applied on cotton is commonly faded over time and fabrics may produce pilling and rips. Cotton can also be attacked by microorganisms if stored in a humid environment [51]. Cotton wrinkles easily and thus needs frequent ironing.

On the other hand, polyester fabrics are used as easy-care apparel, since polyester is hydrophobic, it resists microbes and also holds its colour during washes. It is wrinkle-free and does not form pilling on the surface easily. However, polyester does not provide enough ventilation properties required in summer (like cotton) and thus can cause odour due to the inhabitation of bacteria from the human body. Besides, synthetic fibres such as polyester, nylon, and acrylic are highly flammable and have melt dripping character in contact with a fire source, which speeds up the fire spread and causes massive damage [52]. The high flammability, melting behaviour, rapid spread of fire, high heat generation capacity, and lack of self-extinguishing properties make synthetic fibres particularly dangerous when used in house furnishings. While natural fibres also have flammability, they burn relatively slower, some have flame-retardant properties and can self-extinguish on their own (such as wool). Figure 2.1 shows two key flammability parameters of some natural and manmade textile fibres: heat release capacity and maximum heat release rate, and Table 2.1 shows an overall comparison between natural and synthetic fibres based on some of the basic features.

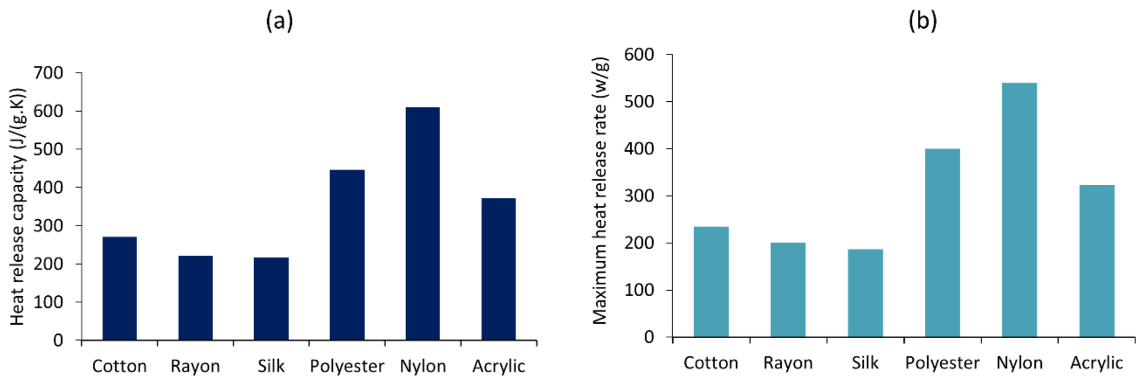

Figure 2.1: (a) Heat release capacity and (b) maximum heat release rate of some common textile fibres during combustion [53].

Table 2.1: Comparison between natural and synthetic fibres.

Feature	Natural fibre	Synthetic fibre
Breathability	Breathable	Not breathable
Texture and feel	Comfortable	Uncomfortable
Skin contact	Hypoallergenic	Can cause skin irritation
Chances for odour	Less	More
Biodegradability	Biodegradable	Very slow in biodegradation
Flammability	Burns slowly, some self extinguish	Burns fast
Durability	Less durable	More durable
Wrinkle property	Wrinkles easily	Wrinkle free
Colour properties	Colour fades over time	Retains colour well

To get advantages from both natural and synthetic fibres and mitigate each other's limitations, a blend of cotton and polyester is a widely chosen option for apparel. A mix of cotton/polyester thus provides all in one, i.e., comfort and durability with easy care features. However, blending cotton/polyester makes the end-of-life phase complicated. If they are thrown into the landfills after use, the polyester part hinders the biodegradation process and pollutes the environment. Recycling cotton/polyester blend is also critical due to the individual chemical requirement of polyester and cotton separation.

Not only the end-of-life, but the production of any garments (including cotton and polyester) requires comprehensive preparatory stages including the fibre preparation (either cultivation or synthesis), manufacturing of yarns, fabrics, and their colouration. All these stages have substantial hazard concerns that are critical to address. Even during the usage phase of these textiles, significant pollution continues and requires attention. The following sections will focus on each of these phases and will identify the most concerning issues. As intended at the end of the previous chapter, an eye will also be kept on finding any identifiable trend coming from the difference in the fabric structures, i.e., woven, knitted and nonwoven.

2.2. Hazards in the fibre production phase

There are many environmental issues during the fibre production stages for both natural and manmade fibres. They are related to the use of hazardous chemicals and processes, the use of fossil fuels and the consumption and pollution of important resources, i.e., water. These are discussed in the following subsections.

2.2.1. Natural fibres production

Natural fibres are environmentally friendly and sustainable, however, some elements in their production stages have negative effects on the environment. Among the natural fibres, cotton is the highest produced and consumed all over the world, representing 74 % of the natural fibre segment [1]. A major drawback of conventional cotton cultivation is its massive water consumption, significantly higher than any fibre cultivation. Figure 2.2a shows the reported consumption of water for cotton cultivation in some key cotton-producing countries. China, the United States, India, and Brazil are the top 4 cotton producing countries, producing around 75 % of global cotton [54]. All of these countries require at least 2,000 m^3 of water per tonne of cotton [55], which is 2,000 L water per kg. However, this should be noted that this is a combination of both irrigation water and rainwater. The irrigation water requirement largely varies depending on the geographical distribution of the country as rainfall can have a significant input [56]. Figure 2.2b shows the requirement of only the irrigation water that needs to be supplied for cotton growth in those countries. Some of the countries, such as Pakistan (3,860 m^3), Uzbekistan (4,377 m^3) and Turkey (2,812 m^3) require more water for irrigation than the others. Australia requires a moderate amount of irrigation water (1,408 m^3), which is higher than India (2,150 m^3) but lower than China (760 m^3) due to the differences in weather conditions.

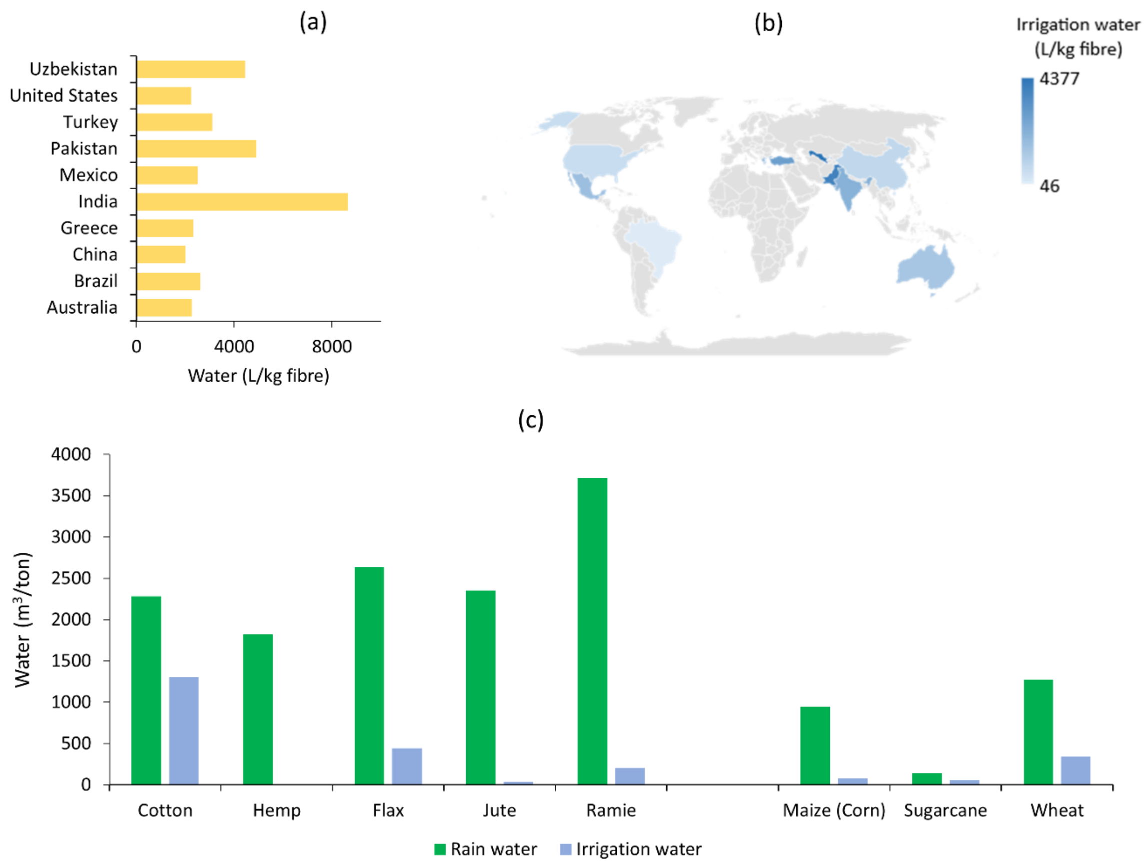

Figure 2.2: Consumption of water during cotton production across different countries, (a) total water consumption including rainfall, (b) the supplied irrigation water only [55], and (c) a global average of rainwater and irrigation water requirements of some key textile producing crops [57].

Regardless of the water source, research shows that a major portion of this consumed water gets polluted from the use of fertilisers and pesticides during the cultivation process [58]. The consumed water in cotton cultivation reportedly produces carcinogens, known for aquatic eutrophication, and acidification, and impacts human health and ecosystem quality [59].

Not only the hazards associated with water consumption and pollution, the production of natural fibres is also known for its contribution towards greenhouse gas emissions, triggering the global warming potential. Figure 2.3a shows the carbon footprint, i.e., CO_2 emission during the production of a few key natural fibres. It is perceived that cotton stands as the second highest (after silk) in the chart among the natural fibres. Given cotton is the major fraction of natural fibres, Figure 2.3b summarises the contribution of different components in cotton farming that are responsible for greenhouse gases. This is found to be affected by varied factors, including the use of fertilisers, chemicals including pesticides, consumption of fuel and electricity and convey water for irrigation. Fertilisers play a major role in this context (58 %) particularly the N-fertiliser accounts for 37 % of greenhouse gas emissions [60].

Data in Figure 2.2c further shows that regardless of the total water requirement (part of which comes from the rain) the global average irrigation water requirement for cotton production is much higher than all other natural fibres, such as hemp, flax, jute and ramie. Besides, both rain and irrigation water needs are significantly low in some common crops (such as corn, wheat, and sugarcane) [57], which are trending sources of regenerating cellulosic fibres. Contrasting cotton, both hemp and flax can grow in a variety of conditions with minimal pesticide and herbicide use. In fact, before the 19th century, plant-based textiles were primarily produced using locally sourced raw materials, mostly hemp and flax. However, processing hemp and flax into usable fibres is more labour-intensive and requires additional pretreatment, e.g., retting [64]. However, the invention of the cotton gin in 1793 revolutionised cotton processing as the machine made it much easier and faster to separate cotton fibres from seeds, significantly reducing labour costs and time. Eventually, hemp and flax lost their significant status to cotton [65]. To this end, other plant-based fibres and natural resources, demand more research attention in textiles to produce fibres more sustainably.

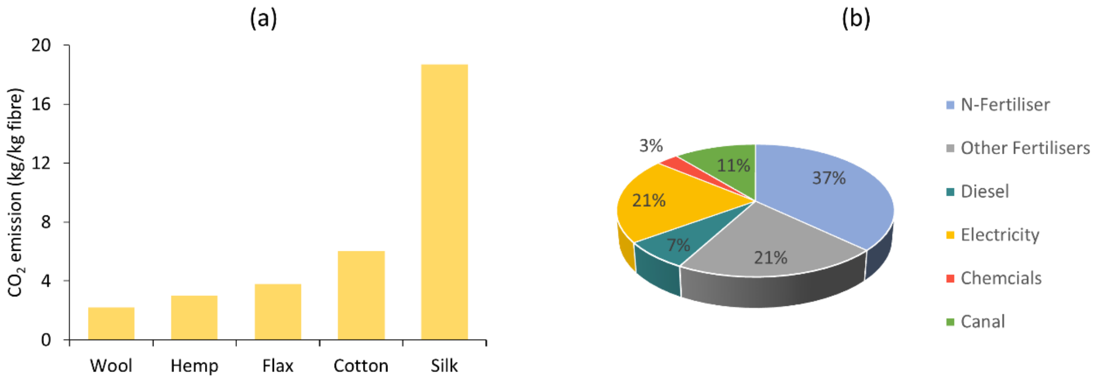

Figure 2.3: (a) Carbon footprint of some key natural fibres during their production stage [58, 66, 67], and (b) a typical distribution of greenhouse gas emission during cotton farming [60].

2.2.2. Manmade fibres production

Manmade fibres are divided into synthetic and regenerated cellulose, which account for 64 % and 6.4 % of global fibre production, respectively. Polyester is the leading synthetic fibre accounting for 84 % of the synthetic fibres, i.e., more than half (54 %) of global fibre production [1]. Non-renewable petroleum resources are consumed to manufacture polyester. It is estimated that the production of polyester requires more than 70 billion barrels of oil annually [68]. During production, it takes more than twice the energy of cotton. Manufacturing of polyester involves the use of unsafe chemicals, including carcinogens, which can seriously affect the environment if released into the air and water. Nylon is the second-highest used synthetic fibre. Though it represents only 5 % of global production, its production process is more energy intensive, even higher than polyester. When nylon is produced, greenhouse gases like nitrous oxide are released into the atmosphere, which has a major impact on global warming [69]. Other synthetic fibres, such as polypropylene and acrylic also cause similar or greater environmental impact. Compared to natural fibres, the production process of synthetic fibres uses a lot less water. However, synthetic fibres often need particular dyes that have a higher environmental impact [68]. Besides, if fossil fuel consumption is to be reduced in the coming years, the production of synthetic fibres will also decrease. This reduction will likely result in a significant shortfall in fibre supply for textiles, thereby creating opportunities for alternative fibre materials to fill the gap. Figure 2.4 shows the energy consumption and carbon footprint of the four main synthetic fibres used in textiles during their production stages.

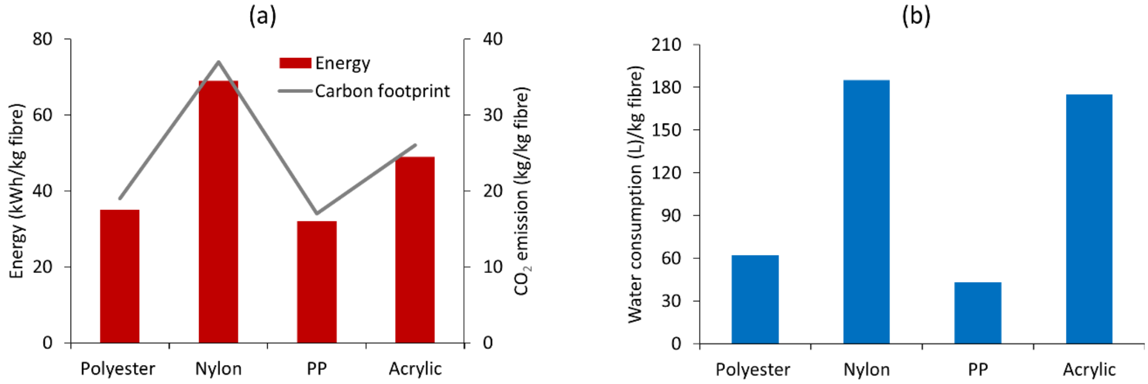

Figure 2.4: (a) Carbon footprint and consumption of energy and (b) water consumption during the production of some key synthetic fibres [58, 66].

Another segment of manmade fibres is regenerated cellulose, which is mostly occupied by viscose rayon. Currently, viscose rayon accounts for 80 % of regenerated fibres (5 % of global fibre production) [1]. The main cellulosic raw material for viscose production is wood pulp. Other resources can also be used for viscose production, such as bamboo. Despite it being one of the few substitutes for cotton, the process used to produce viscose fibres is not eco-friendly. This process requires a large amount of hazardous chemicals, such as sodium hydroxide, carbon disulphide, and sulfuric acid. Exposure to carbon disulphide triggers many health hazards, including cardiovascular, neuropsychological, and reproductive disorders [70]. From many studies, the detrimental effect of this chemical on the health of viscose industry workers has been confirmed. The production of viscose also contributes to atmospheric sulphur and can produce hazardous carbonyl sulphide as well [71]. A byproduct of viscose production is hydrogen sulphide gas which can cause mucosal irritation, pulmonary oedema, olfactory paralysis, abrupt loss of consciousness and so on. In addition, viscose rayon needs 640 L water per kg production (higher than all synthetic fibres) [58] needs 28 kWh energy per kg fibre production and emits 15 kg CO_2 per kg fibre (both slightly lower than that of polyester) [66]. Figure 2.5a shows the emission rates of these two gasses from a viscose staple fibre plant in India and Figure 2.5b shows the same across the world.

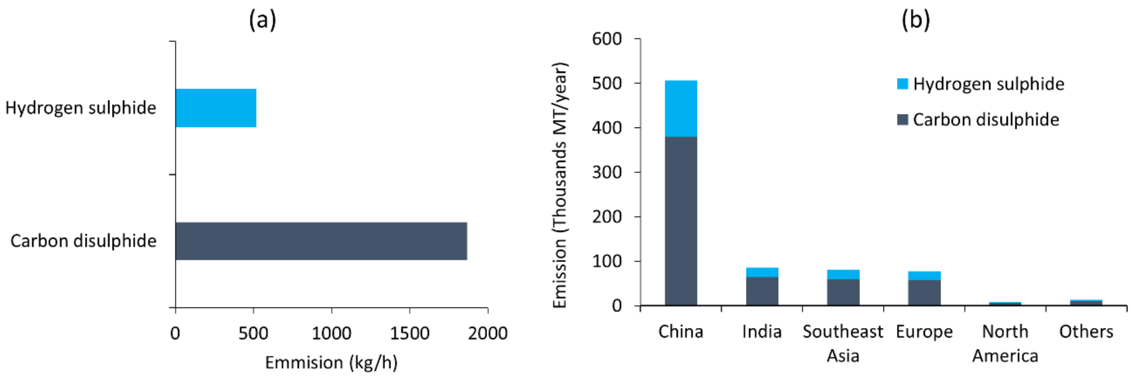

Figure 2.5: (a) Emission of hazardous carbon disulphide and hydrogen sulphide from a viscose production plant in India) and (b) the global scenario [70].

2.3. Hazards in textile manufacturing phase

Textile manufacturing is a vast area with different segments and interconnections. There are multiple ways a garment can be manufactured. Aside from the geometry (woven, knitted or nonwoven), there are also other divisions and the processing route may vary depending on the type of initial fibre (staple or filament) as well as the design of the final product. Figure 2.6 shows a typical flow diagram of textile manufacturing processes with their interconnections.

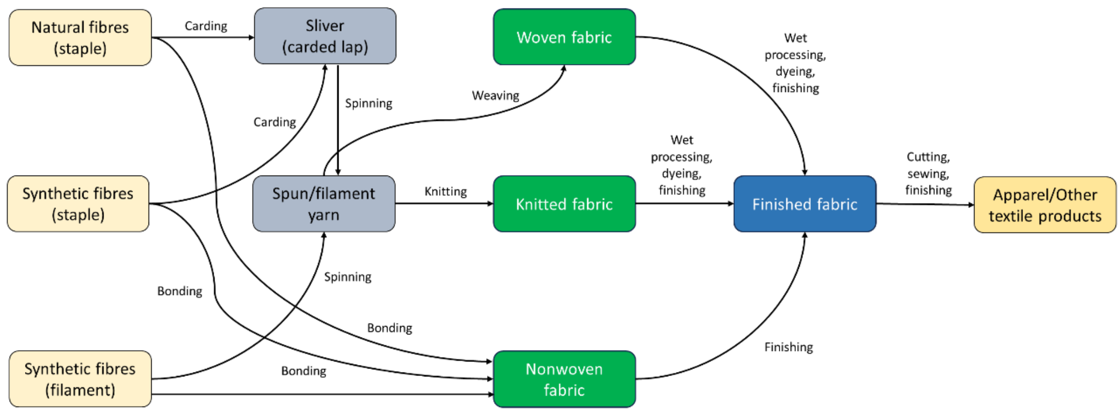

Figure 2.6: Process flow chart from fibre to textiles using different pathways.

2.3.1. Energy uses and carbon footprint

Spinning is the first step to converting the staple fibres into a yarn. The spinning industry consists of a series of preparatory machines (such as a blow room, carding, and drawing machines) to process the fibres into a spinnable form [66]. The energy consumed in a spinning process can largely vary depending on the targeted count or linear density of the yarn. For example, the preparation of thin yarns (finer count) requires more time and energy than a coarser yarn as the production of a finer yarn needs added processes, such as combing before spinning and/or a higher amount of twist [72]. Figure 2.7a shows the variation in energy consumption when yarns of four different counts are produced. The unit 'dtex' (deci-tex) represents the weight (g) of 10,000 metres of yarn. With the increase in fineness of the yarn (i.e., from 300 to 45 dtex), energy consumption has risen from 3.4 to 22.4 kWh/kg which is almost a 560 % increase [73].

Between the weaving and knitting process, the energy consumption is significantly higher in weaving. One of the reasons is the preparatory processes involved in weaving, such as sizing and warping. The processes in weaving can consume 4.9 to 32.9 kWh of energy per kg of fabric, which is significantly higher than that reported for knitting (0.14-0.51 kWh/kg) [73]. If the preparatory processes in weaving are excluded, one of the most modern looms in weaving, i.e., the air jet loom, consumes 2.97 to 4.38 kWh/kg energy [74], which is still 5 times higher than that of knitting. Figure 2.7b shows the typical range of energy consumption in weaving and knitting, compared to nonwoven production. Since nonwoven is a newer technology, data for this segment in energy consumption is still not adequately available. However, a report has hinted that the nonwoven preparation processes, such as opening and blending of fibres, carding, and bonding through needle punching and padding operations consume 5.4 kWh energy combined [74], which is higher than the knitting process. However, that estimation for knitting is only for running the knitting machine but does not include all the preparatory stages (i.e., spinning for preparing yarn). Since both weaving and knitting machines need yarn as their raw materials that is indeed the requirement of a whole industry set up (Spinning industry). Therefore, the total energy consumption for preparing a unit of woven or knitted fabrics is significantly higher and incomparable to that for nonwoven.

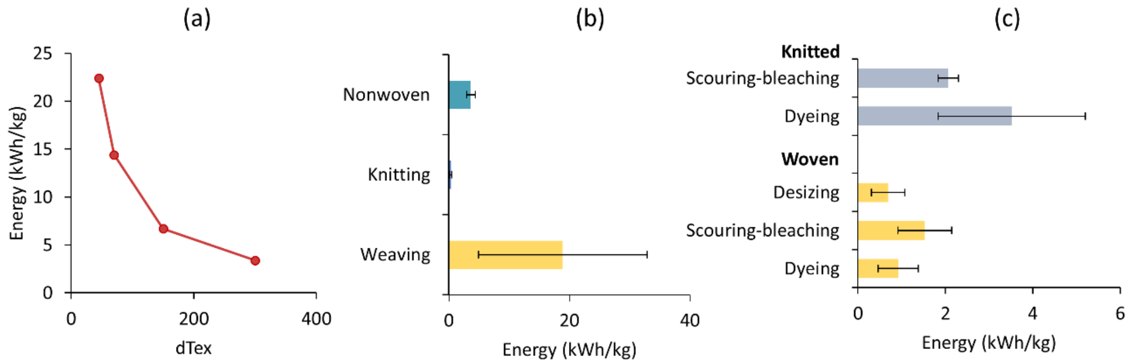

Figure 2.7: (a) Variation of energy consumption in spinning due to yarn thickness, (b) Typical range of energy consumption in weaving, knitting and nonwoven production, and (c) Typical range of energy consumption during dyeing of woven and knitted fabric [73-75].

The next step of the process is the wet processing and finishing. This is a more complex segment in textile manufacturing as pretreatments, dyeing, printing and finishing can happen on the same piece of fabric, depending on the product look anticipated. Woven fabrics are commonly wet-processed in an open-width form in a continuous pad-dray method, while knitted fabrics are typically processed in a rope or batch method in a discontinuous manner. Scouring and bleaching are two pretreatment steps of fabrics (particularly cotton) to remove the impurities and get a white colour, respectively. These two processes can be combined in one step. However, woven fabrics need an additional process called de-sizing, to remove the size chemicals used during weaving to strengthen the yarns to undergo the weaving stress. Figure 2.7c shows a comparison between woven and knit dyeing processes, showing knit dyeing has a higher range of energy consumption. Data specific to nonwoven are still not available to compare with woven or knit dyeing. However, other than de-sizing, scouring, bleaching, and dyeing, there are many other essential machines in wet processing industries which consume a significant amount of energy, such as machines for printing (0.8-2.6 kWh/kg), drying (0.8-2.3 kWh/kg) and heat setting (1.2-2.8 kWh/kg).

Since there are multiple variables present in textile manufacturing (such as type of yarn, fabric, wet processing strategy and making up garments), which can greatly affect the life cycle analysis, a great way to compare the environmental impact is based on the end-product. Figure 2.8 shows a comparison of 1 kg of cotton apparel, knitted t-shirts, and woven pants in terms of their global warming potential, starting from the fibre preparation phase to the disposal [76] and how these values are translated to some common metrics, calculated from the greenhouse gas equivalencies calculator [77]. It is perceived that the woven production has a slightly higher carbon footprint than the knitted production. In this report from Cotton Incorporated, yarn spinning was observed as the main contributor to greenhouse gas emissions due to the extensive energy needed for opening, cleaning, and mixing, followed by carding, drawing, combing (for finer yarns), and spinning operations. Despite such data not being available for nonwoven, given the elimination of the spinning stage (although some similarities remain in processes including opening, cleaning, and carding) nonwoven production is likely to be less energy-intensive compared to woven and knitted productions. However, not to forget, garment manufacturers creating textiles and clothing for many leading global fashion brands are discarding an average of 25 % of production leftovers. In some instances, this waste volume reaches as high as 47 %, significantly more than what brands typically realise [78]. This means more energy is wasted than the current estimation that is done only based on final production, bypassing the offcuts in the manufacturing process.

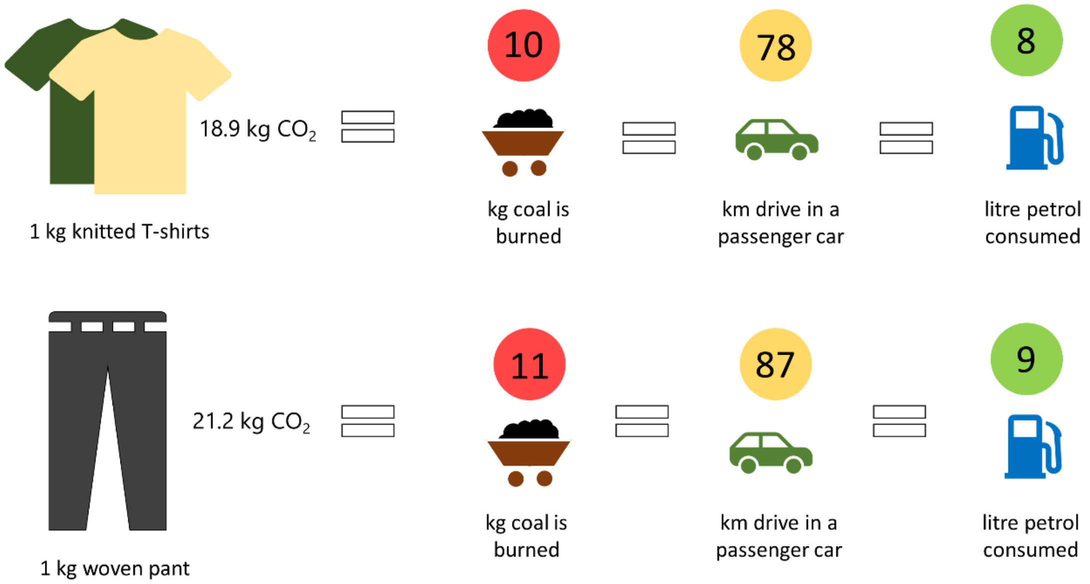

Figure 2.8: Impact of cotton knitted t-shirt and cotton woven pant on greenhouse gas emissions, starting from fibre production to end of life (cradle-to-grave).

2.3.2. Water pollution and chemical hazards

Textile industries, including the dyeing industries are known to be the major contributor towards global water pollution. Figure 2.9a shows their stand among the other industries that generate dye-containing wastewater worldwide, having a 75 % share [79]. Textile wastewater may contain a variety of pollutants, including dyes of complex structures, different salts, surfactants, heavy metals, chlorinated chemicals and auxiliaries [80], coming from different segments of industries. Figure 2.9b shows the contribution of different segments into the wastewater stream. Some of the key segments include the pretreatment stage, dyeing and hot water used in the boiler to gradually lift the process temperature [79]. Around 150 L of water is needed for the wet processing of 1 kg of textiles, which translates into the discharge of 1.5 million L of wastewater for 10 tonnes of fabrics in a day from a moderately sized industry [81].

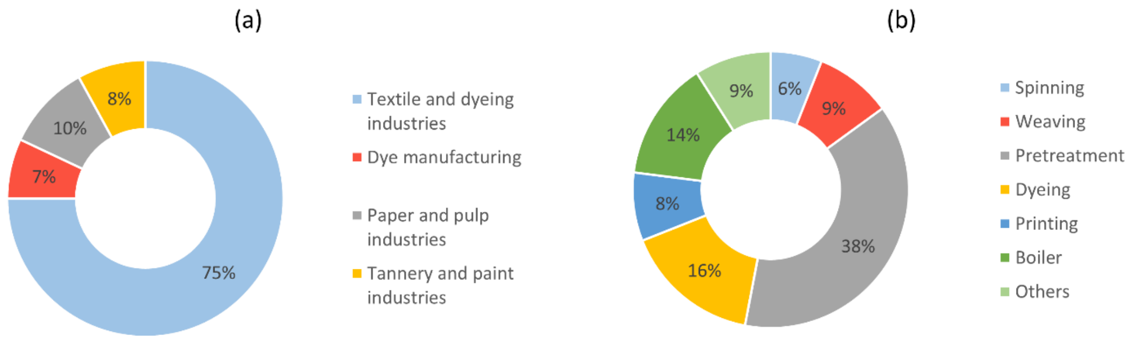

Figure 2.9: (a) Contribution of textile and dyeing industries to global dye-containing wastewater and (b) Use of water in different segments in a composite (Spinning, weaving, and wet processing) textile industry [79].

Not only that textile industries require enormous amounts of raw water but also more than 8000 different chemicals in their different manufacturing processes [82]. As there are so many different substances involved in processing, it has proven challenging to determine the precise concentrations of chemicals lost. In a typical dyeing scenario, 70-95 % of the dyes are attached to the fibres, with the remaining going towards the wastewater. Overall, coloured wastewater makes up a large portion (93 %) of the stream, with other chemical complexes making up the remainder [81]. This wastewater contains persistent dyes such as Disperse Yellow 3, Blue 124, Blue 106, and organic loads that are not biodegradable. Those disperse dyes are mainly used for synthetic textiles, such as polyester, acetate, and nylon fibres, and are the source of several diseases that can enter the human body through ingestion, inhalation, or dermal contact [82]. For example, despite no skin issues brought on by the natural and synthetic fibres used to make clothing, the dyes and chemicals used in their production are typically blamed for clothing dermatitis. Among the dyes, the class known as 'disperse' is the leader in causing several issues, including sensitisation and atopic dermatitis [83]. Among different disperse dyes, 60 % contain the azobenzene groups, also known as azo dyes [84]. Contact with azo dyes can have a variety of toxic effects on reproductive performance, and different health hazards including in occupational scenarios [85]. Longer exposure to some azo dyes was also found to be related to cancer, lung, and sinus diseases. Research has also shown that exposure to azo amine dye dust through inhalation or skin contact can cause allergic skin reactions, lung and urinary tract cancer, damage to red blood cells, and respiratory diseases [82].

Different chemicals used in wet processing have a wide range of impacts towards humans and the environment. For example, nonylphenols used in dyeing and cleaning are hazardous to aquatic life, capable of building up in body tissue and becoming more concentrated through the food chain. Another example could be the tributyltin which is used for antifungal finish in textiles but found to affect the immune and reproductive systems. Perfluorinated chemicals are used in textiles to produce a water-resistant or stain-resistant finish. However, these can biomagnify in the human body and affect the liver and hormones. Chlorobenzenes are used in dye manufacturing and chemical agents which impact the thyroid, liver, and nervous system [83].

In addition, the traces of heavy metals present in textile wastewater can cause several health problems. Since complex dyes and metal-containing chemicals are used in textile processes, heavy metals come out almost from all stages of wet processing, i.e., pretreatment (scouring, bleaching or other chemical treatment), dyeing, printing, and different finishing processes. The most prevalent metal ions observed in textile effluents are chromium, cadmium, lead, and zinc. These metals are stable, poisonous, and carcinogenic, and their buildup in living organisms can have a serious negative impact on health [79].

Some processes other than textile wet processing also use chemicals or wet treatment and produce hazards. For example, different chemicals used in sizing can be mutagenic, carcinogenic and able to impact the central nervous system [79]. Unlike woven and knitted structures, nonwoven often need the use of binders for maintaining stability, if not mechanically or thermally bound. For example, one of the chemical bonding techniques uses hydrogen chloride gas [86], and exposure to this chemical can cause health hazards [87]. Further, a common nonwoven binder is an acrylic resin, which can cause health problems like allergic reactions [88].

2.3.3. Health cost

Manufacturing of textiles poses significant health risks, potentially leading to substantial costs in healthcare. While it is challenging to quantify these costs precisely without specific data, we can outline the potential impacts and associated costs based on some existing research findings. For example, workers in textile manufacturing are exposed to dust, chemicals, and fibres, leading to respiratory problems such as chronic bronchitis, asthma, and byssinosis (a lung disease caused by cotton dust) [89-91]. Treatment for such chronic respiratory conditions can be expensive, involving hospital visits, medications, and long-term care. Managing such chronic conditions can cost thousands of dollars annually per patient.

The use of dyes, solvents, and other chemicals in textile production can lead to skin diseases, allergic reactions, and even cancer [92]. Persistent exposure to toxic chemicals can have long-term health consequences. Cancer treatment is particularly costly, with treatments such as chemotherapy, surgery, and radiation therapy running into tens of thousands of dollars per patient. Chronic skin conditions also require ongoing treatment and medications.

While specific figures are hard to pinpoint without detailed studies, the potential costs could be both direct, such as hospitalisations, treatments, medications, and long-term care as well as indirect, such as loss of income due to illness, disability or reduced economic productivity from a workforce suffering from chronic health conditions. These costs encompass direct medical expenses, loss of productivity, and the burden on social welfare systems.

2.4. Hazards in the consumption phase and disposal

The usage and disposal phase of textiles causes substantial harm to the environment. These include the pollution that occurs from home laundering, shedding of microplastics and accumulation of non-degradable textiles in the environment. The following subsections discuss these issues.

2.4.1. Pollution of water by home laundering

A significant amount of water is polluted during the use of textiles through the regular laundering processes. As shown in Figure 2.10, for cotton woven textile (a pair of jeans), the water consumption for washing during its use phase (2,529 L/kg) is estimated higher than that required in its production phase (1,609 L/kg) [93, 94]. The water use for polyester washing is significantly higher than these numbers (16,667 L/kg) as polyester requires more washing during its use phase [95]. This is because polyester holds more body odour than natural fibres and undergoes frequent washing between the wears. Research suggests that some human body components (i.e., sebum) are particularly challenging to eliminate even through washing, especially from hydrophobic materials like polyester. Those fatty substances persist on the fabric, providing a potential substrate for microbial growth and odour development.

The washing habit varies across countries as higher (1,049 L in the United States) and lower (679 L in China) amounts of water consumption are also recorded per pair of jeans. This is because of the frequency of wear between washes, which also differs in countries, such as 2.3 and 3.9 times wear between each wash of jeans in the United States and China, respectively. The primary cause of the effects of domestic laundering is the phosphorous element found in detergents which pollutes the water [96].

Water eutrophication is a measure of the depletion of oxygen due to the accumulation of nitrogen and phosphorus in fresh or marine water [97]. Study shows that eutrophication from the usage phase of denim is lower than that occurs in other stages (16 % of its total life), though is still an amount equivalent to the phosphorus that could be found in 272 tomatoes [93]. A separate study also suggested that the proportion of eutrophication during the consumption phase could be as high as 42 % of its total life, analysed based on a cotton t-shirt after 45 washing cycles [98]. Since polyester needs more washing during its life, this is more likely that it causes more water eutrophication than cotton.

Not only the pollution of water but also a higher carbon footprint is connected to the number of washes a garment undergoes during its lifetime, due to the consumption of energy during the laundering. The report suggests the carbon dioxide emission from jeans in the usage phase (36.8 kg CO_2-e/kg fabric) is not far behind when compared to that from its manufacturing stages (50.3 kg CO_2-e/kg fabric) [93], but reported significantly higher for polyester garment during consumption phase (458.7 kg CO_2-e/kg fabric) [95].

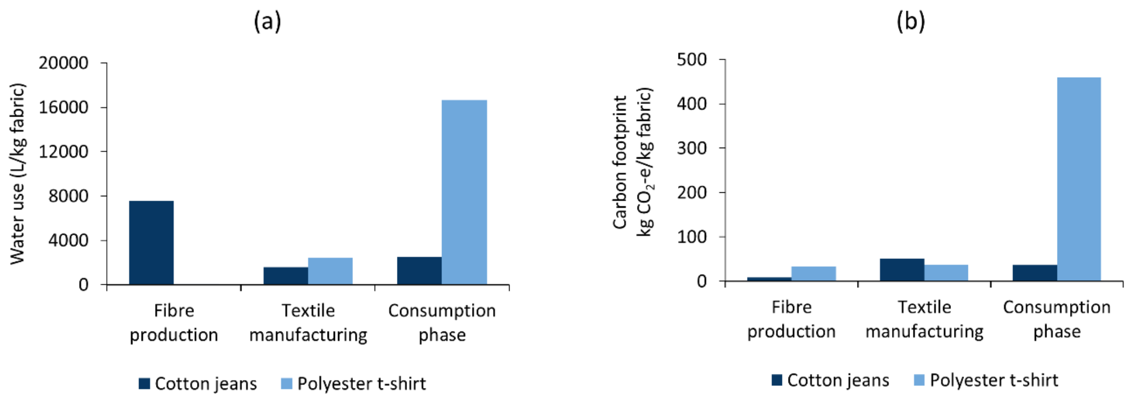

Figure 2.10: Impact of cotton and polyester garments throughout their life starting from cultivation/production to manufacturing, and their consumption, (a) water consumption and pollution, and (b) carbon footprint. Data were converted to per kg unit as per the information provided, i.e., denim 340 g and polyester t-shirt 150 g) [93-95].

2.4.2. Microplastic pollution

One of the newly recognised pollutants in the world is microplastic. Although these particles have been reported to come from a variety of sources, textiles and clothing are known to be major sources of these but in fibre form when they are laundered in the household during regular wear. These are also classified as fibrous nanoplastics (3 to 3000 nm), fibrous microplastics (3 to 3000 µm), and fibrous mesoplastics (3 to 15 mm), depending on their length range [99]. Since synthetic fibres are more produced and used, and also need more washing, they are the main source of fibrous microplastics in textiles. The polyester fibres from textiles are chemically the same as the plastics used in PET bottles for commercial beverages, only the shape is different. Shedded polyester fibres from textiles are already micro-sized that are more susceptible to being ingested by marine life and potentially entering into the food chain, posing environmental and health concerns.

Many influential factors dominate the shedding of fibres from a textile. These include the types of fibres (staple or filament, synthetic or blend), yarn properties (such as twist and linear density), fabric geometry (such as woven, knitted or nonwoven, density, and alignment of yarns in a fabric), finishing process and sewing characteristics [100]. The parameters of washing the textiles (such as temperature, time, detergent and speed of rotation) also affect the shedding [100]. Figure 2.11 shows results from different studies showing the differences in microplastic shedding based on the fabric structure and fibre combinations and washing machine. Studies have shown that knitted fabrics are more prone to microplastic release compared to woven fabric as woven fabric has a tighter and denser structure. When yarns are made from filaments rather than staple fibres, their resistance to shedding is better. However, a blended fabric such as cotton/polyester will release more shedding compared to a pure polyester fabric. A study with a 50/50 polyester/cotton knitted fabric showed a 1054 mg microfibre release per kg fabric, though, for the pure polyester knitted fabric, it was near 20 % [101]. In both woven and knitted structures, the release of plastics (polyester) was found less or near 300 mg per kg fabric, though in cases of nonwoven, this was reported 2000 mg microplastics per kg fabric [102]. This indicates nonwoven fabrics are more prone to shedding. The shedding can also vary based on the household machine types. For example, top-load washing machines are responsible for more shedding compared to front-load machines as there are more chances of abrasion on fabrics in a top-load machine due to a central agitator [103].

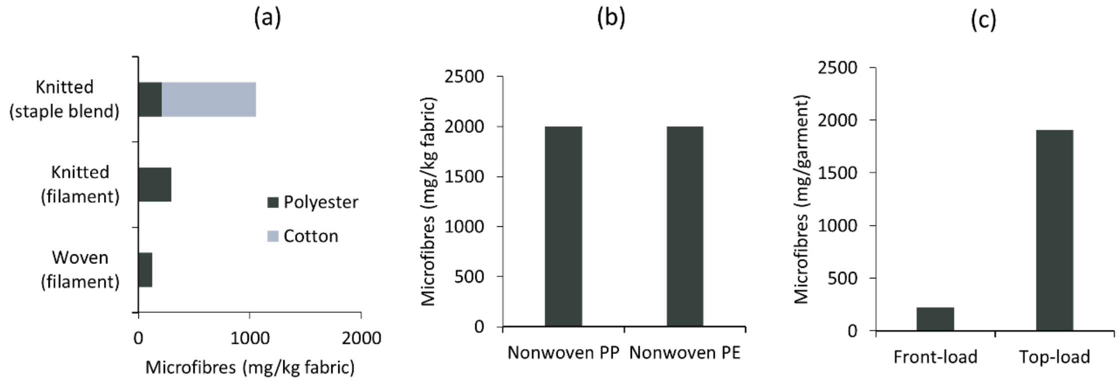

Figure 2.11: Variation in microfibre shedding in (a) woven and knitted structure (b) nonwovens and (c) due to washing machine type [101-103].

Not only in the use phase, but the shedding of textile microplastics also occurs in every stage of processing during the production phase [104]. Given the results from only the home laundering process, the number of fibres shed in the textile production stages should be extremely large, considering the wet treatment processes involved and the extensive washing cycles between the processes. This is also confirmed by the presence of microplastics in the wastewater wet processing industries [104].

Microplastics that are released into the environment from synthetic textiles are ingested by humans through food and water. Since microplastics are now everywhere including soil, water and air, we are drawing in them from the air, eating from our foods, and drinking with our coffee. A recent study reported that we take approximately 16.2 bits of microplastics per hour, which is a credit card's worth of microplastic each week in our body [105]. The long-term health effects of microplastic ingestion are still being studied, but potential impacts include increased healthcare costs for managing chronic diseases, hormone-related disorders, and cancers [106].

2.4.3. Biodegradation profiles of textile fibres

The biodegradation timeframe of textile fibres widely varies depending on their chemical components. Plant-based natural fibres are cellulosic (such as cotton and flax) and are more prone to biodegradation compared to animal-based fibres (such as wool and silk) [107]. This is similar to manmade fibres made from plant sources, i.e., regenerated cellulose or rayon fibres, which also have a reasonably quick degradation rate [108]. Figure 2.12 shows the average timeframe for degradation of these fibres naturally compared to the timeframe of some synthetic fibres. Though there are variations observed across different reports, the average value shows that wool and silk fibres have a slower degradation behaviour compared to cellulosic fibres. This is because of the water-repelling behaviour on the surface of these fibres which slightly delays their biodegradation operation [109]. A maximum of 48 months of degradation time was reported for silk [110] while 60 months for wool [111], though as early as 4 months was also reported for wool degradation [107]. However, when the natural fibres are blended with synthetic Fibres this time will be further prolonged. For example, even though a 100 % cotton shirt can be degraded in 6 months, a pair of jeans made from mostly cotton and minor elastane fibres can take more than a year to degrade (though the elastane part will not be degraded) [110].

The synthetic fibres' degradation rate is counted in years rather than months, due to their strong non-biodegradable nature. Worth noting that time frames are only predicted by different reports, not with actual evidence of their complete biodegradation. Most common textile synthetic fibres like polyester can take 200 years to degrade, while nylon can take 30 to 40 years [110, 111]. The biodegradation of other synthetic fibres, such as polyethylene (PE) and polypropylene (PP) (used in nonwoven such as in diapers and wipes) can take 600 years [102, 112]. Polyvinyl chloride (PVC) is also getting popular with textile designers due to its ability to be engineered as synthetic leather, though is assumed to take 150 years to degrade [112]. A major portion of synthetic fibres is currently used for the rapidly growing nonwoven segment, which is a huge concern from the environmental perspective as these fibres have a very slow rate for biodegradation.

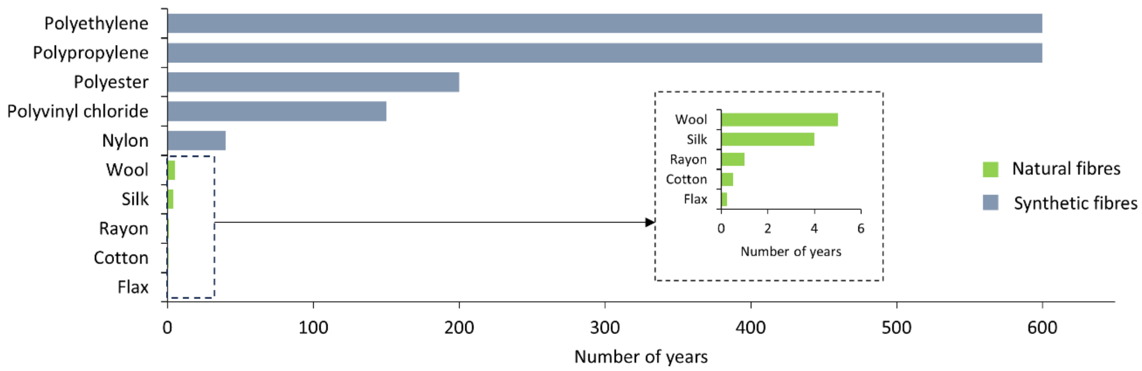

Figure 2.12: Biodegradation timeframe of different natural, regenerated and synthetic fibres.

2.4.4. Impact of fast fashion

Fast fashion is a business model in the fashion industry characterised by the rapid production and distribution of high volumes of clothing that replicate current fashion trends at low prices. It is marked by frequent releases of new collections, typically made from inexpensive materials (mostly synthetic materials). The low prices and constant influx of new styles encourage consumers to purchase clothing more frequently. This has led to a culture of continuous buying, where consumers regularly update their wardrobes to keep up with the latest trends. The affordability and availability of fast fashion items promote impulse buying. Consumers are more likely to make unplanned purchases because the financial commitment is low.

Figure 2.13 shows the impact of fast fashion on consumers across the world. There has been a gradual increase in textile production per person over the years, and Australia is currently the top buyer of new clothing, averaging 27 kg per person per year which is two-fold the global average (13 kg) [113]. This is estimated at 56 items per person per year, though the value per item is much lower than in many countries [114]. The data indicated that the majority of the clothing surge in Australia is due to fast fashion, with over 200,000 items of clothing being discarded in landfills annually.

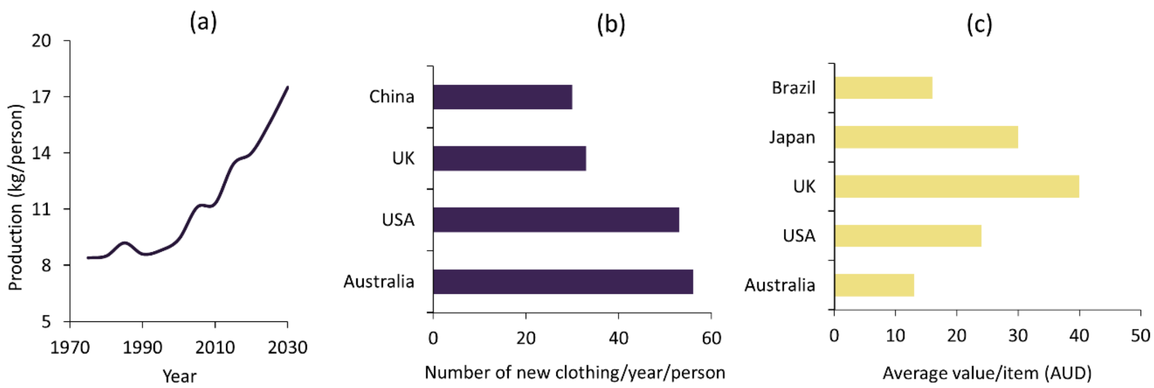

Figure 2.13: (a) Increase in fibre production per person over the years, (b) Top countries purchasing the highest amount of cloths, (c) Average value per item of purchased cloths.

In the fast fashion trend, consumers are conditioned to expect and seek out new styles frequently, leading to a shortened lifecycle for individual garments. The low cost of fast fashion items often leads to a perception that clothing is disposable. Consumers are less likely to view their clothing as long-term investments and more likely to dispose of items after a few wears. This disposable mindset contributes to higher levels of textile waste, as consumers discard clothing more frequently, often after minimal use. However, these 'cheap' textiles are mostly made of non-biodegradable materials, that are increasingly polluting the environment and ecosystem. Transitioning to more sustainable practices in the fashion industry, consumer perceptions and awareness, and culture of consumption is crucial for minimising environmental harm and promoting long-term economic and social well-being.

2.5. Status of current remediation

Given the massive hazard concerns discussed in every stage of textile processing, some alternative ways to alleviate the hazards have been initiated and currently are in practice. The following section will discuss some of these attempts and their current standing.

2.5.1. Fibre production phase

Over the years, a few sustainable ways of fibre production have been developed. Organic cotton is one such way of avoiding the synthetic fertilisers or pesticides used in conventional cotton cultivation. Organic cotton is known for its lower CO_2 emission (2.5 kg/kg fibre) compared to conventional cotton (6 kg/kg fibre) and is not likely to release pollutants into water as the cultivation of conventional cotton does [58]. However, organic cotton has drawbacks, such as lower yield, i.e., more land is required to match the same volume of cotton that is conventionally produced [115] and its market price is also high, reflected by only 1.4 % current share in global cotton production [1]. Another example of human effort for sustainable fibre manufacturing is the invention of the lyocell process to produce rayon (commercially known as Tencel), which can be an alternative to hazardous viscose rayon production. The lyocell process is a direct dissolution process and does not involve harmful chemicals. The solvent used can also be recycled (99 %), which lowers the amount of effluent produced [116]. However, despite the chemical hazards being avoided, its production cost is higher than viscose rayon as it needs more energy to process, resulting in a higher global warming potential than viscose rayon production [117]. Therefore, it is no wonder that it currently represents less than 5 % of global regenerated cellulose production [1]. Another side of sustainable fibre development is the manufacturing of bio-polyester, e.g., synthesising polyester from natural resources (such as fats, and oils), rather than fossil fuels [118, 119]. They are currently more experimented in packaging and other fields and now represent only 0.02% of global polyester production [1]. But they are not cheap like conventional polyester and are not biodegradable.

2.5.2. Manufacturing phase

The manufacturing processes of textiles need robust arrangements and types of machinery. There are requirements for significant energy during the processes which drive the carbon footprint. Energy from sources like steam, diesel oil, and electricity is discovered to make up the great majority (90 % for each process). Among them, steam-related emissions account for a significant portion of nearly every process. This is due to the enormous need for humidification and heating in different cycles of processing and tonnes of fossil fuels are consumed to produce steam, increasing the global warming potential [120]. Though there are alternative energy-efficient methods available, they are not comprehensively used in textiles. For example, the use of plasma to treat textile surfaces, particularly for pretreatment of both natural or synthetic fibres [121, 122], is a long-proposed context which is proven to reduce the processing time, energy and water consumed. However, it has not yet received enough attention in textile bulk industries due to a high initial setup cost and lack of understanding about how plasma interacts with the surface geometry of textiles [123]. Moreover, the decentralised nature of most operations in developing and underdeveloped nations has hindered the adoption of best practices for sustainable processing and often lacks the resources necessary to establish and maintain the upgraded facilities and procedures [124].

Regarding the wastewater generation in textile processes, there are different purification techniques available categorised in physiochemical (such as adsorption, ion exchange, coagulation), chemical (such as oxidation, ozonation, photocatalysis), and biological (aerobic or anaerobic microbial biomass) treatments. However, due to the complex elements present in the effluent, no single method is appropriate alone and in practical cases, a combination or hybrid of these treatment processes is required that greatly affects the cost of production [125]. Besides, studies [126, 127] reported that the amount of wastewater that the industries discharge frequently fails standard allowable limits. These include a high copper level, high pH level (up to 10.5), low or even zero dissolved oxygen, high suspended and dissolved solids and so on.

2.5.3. End of life of textiles

Reusing and recycling textiles are crucial strategies for promoting sustainability and reducing the environmental impact of the textile industry. The production of textiles requires significant natural resources, including water, land, and raw materials. Reusing and recycling textiles help conserve these resources by reducing the need for new raw material extraction and limiting the use of dyes, chemicals and energy-intensive processes. Reusing and recycling textiles helps in diverting waste from landfills, reducing methane emissions and other environmental hazards associated with waste decomposition. Table 2 shows some practices for reusing and recycling textiles reported across different regions. In Australia, textile waste cannot be accepted in the municipal solid waste recycling stream; it can only be disposed of in the regular garbage stream, that goes to landfills. Though some countries have a better reuse and recycling policy for textiles, the global scenario is not satisfactory. Currently, 87 % of the textile waste worldwide is disposed of by burning or landfilling. Sadly, 70 % of the clothing's useful life remains when it is disposed of [128], which means fibre properties are degraded only about 30 % when they are thrown away. Therefore, it is imperative to manage the discarded clothing sustainably.

Table 2.2: End-of-life practices with textile wastes in some countries or regions [129, 130].

Region	Practices with textile wastes
United States	35 % reused, 33 % recycled into fibres, 25 % recycled into wipes, 7 % landfilled.
United Kingdom	47 % reused, 45 % recycled to wipes, 8 % landfilled.
Europe	Most of them are burned with energy recovery.
China	18.9 % recycled, 26.55 % used for other purposes, 54.6 % landfilled.
India	25 % recycled or repurposed, 48 % of them reused, 20 % recycled into wipes, 26 % recycled into fibres.
Global	87 % ends up in landfill, 1 % recycled into new textiles.

Currently, the recycling processes mainly involve mechanical processes. Though chemical processes should be more effective in separating fibres (such as from a natural/synthetic blend) for their more effective and tailored reuse, these techniques are still limited due to high cost and inadequate technological progress [129]. A significant portion of textiles are made from blended fibres, which demands further research progress in this area.

Some of the fundamental requirements in this segment include enhanced recycling infrastructure, supportive policy framework and regulatory measures from the government, consumer awareness and education, research and innovation, and collaboration across government, private sector, and researchers to meet a sustainable target.

2.6. Summary

It is perceived that all kinds of textile fibres produce environmental hazards at every stage in their life. While natural fibres have the least impact due to their biodegradability, non-degradable synthetic fibres have a long-term effect for many generations to come. Though nonwoven is a rising technology, it is highly prone to microplastic pollution compared to woven and knitted fabrics. While nonwoven technology is expected to further grow over the next years, this is important to note that it is now more inclined to use synthetic fibres. Therefore, its higher tendency to shed microplastics is a big environmental and health concern that is required to be addressed urgently. Nonwoven preparation from natural fibres should also get more attention. However, increasing the agricultural production (in any form) of natural fibres to replace synthetic fibres would be extremely difficult, especially given the need for resources (such as land and water). Hence, it would be highly logical to re-use or re-manufacture using a high percentage of existing materials rather than virgin materials.

Given the poor rate of current textile recycling worldwide, pressing attention is needed in this area so that the existing resources are not wasted in such a high proportion. Existing technologies are also required to move towards attaining such capability sooner rather than later. Chapter 3 will look at some of the recent technological advancements that can be utilised in the near future to map the directions of textile manufacturing. These technologies are required to be hypothetically capable and feasible for re-using or re-manufacturing the existing textiles.

Chapter 3

Industry 4.0 and the Sustainability Trend

Preamble

This chapter gives insights into the global drive towards sustainability manufacturing and the integration of smart technologies and intelligence which have been getting increasing attention over the past two decades. The discussions summarise how the human lifestyle has been transformed through these significant changes and how it has affected the progress in the textile manufacturing domain, and now where they are directed.

3.1. Current Industrial Revolution

The term "Industrial Revolution" is commonly linked with a specific historical period in the late 18th century as discussed earlier in Chapter 1. However, in recent times, a new concept has been emerging that defines an ongoing Industrial Revolution, labelled as 'Industry 4.0', believing the continuation of three prior Industrial Revolutions (Figure 3.1) [131]. The duration of Industry 1.0, the first Industrial Revolution, is now suggested from the late 18th to the early 19th century when mechanisation first evolved with the invention of steam power. Following that, Industry 2.0 (late 19th to the early 20th century) is thought to be the 'age of electricity' which led to mass production in industries. The latter half of the 20th century is now defined as the 'information age' or Industry 3.0 which is branded by its extensive digitalisation during this period [132]. This is the early phase of information and communication technology in the industrial sector using computers and automation. In this period, the Internet became widely accessible to the public (in the 1990s), leading to a fundamental shift in communication, information spreading, and commerce.

While some thinkers believe Industry 3.0 has ended by 2000, some others think that it is still going strong now (early 21st century), seamlessly transitioning into the new industrial era, Industry 4.0, which integrates information technology, telecommunications, and manufacturing by blending the real world and virtual realms [133]. Figure 1 shows a schematic assumption of the transitions from Industry 1.0 towards Industry 4.0.

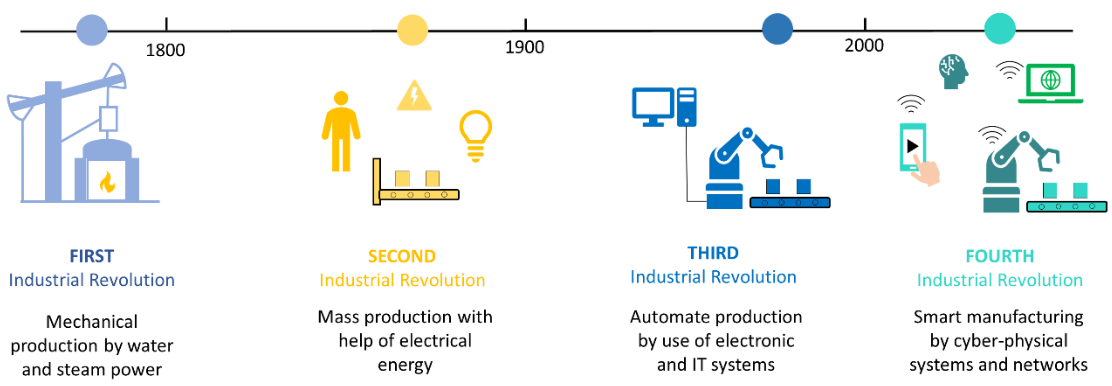

Figure 3.1: A schematic of the Industrial Revolutions from history to the present.

3.1.1. The shift in dynamics

Driven by the wave of so-called Industry 3.0 and 4.0, technology and inventions have been progressing at a significantly higher speed than ever over the past few decades. This accelerated pace of advancement has led to substantial changes in the way we live, work, and communicate. The invention and widespread adoption of the World Wide Web (www) and the Internet in the late 20th century revolutionised communication, information sharing, and business [134]. It has transformed the way people access and exchange information nowadays globally. The introduction and evolution of smartphones have further changed the way people communicate, access information, and perform various tasks. Increased connection and globalisation have facilitated the exchange of goods, services, and ideas on a global scale. Later, innovations in Artificial Intelligence (AI) as well as machine learning technologies have escorted the advancement of intelligent systems and applications. AI is now being integrated into many applications, from virtual assistants to autonomous operations [135].

Current trend promotes the concept of smart manufacturing, where the Internet of Things (IoT), automation systems and data analytics are applied to create intelligent and interconnected production environments. Figure 3.2 shows some key technologies that are currently triggering the rise of Industry 4.0.

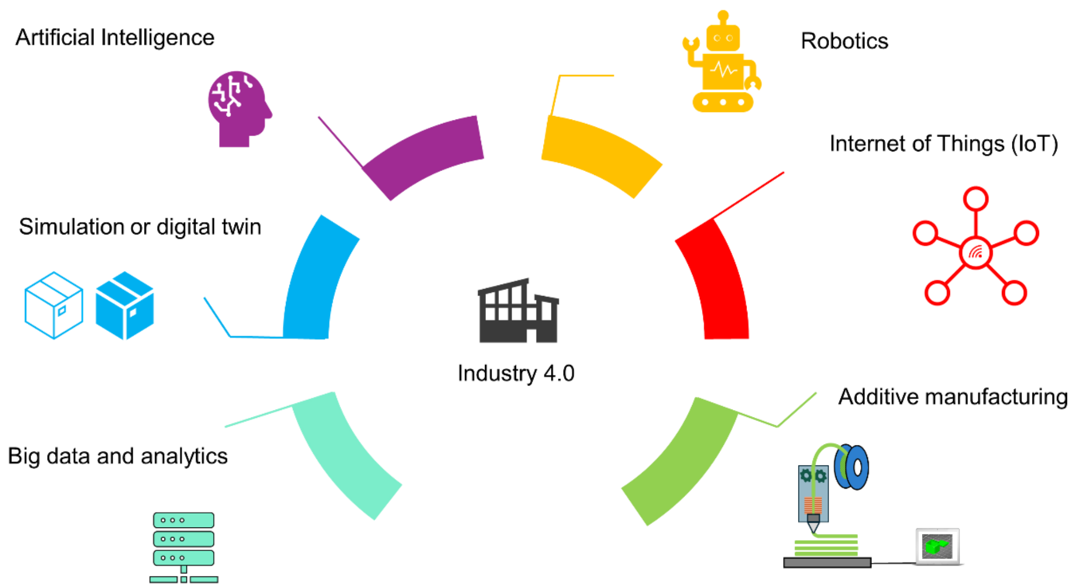

Figure 3.2: Some key technologies that are facilitating the advance of Industry 4.0.

In general, IoT networks produce vast volumes of data that are gathered, combined, and disseminated to achieve effective industrial automation [136]. This leads to more efficient, flexible, and responsive manufacturing processes. Automation is facilitated through the deployment of sensors and connected tools in the industrial setting. These devices collect real-time data, enabling better monitoring, control, and optimisation of various processes and equipment. Automation in manufacturing has seen the increased adoption of robots and cobots (collaborative robots) that work alongside human operators [137]. AI and machine learning play a crucial role in automation by enabling machines to learn from data and make intelligent decisions. This is applied in predictive maintenance, quality control, and optimisation of production processes. Besides, additive manufacturing techniques are nowadays more promoted compared to conventional subtractive manufacturing processes. In a subtractive manufacturing technique, the final material is prepared by cutting its parts from a bigger material (such as a dress from a sheet of fabric) and rest is wasted. But in additive manufacturing, a layer by layer approach is taken (though not in practice for textiles) to use the exact amount of resources that is needed for manufacturing, without producing any residue [109]. The manufacturing process is further progressing through the use of simulation or digital twin, which is a virtual imitation of an actual machine, item, system, or process that can be derived from data from IoT sensors [138].

3.1.2. The power of information

Today people are more informed, connected, and conscious of their choices which has greatly affected our daily lives. People now have access to a wealth of product knowledge, reviews, and alternatives. This liberation has led to increased expectations for personalised experiences, including customisable products. Advances in technology, such as Three-dimensional or 3D printing (additive manufacturing), customisation software, and online configurators, have made it more feasible and cost-effective for businesses to offer customisable options. This has further prompted the demand for personalised products [139]. Many online retailers now offer tools that allow customers to personalise items even before their purchase. The next generation of 3D printing will probably be able to print objects with multiple materials simultaneously with enhanced functionality and complexity. This is likely to be integrated with other technologies that will optimise printing processes, material selection, and error detection. Smart 3D printers connected to IoT will enable real-time monitoring and remote management, providing users the best possible flexibility to choose or purchase an item.

Not only about purchasing a product, but people are also getting information and are now more concerned about how the product is being produced including any background environmental issues or health concerns. The internet along with social media plays a crucial role in spreading awareness about environmental issues and sustainability practices [140]. Since the information is easily accessible it allows individuals and businesses to educate themselves about sustainable living, ethical consumption, and environmentally friendly practices.

Therefore, the current Industrial Revolution has a strong link with the rising awareness of 'Sustainability' worldwide, which is perceived to be also rising in the last two decades.

3.2. Global sustainability awareness

The meaning of sustainability is the capacity to sustain a process consistently over time. A true sustainability practice prevents the phasing out of natural or physical resources, ensuring their continuing availability for the long term. There are three key pillars of sustainability (Figure 3.3) which are known as (1) Environmental conservation, (2) Social responsibility and (3) Economic viability [141]. In recent decades, there has been a notable surge in the global awareness of sustainability among consumers, businesses, and governments. Over the last 20 years, a substantial rise in global awareness and discussions has been observed related to sustainability. This has been amplified by the perceived environmental challenges (such as climate change, reduced biodiversity, deforestation, pollution, and health hazards) [142] as well as scientific findings that have uncovered many issues that were unforeseen before. This also has exposed the frightening concerns in the manufacturing and disposal processes of textiles that need immediate attention for a sustainable future.

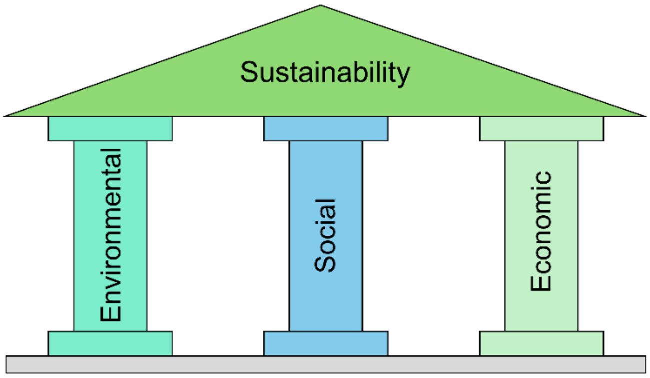

Figure 3.3: The 3 pillars of Sustainability.

A great example of the rise of sustainability concerns across the world is the Numbers counted from the Web of Science, which is a frontier database for worldwide scientific knowledge. In 2004, only around 2,000 reports were found there discussing the term 'Sustainability', while the number has dramatically increased in the past years and reached 60 thousand by 2023 [143]. These data have been contributed from nearly 200 countries worldwide and as seen in Figure 3.4, the top 10 countries are scattered in Asia, Europe, North America, South America and Oceania, meaning a perception has already been developed globally. Scientific research and reports have highlighted the severe consequences of human activities on the planet, leading to increased perceptions about the need for sustainable practices.

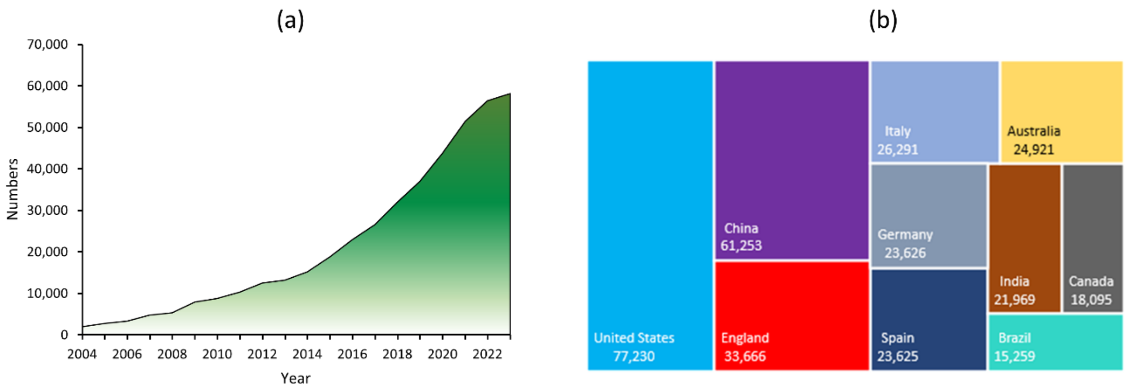

Figure 3.4: (a) Reports published in the Web of Science database related to Sustainability over the past 20 years and (b) top 10 contributing countries in this data.

3.3. Standing of textiles among other sectors

The textile industries are in general coupled with significant environmental impacts, including energy consumption, water pollution, and the extensive use of chemicals. They rank as the second most significant contributor to environmental pollution worldwide, surpassed only by the oil and gas sector [144]. The apparel sector is solely responsible for 10% of worldwide carbon emissions [130], more than that generated by global travel and shipping put together [145]. It is expected that the share of carbon emissions from textile industries will reach 25 % by 2050 [146]. Further, the amount of water used annually by the textile industry to dye clothing is 1.3 trillion gallons which is enough to fill 2 million swimming pools [147]. The majority of this water is contaminated with hazardous chemicals and colours and often enters rivers and streams untreated. It is estimated that the textile dyeing and finishing industries are responsible for 20 % of global water pollution [146]. Around 43 million metric tons of chemicals are used in their manufacturing processes, of which 165 chemicals are classified by the United Nations as hazardous to both human and planetary well-being [148].

Not only in their manufacturing stage but also textiles are largely contributing to severe hazards in their use phase compared to any other industrial products. Around 35 % of the global microplastics discharged into the environment are credited to the washing of synthetic clothing, e.g., polyester. While from other sources, plastics are gradually fragmented over time to become microplastics, the fibrous microplastics shedding from synthetic textiles are already in micro-form. These are therefore far more dangerous, given that 700,000 microplastic fibres can be released from a single polyester laundry load and eventually could enter into the food chain.

Over the years, there have been heightened discussions around these issues caused by textiles, leading to a push for more sustainable and eco-friendly practices.

3.4. Latest ideas in textile manufacturing

Advances in technologies and sustainability concerns combined have played a key role in developing sustainable textile practices in recent years at least to some extent, if not industrially, at least at the laboratories or pilot level. This includes the use of innovative materials, such as the separation of used fibres for efficient reuse, the development of new fibres from bio-based polymers, and the application of technologies and different biological processes for more efficient and environmentally friendly manufacturing processes.

3.4.1. Separation from blended textiles for reuse

A major portion of research on fibre separation from blended textiles is conducted on cotton/polyester blends given it is the most popular combination. The techniques proposed for the fractionation and/or separation of them fall into three broad categories: mechanical, biological, and chemical [149]. No matter which method is employed, the fibres need to undergo pre-treatment to clean them and get rid of the additives and dyes.

Mechanical processing of textile wastes is more economical and less complicated than other methods and hence is a frequently used process. However, it is challenging to effectively and mechanically fractionate the mixed fibres and separate them based on type. The length of the fibres is often shortened by the shredding process, which affects the mechanical properties and quality of the original fibres. These are often combined with other virgin fibres to mitigate this issue [150]. However, worth noting that even though the mechanical processing of blended textile waste has already reached a larger scale, most of the time it still does not address the separation of fibres inside the blend [149].

The biological process of separation involves mainly the use of enzymes that can breakdown one of the components, e.g., cellulase enzyme to break down cellulose, or cutinase and lipase enzymes to break down polyester. The broken-down cellulose part is not practised for re-making textiles (but for ethanol, biogas, glucose syrup and other purposes), and the polyester monomers are transformed into new fibres [151-154]. However, enzymatic processes can take a long duration and result in low yield which is one of its major difficulties.

The chemical process of separation can be done either by depolymerisation or by dissolution of any one of the components and separating the other (Figure 3.5). Cotton, which is chemically pure cellulose, is generally difficult to dissolve and specialised solvents like ionic liquids [155] or N-methylmorpholine N-oxide (NMMO) are utilised [151]. These are typically pricey and can add further costs if not recovered after processing. The dissolved cellulose is possible to retrieve with good integrity and can be used to create regenerated cellulose, like viscose and lyocell. However, depolymerised cotton is the glucose monomer which cannot be re-polymersied to get the fibre again but can be used in other applications [149]. Polyester can also be dissolved and separated from a blend by use of chemicals, such as switchable hydrophilicity solvent [156] or dimethyl sulfoxide [157]. Polyester can also be de-polymerised through different approaches like hydrolysis, alcoholysis, glycolysis and methanolysis and unlike cotton, the derived monomer can be re-polymerised to get the polyester again. However, the recycled polyester must meet acceptable purity standards. If the recycled fibre is not sufficiently pure, re-spinning would be difficult, thus complex procedures need to be followed that increase cost [149]. Though the chemical process is still now found as the most effective pathway, the majority of these widely used chemical treatments use a lot of toxic and harsh chemicals that harm the ecosystem.

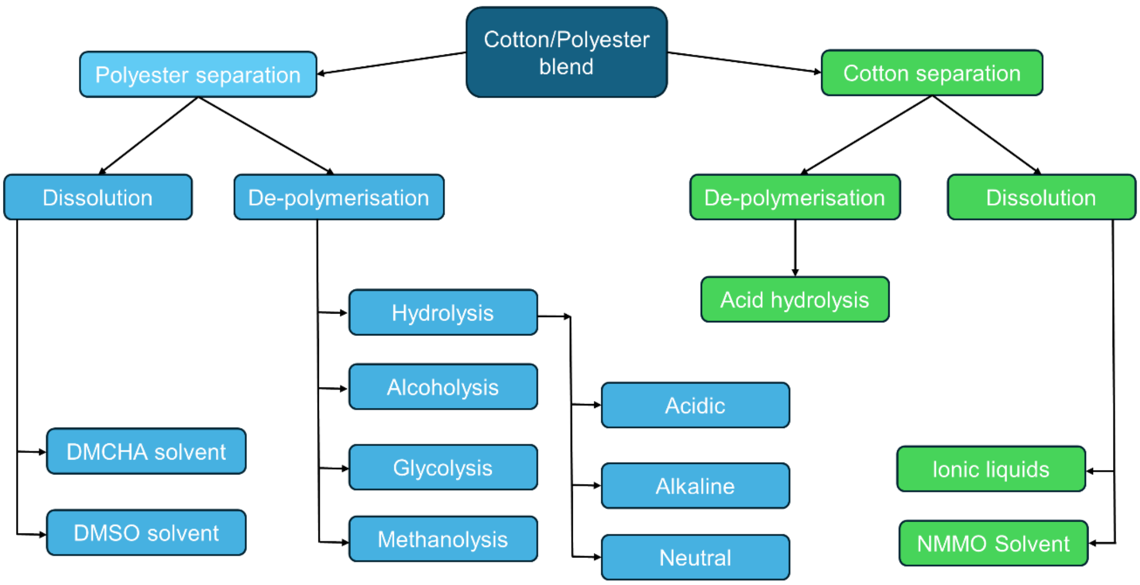

Figure 3.5: Ways to chemically separate cotton and polyester to date.

Efforts have been made in recent years to sort textiles in large continuous flow based on fibre chemistry and colour differences. SIPTex, a Swedish research project, has demonstrated this possibility using near-infrared and visual spectroscopic (NIR/VIS) techniques combined. In this technique, the fabrics are illuminated and then separated by sensors based on how the light is reflected. Compressed air is used to force the fabric into the appropriate container. SIPTex has worked with textile wastes coming from different flows, such as production wastes from industries as well as post-consumer textiles. It was possible to deliver the sorted products in a wide range, such as cotton, wool, polyester, viscose and acrylic. A different project from the Hong Kong Research Institute of Textiles and Apparel (HKRITA) also showed the sorting capability of garments using smart technologies such as AI, image analysis and hyperspectral cameras [158]. The robotic arms are used to pick the garments piece by piece to put on the conveyor belt. The trained AI model has an accuracy of recognising garment type more than 90 %. Then the image analysis tool is used to differentiate between woven, knitted and nonwoven structures. Hyperspectral cameras are used to identify fabric materials' composition and colour.

In a separate project, the separation of wool and polyester fibres was claimed by HKRITA using a dry separation method. The project developed a system to separate those fibres using their triboelectrical properties. The system has a fibre disentangle and a separation chamber connected with copper helix pipes. Cut fibres are fed into the fibre disentangler and airflow is used to draw them through it to the separation chamber. During this process, the wool fibres release electrons in contact with copper, while the polyester fibres gain electrons by the same. That is how they become positively (wool) and negatively (polyester) charged and become separated in the separation chamber where high-potential electrodes are used. In 2022, HKRITA also submitted a patent on this technology and claimed extraction of single fibres from mixed fibres (a blend of protein-based, cellulose-based and synthetic fibres) maintaining at least 20-30 mm of length, so that the opportunity remains for them to be again used in textiles [159].

Meanwhile, HKRITA also has introduced a Garment-to-garment (G2G) concept by establishing retail stores that can receive consumed garments (preferably sweaters and t-shirts) from customers and re-process them into new clothes [160]. This is done through a miniature production line which consists of all the required segments (e.g., carding, spinning, knitting) in a 21-day timeframe. However, garments having spandex fibres, down, leather, rubber print, or special coating are not appropriate for G2G recycling. The recovered fibres are mixed with virgin fibre, such as cotton and lyocell, in a proportion based on the quality of the consumed fibres, to increase the strength of the yarn spun from it.

3.4.2. New resources: Biosynthetic fibres

Biosynthetic fibres are currently thought to be a viable alternative to conventional synthetic fibres. They can be a more environmentally responsible option than their fossil fuel-based equivalents because they can be obtained entirely or in part from natural, renewable sources including corn, sugar beetroot, sugarcane, wheat, and more [1]. Nowadays they are drawing a lot of attention from the fashion and textile industries. These fibres can be classified into 3 major streams as follows: Type 1– Bio-based non-biodegradable polymers, Type 2– Fossil-based biodegradable polymers and Type 3– Bio-based and biodegradable polymers [161] and some of the examples are shown in Figure 3.6.

Type 1 fibres are chemically the same as their fossil-based counterparts (such as PET and PP) but are sourced from natural resources, and hence named Bio-PET, BioPP, etc. These bioplastics pose the same harm as conventional plastics, according to the European Bioplastic Association, and are not biodegradable [162]. Their accumulation in nature is just as hazardous as their fossil-based counterparts.

Type 2 fibres are sourced from fossil fuels, thus contributing to their depletion, but at least they are biodegradable to some extent. Two major examples of this type are polycaprolactone (PCL) and polybutylene adipate-co-terephthalate (PBAT) whose ester linkages can be hydrolysed and degraded by biological enzymes or microorganisms. These fibres have good strength and flexibility and are proposed for textiles from different scientific areas.

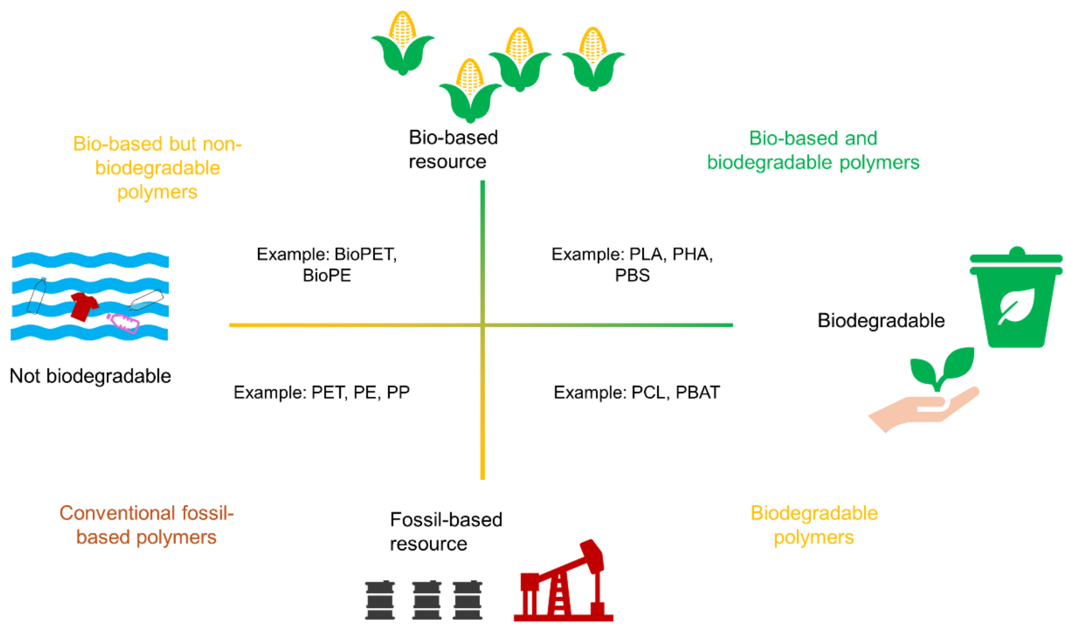

Figure 3.6: Classification of current bio-based polymers [161].

Type 3 is probably a more sustainable group as both their source and end-of-life are non-threatening. However, worth mentioning that the term 'biodegradable' can be misleading sometimes as it includes 'compostable' polymers, and not all compostable polymers can be just be thrown in a landfill and will be degraded. Materials classified as biodegradable are those that microbes can break down into organic biomass, water, carbon dioxide or methane, and inorganic chemicals. However, the materials that may biodegrade in a composting process under controlled circumstances, such as temperature, humidity, and time frame, at a composting facility, and without leaving any noticeable, recognisable, or harmful residue are considered 'compostable'. Hence, many of the biodegradable-claimed polymers essentially need certain conditions to be degraded in the soil, or preferably an industrial compost facility.

Polylactic acid (PLA) is undoubtedly the most studied polymer among the Type 3. It is derived from renewable resources, most commonly corn starch or sugarcane. It belongs to the polyester family and is a type of polymer made by combining lactic acid molecules through a process called polymerisation. The harvested crops undergo processing to extract the starch. The extracted starch is then converted into simple sugars through enzymatic or acid hydrolysis. The sugars obtained from the starch are then fermented by bacteria in a controlled environment. The lactic acid produced in the fermentation step is then purified and undergoes a polymerisation process. PLA polymer is then processed into various forms such as pellets, fibres, or films through methods like extrusion, injection moulding, or spinning, depending on the desired application. For textiles, PLA fibres can be spun and processed into yarns, fabrics, and other products. PLA fibres can be engineered to have a soft and comfortable feel, making them suitable for various apparel and textile applications. It is also often blended with plant, animal or regenerated cellulose fibres to produce different textile materials [163]. Though PLA textiles are commonly claimed as biodegradable, it is indeed in the compostable category and needs certain conditions (such as a temperature above 50 °C to degrade in soil). Therefore, they will not degrade by themselves in soil but may contribute to microplastic generation.

A member of Type 3 is polybutylene succinate (PBS) which was previously prepared from fossil-based resources but nowadays can be obtained from renewable sources, such as corn, sugarcane and cassava [164]. PBS and its relative copolymer polybutylene succinate-co-adipate (PBSA) are compostable polymers. While PBS can be composted only in an industrial setup, PBSA can be composted in home composting as well as in soil at 25 °C, though not just by landfilling. Besides, studies are limited to the melt spinning process of PBS or PBSA to prove their true feasibility for textile fibres.

Another member of Type 3 is thermoplastic plasticised starch (TPU), which indeed is biodegradable in all conditions and made from starch derived from plant resources such as corn and potatoes. However, TPU is unsuitable for the melt spinning process to produce fibres, due to poor melt strength and processability [165]. Table 3.1 shows the biodegradation behaviour of relevant Type 3 polymers in the environment along with some Type 2 polymers, as per established standards and certification [18].

Table 3.1: Biodegradability of different polymers sourced from natural resources.

Conditions	Temperature	Type 2		Type 3				
		PCL	PBAT	PLA	PBS	PBSA	PHB	TPU
Landfill	No standard	✗	✗	✗	✗	✗	✓	✓
Soil	25 °C	✗	✓	✗	✗	✓	✓	✓
Freshwater	21 °C	✗	✗	✗	✗	✗	✓	✓
Marine water	30 °C	✗	✗	✗	✗	✗	✓	✓
Home composting	28 °C	✓	✓	✗	✗	✓	✓	✓
Anaerobic digestion	37 °C /52 °C	✗	✗	✓	✗	✗	✓	✓
Industrial composting	58 °C	✓	✓	✓	✓	✓	✓	✓

Another bio-based biodegradable polymer that is relevant here is polyhydroxyalkanoate (PHA). There are a few kinds of PHAs, such as PHB (poly(3-hydroxybutyrate)) and PHBV (poly(3-hydroxybutyrate-co-3-hydroxyvalerate)). The technology for PHA production is distinct compared to other bio-based polymers. It is based on a biological process that generates PHA intracellularly using a microbial culture. There is no chemical synthesis involved as all of the polymerisation is carried out by the bacteria. A carbon source, such as sugar, is provided to the bacterial culture to promote biomass growth and raise the concentration of microbial culture. After that, the culture is depleted of vital nutrients (such as oxygen, nitrogen, or phosphorus), which prevents the culture from growing and instead causes the carbon to be stored as PHA inside the cells. The major advantage of PHA over PLA and PBS is its biodegradability in any condition. While both PLA and PHS need specific conditions for biodegradation, PHAs, however, are capable of biodegrading in natural settings, including the ocean. In the presence of oxygen, they will break down into water and carbon dioxide, while in the absence of oxygen, they will break down into methane and prevent the buildup of micro and nanoplastics [166, 167].

However, the realities of continuing a clean culture of PHA-accumulating bacteria and the energy requirements of cooling down the exothermic bioprocesses continue to limit this technology for commercial production. PHA production costs are also 5 to 15 times higher than those of petroleum-derived polymers. The cost of the carbon substrate makes up 45–50% of the total production cost, further to the expenses associated with bacterial growth, extraction, and refinement processes. To produce PHA, researchers are now seeking less-priced raw materials. Among different PHAs, PHB is thought to be more appropriate in textile fibre manufacturing due to its thermoplastic nature [168]. However, the melt-spinning technique to produce fibres is challenged by the brittleness and limited processability range of this polymer. Beyond 160 °C, which is near its melting point (175 °C), PHB becomes unstable and a random chain scission reaction occurs which results in a considerable molecular weight loss [169]. As a result, up to now, it has not been feasible to melt-spin PHB into fibres on a wide scale, and the focus has been on manufacturing on a laboratory scale [170].

3.4.3. Innovative dyeing solutions

Since the dyeing process is the major polluting segment of textiles, there have been many ideas related to innovative and sustainable dyeing of textiles in recent years. For example, COLOURizd has reported a dyeing process of cellulosic and synthetic yarns (named QuantumCOLOUR for yarn) by a patent-pending colour diffusion technique that will dye the yarns with 98 % less water and half energy consumption than common processes, with no harmful chemicals and wastewater discharge. The dyed textiles also meet the industry standards for performance and fastness [171]. There are also carbon dioxide-based waterless dyeing techniques, such as those proposed by DyeCoo, where supercritical carbon dioxide is used to dissolve dyes and penetrate fibres. As per DyeCoo, 98 % of dyes can be absorbed into textiles by this technique, with a minimal loss and the method can be adopted in large-scale production [172].

Recycling and reuse of textile dyes are also proposed where the transformation of dyes from old clothing has become possible into new garments [173]. The process explained by DyeRecycle begins with the extraction of colours from discarded textiles, producing decoloured fibres that may be recycled or reused. The recovered dyes are used to responsibly and sustainably dye fresh fibres in the second step. They use a solvent-based dyeing system (ionic liquids) to design the dyeing process waterless. This process is claimed to eliminate the need for fresh dyes in the dyeing process and facilitate more effective fibre-to-fibre recycling. As per their estimation, every item of clothing coloured using DyeRecycle emits 75 % less carbon dioxide and saves 66 % water and 85 % chemicals.

Concepts have also been highlighted in recent times on using biological processes to produce and colour textiles (Figure 3.7). For example, Colorifix has developed a facility where bacteria grow and replicate the DNA sequence that programs for colour in an organism [174]. The genetic code responsible for producing colour is transferred by Colorifix to a bacterial cell that divides 2-3 times every hour. This cell is kept in a fermentation apparatus where it grows rapidly and generates more pigment in each cell. The bacteria are fed sugar syrup and nitrogen byproducts sourced from the agricultural sector. Not only producing the colour, but Colorifix utilises bacteria immediately on the textiles to colour it, instead of using water and chemicals. In elevated temperatures, the membranes of microorganisms rupture and release the colour that forms a chemical bond with the fibre. The leftover cells of bacteria are then removed by rinsing, revealing brightly coloured clean clothes. Interestingly, unlike enormous amounts of dye transportation, in this way, only 5 grammes of colour-packed bacteria could be supplied to a dyeing industry and after 10 days they would multiply and produce 50 tonnes of dye solution per day [175]. Unlike the traditional plant/animal-based or mineral dyes which are known for limited productivity and reproducibility, dyes sourced from the microbial route can be more adaptable and can replace synthetic dye production.

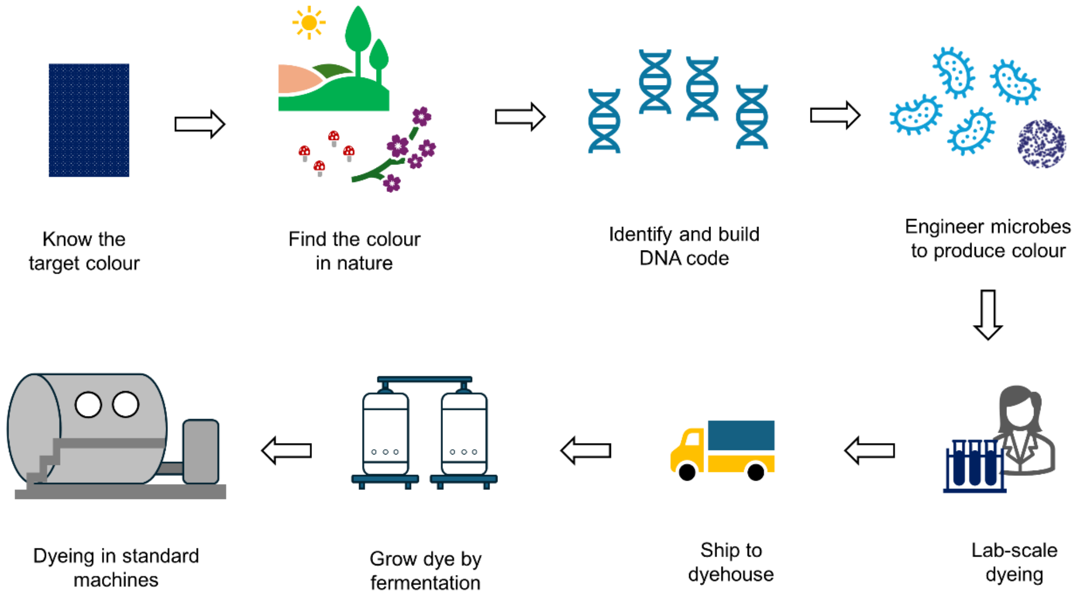

Figure 3.7: Process of making bacterial colourants and dyeing textiles with them.

3.4.4. Use of Internet of Things (IoT)

The term 'Internet of Things' was initiated by Kevin Ashton first in 1999. Though the idea behind IoT was considerably older, it took another 10 years for the word to become widely used [176]. Kevin further defined this in 2009 as giving computers the ability to collect data so they can see, hear, and smell the world for themselves and react accordingly. Sensors and radio-frequency identification (RFID) provide computers with the ability to see, hear, and comprehend without being limited by manually supplied data [177].

There are many recent examples of incorporating IoT in textile machinery for weaving, knitting, nonwoven, and colouration purposes [176]. For example, digital services have been provided by different original equipment manufacturers, such as Vandewiele and ITEMA in weaving to control design, monitor efficiency, and download and upload information into the machines [176]. The employment of a digital environment was also explored in the weaving mill using augmented reality. The capability of workforces was found to be enhanced by such digitisation of manufacturing, skipping repetitive activities by users [178]. In knitting as well, intelligence and cloud-based services are well introduced. For instance, Shima Seiki, a knitting equipment manufacturer, provides an IoT package that offers a three-dimensional design method that generates machine-dependent files for knitting objects manufactured on flatbed machines. It also includes an online cloud service that suggests content to assist with planning and design work, consisting of a 50-year archive of fashion trend data and future projections [179]. Osprey Corporation, an equipment manufacturer in soft-disposable industries (nonwoven), introduced the OspreyCONNECT technology, which offers data trending, predictive maintenance, quick diagnosis, and troubleshooting like other IoT solutions. Osprey also offers an interesting additional service called 'Virtual Mentor' that enables staff members to see what field technicians see and send necessary information or documentation to the technicians directly through a headset [180].

Some other IoT applications in textile manufacturing include automated sewing machines, fabric-defect-detection systems and so on. However, these solutions presently support manual operators and their greatest potential lies in utilising machine learning and AI in future [176]. Figure 3.8 shows the concept of integrating IoT in an industrial setting.

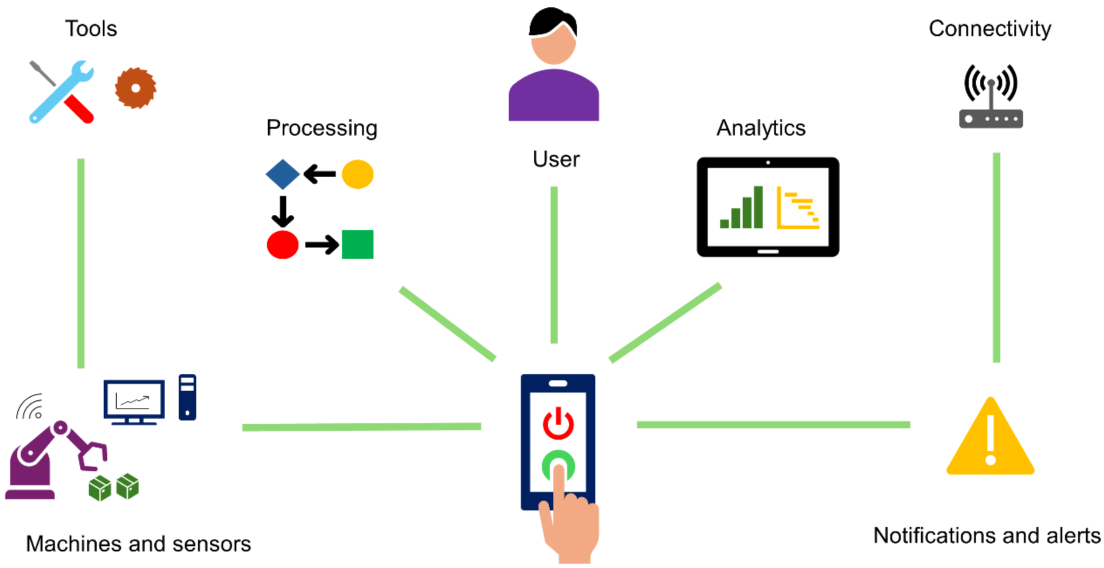

Figure 3.8: Concept of using the Internet of Things in an industrial environment.

3.4.5. Manufacturing of garments

The fundamental mechanism of preparing garments from woven or knitted fabrics has not significantly changed in many centuries, though the in-processes have been continuously upgraded with more advanced machines and technologies, to get faster production. A fundamental change in garment fabrication technique came with the invention of seamless garments in 1995 from knitting, in which technique no cutting or sewing is required (discussed in Chapter 1) [30].

Until now, nonwoven production is more concentrated in technical or industrial textiles, rather than any use as a pure garment. One of the reasons behind it is probably its structural property, which can be summarised as the difference in its 'bending rigidity' compared to woven and knitted fabrics [181]. Bending rigidity controls the wrinkles, formability, buckling, drape, handling, comfort, and stitchability of fabric [182]. Fibres in woven and knitted fabrics move relatively freely, as they have low bending rigidity, whereas nonwoven textiles commonly exhibit greater structural stability and hardness due to their higher bending rigidity. However, to produce fabric for clothing more effectively, businesses and researchers are looking for simplified ways to cut expenses and time without sacrificing quality. Thus nonwovens are getting more interest and there is room to create and design various nonwoven fabrics that might be used in clothing applications. There are studies to customise the process parameters in large-scale nonwoven preparations, such as adjusting web composition, pressure, speed and web mass [183] as well as the inclusion of machine learning [181] to tailor the produced nonwoven to be more flexible and comfortable to wear.

An example of a completely new way of manufacturing garments using nonwoven has been demonstrated by the Fabrican in recent times [184]. The fabric sprayed from a can (Fabrican), is one of the latest technologies about how nonwoven is possible to create [184]. This method was invented by Manel Torres and Paul Luckham and patented in 2003 [185]. Fabrican Ltd was formed in 2003 by

Manel Torres. This is probably also a great demonstration of how nonwoven can be used as a cloth and shows a new way of textile manufacturing that could be adaptable in the fashion segment.

The patent suggests that the spray solution can be worked for both natural and synthetic fibres, however, the fibre length should be low, such as substantially from 0.02 mm to 0.15 mm to avoid blocking the nozzle [185]. Worth noting that such small lengths of fibre are considered non-spinnable through traditional spinning and are known as waste from the textile industries, and also lie between the range of fibrous microplastics [99]. The spray solution consists of binder (such as polyvinyl acetate), solvent (such as acetone or ethyl acetate) and adhesive (such as epoxy resin). The prepared nonwoven can be peeled off from the substrate (or human body) and can be re-dissolved and sprayed again. Fabrican Ltd. Suggests that they have adopted solvent recovery systems in closed-loop industrial processes and are capable of recycling up to 99 % of solvents. In 2020, Fabrican also introduced a robotic arm spray system (Figure 3.9), in conjunction with a programmable logic controller (PLC). It is claimed to create different products with varied properties by either changing the liquid fibre solution, reprogramming, or both. With such automation, the production speed was claimed to be 9 metres of material every second.

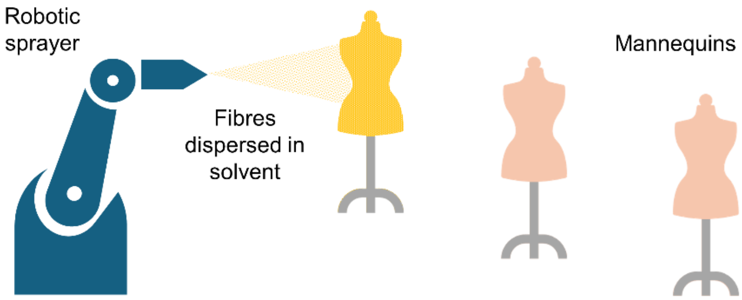

Figure 3.9: The idea of nonwoven clothing preparation by robot sprayer.

3.5. Future direction

Based on the tracks of recent scientific advances, and changes in user behaviours combined with overall sustainability urges, the future of garment manufacturing is likely to be shaped by innovative technologies that enhance efficiency, sustainability, customisation, and automation. A few key concepts and/or technologies that could play a significant role in transforming the garments manufacturing industry in the near future could be identified as follows:

Sustainable manufacturing: The technologies that are focused on sustainability, such as more use of biodegradable fibres either natural or biosynthetic, environmentally friendly dyeing techniques, recycling of fibres and reuse in garments should become more prevalent in garment manufacturing to address the environmental concerns.

Artificial intelligence and digital designs: Advancements in digital design tools and virtual prototyping are likely to streamline the garment design process, reducing the need for physical samples and accelerating time to market. Technologies for accurate 3D body scanning will become more widespread, allowing for personalised garment sizing and fit.

Advanced robotics: Garment manufacturing is likely to increasingly rely on advanced robotics for tasks like fabric preparation and processing. Robots equipped with machine vision and AI algorithms will be able to handle complex garment assembly processes with high precision and efficiency.

3D printing of textiles: It is possible that in the future 3D printing could revolutionise garment production by enabling on-demand manufacturing of customised clothing items. This technology aligns with sustainability principles and also has excellent customisability for products. This process can reduce waste by producing garments precisely to fit individual body measurements.

The available technologies and inventions pave the way for a wealth of new clothing designs, introducing dynamic concepts and a spectrum of possibilities in the fashion design industry that were previously unattainable. These technologies are already in development or early adoption stages and are likely to converge in the coming years to reshape the garment manufacturing landscape, making it more sustainable, efficient, and responsive to consumer demands, and making spinning and weaving, cutting and sewing and waste a thing of the past.

3.6. Summary

There has been a significant advance in technologies in the recent past, moving towards more automation and smart manufacturing and the impulse for accepting sustainable techniques is also persistently increasing to save the global environment. There have been many efforts from different segments of textile manufacturing to reduce the current environmental costs for textile manufacturing and prepare clothing more competently. This trend of progress is likely to further grow in the future at a faster pace and utilise more of the technological advances to supply textiles both efficiently and sustainably. To this end, Chapter 4 will explore what is required within the textile materials and processes by this time to reach future textiles.

Chapter 4

Road to the Future Textiles

Preamble

This chapter explores the prerequisites for achieving the anticipated future of textile manufacturing. It elaborates on the current scientific foundations and the requisite knowledge and research needed to advance towards the projected future trajectory. Central to this endeavour is the design for developing a garment that can be constructed, deconstructed, and reconstructed repeatedly with minimal degradation.

4.1. Requisites for Future Textiles

With the future trend towards more automated, intelligent, and sustainable textile manufacturing, it may one day be possible to design and produce garments domestically. These garments could be deconstructed and reconstructed again and again using the same raw materials. However, significant milestones in research and innovation must be achieved to reach that level of production. Industry 4.0 is probably ready enough to integrate textile preparation through complete automation. However, to make the process not only smart but also sustainable, there are opportunities to innovate within textile materials and processes to make the whole procedure meaningful.

These could be summarised in five key elements as the following:

- *Sustainable materials:* Raw materials for textiles production, such as fibres that are natural, regenerated, or biosynthetic, reusable to some extent and degrade naturally in the environment.
- *Sustainable colouration:* A way of adopting natural dyes in large-scale production, to substantially replace synthetic dyes.
- *Green chemical processes:* Replacement of hazardous chemicals that are currently used in different sectors by adopting green chemistry and processes.
- *Separation and reuse:* A separation mechanism for the components used in garments by not deteriorating the properties of materials, e.g., fibres and can separate based on fibre types, colour and grades.
- *Circular garment production:* Incorporation of complete automation with garment preparation in a circular manner, with a washing facility, and collection and reuse of materials.

Figure 4.1 shows a schematic of the requisites reaching towards Future Textiles. These 5 key points are further detailed in the following sections.

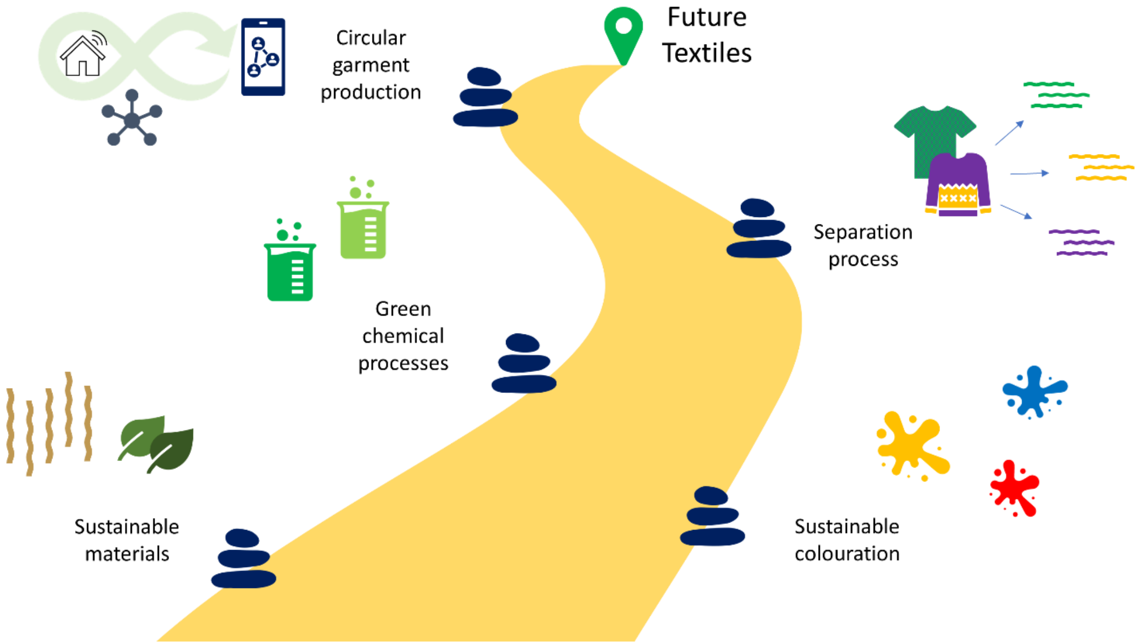

Figure 4.1: The Road to the Future Textiles

4.2. Sustainable materials

Fibres are a special class of materials distinguished by their high length-to-diameter ratio. Their unique properties, including flexibility, strength, versatility, comfort, functionality, and aesthetic qualities, make them indispensable for traditional textile production. Fibres have been fundamental to textiles since the inception of textiles, and ongoing research and innovation will continue to drive advancements in the future. Therefore, this paper recognises fibres as the key material element for Future Textiles and discusses and analyses them more extensively than any other form of materials. However, it may eventuate that new material form is required to address the mounting challenges of ongoing material reuse. If a new material form were to emerge in the future, it would also need to offer all the benefits that fibres currently provide.

Current textile fibre production relies heavily on fossil fuels. If global fossil fuel consumption continues at its current rate, it could lead to the depletion of known reserves within the coming decades. There are estimations that fossil fuels are going to be permanently exhausted probably between 2050 and 2070, and certainly between 2070 and 2090 [186].

In 2050, worldwide production and consumption of fibre will be around 215 million tonnes at a 2% compound annual growth rate from present levels; with a 3% growth rate, that amount would rise to 275 million tonnes [187]. The current production of natural fibres and regenerated fibres combined is only 40 million tonnes which has merely increased recently. The rest fractions of the fibres are derived from fossil fuels and have continuously grown in production over the past decades. If we cannot find an alternative soon to fill this huge amount of fossil fuel-based fibres, there will be a massive material shortage. Therefore, the first and foremost area of textile research should be oriented on the new sustainable sources that could replace fossil fuel-based synthetics. Natural, regenerated, and biosynthetic fibres from renewable resources should get a high focus.

This should be noted that the production of natural fibres and regenerated fibres also consumes fossil fuels in their processing stages (discussed in Chapter 2) [66]. Therefore, the use of renewable energy should constantly be encouraged and adopted in every stage of production to limit the current consumption rate of fossil fuels. Conversely, the production of virgin, organically derived materials for matching fibres should be aligned with the economic sustainability standards observed in the production of other organic resources, such as food and timber.

4.2.1. Natural materials

Current natural fibre production is led by plant-based fibres, i.e., 31.3 million tonnes compared to only 1.8 million tonnes of animal-based fibres [1]. The reason behind this is the abundance of cellulose in the plant-based fibres. Cellulose offers desirable properties such as high absorbency, breathability, and comfort, making it suitable for a wide range of applications from everyday clothing to technical textiles [188]. They are also easily dyeable, which adds to their versatility. While protein fibres like wool are known for excellent insulation, moisture-wicking, and elasticity, and silk for its luxurious feel and strength, these properties are not universally required. The maintenance and care for protein fibres can also be more demanding (e.g., wool shrinking, felting, and moth attack). The versatility of cellulose fibres allows them to be used in a wide variety of textile products, from lightweight summer clothing to heavy-duty workwear, home textiles, and industrial applications. Protein fibres are often used in more specific applications where their unique properties are essential, such as in luxury fashion, performance wear, and certain traditional garments [189]. Therefore, cellulose is fundamental to the textile industry when natural fibres are considered.

Among the plant-based fibres, cotton holds the major part in textiles with a current production of 25 million tonnes [1]. There is continuous research on cotton and over the years it may be possible to raise the fibre yield per cotton plant per acre through genetic modification [190]. However, this is very unrealistic to multiply cotton production more than 8 times by any means by 2050 to fill the gap of fossil fuel-derived fibres. Rather, it is more logical to make more use of other plant-based fibres or natural resources.

One important criterion that distinguishes cotton from other plant-based fibres is its high cellulose content (83–92 %), or in other words, negligible impurities (such as lignin). This cellulose content is higher than any other plant-based fibres such as hemp (68–75 %), flax (64–75 %), banana (60–65 %), jute (61–71 %), ramie (62–85 %) and sisal (60–78 %) [191]. The rest of the composition of these fibres consists of a considerable amount of lignin that creates a key difference in their properties compared to cotton. Low lignin content makes cotton easier to process. During the spinning and weaving processes, cotton's pliability reduces wear on machinery and allows for smoother, more efficient processing. This contrasts with other plant-based fibres that have higher lignin content, making them tougher and more rigid. While they have their benefits, such as strength and durability, the high lignin content requires more intensive processing methods to make them suitable for textiles [192]. This can include retting, scutching, and hackling, which are labour-intensive and time-consuming.

Besides, to create a robust and improved supply chain for textile fibres, it is essential to optimise each stage from seed to garment. This includes selecting high-quality seeds, implementing sustainable farming practices, efficiently processing biomass, and refining fine fibre production. Innovations in these areas can enhance yield, fibre quality, and environmental sustainability.

Considering the overall truths and limitations of other plant-based fibres and their use in textiles, future research on them could focus on several key areas (as shown in Figure 4.2) to enhance their usability and competitiveness in textile making. These include:

- *Efficient retting methods:* Develop advanced retting techniques using biological, enzymatic, or chemical, such as using deep eutectic solvents, that are faster, more efficient, and environmentally friendly to break down lignin and separate fibres with minimal impact on fibre quality. Moreover, it is also essential to utilise the separated lignin from these processes towards other value-added applications to offset the cost of removal.
- *Mechanical processing innovations:* Innovate mechanical processing methods to streamline the extraction and refinement of bast fibres, reducing labour intensity and costs. Automated and precision machinery could improve the scalability and efficiency of plant-based fibre processing.
- *Chemical treatments:* Explore eco-friendly chemical treatments to modify the surface properties of these fibres, making them softer, more flexible, and easier to blend with other fibres. These include technologies for advanced biomass processing and refining fine fibre, and could involve treatments that enhance dye uptake and compatibility with other fibres.
- *Blended fabrics:* Investigate optimal blending ratios and processing methods for combining plant-based fibres with other natural or synthetic fibres to create fabrics that leverage the strengths of each component. This could lead to textiles with improved durability, comfort, and functionality.
- *Product development:* Encourage innovation in product design to incorporate plant-based fibres into a wider range of textile products, from high-end fashion to functional and technical textiles. Specific apparel could be designated to specific fibres based on their intrinsic properties. For example, the strength and coarseness of hemp have already been found handy for denim application [193].
- *Genetic modification and selective breeding:* Research into genetic modification or selective breeding to develop fibre crops with desirable traits, such as reduced lignin content, increased fibre yield, and improved fibre fineness and strength, along with sustainable farming. As a relevant example, a study by Commonwealth Scientific and Industrial Research Organisation (CSIRO) scientists showed that it is possible to even grow naturally coloured cotton through genetic modifications, which can minimise dyeing needs [194].

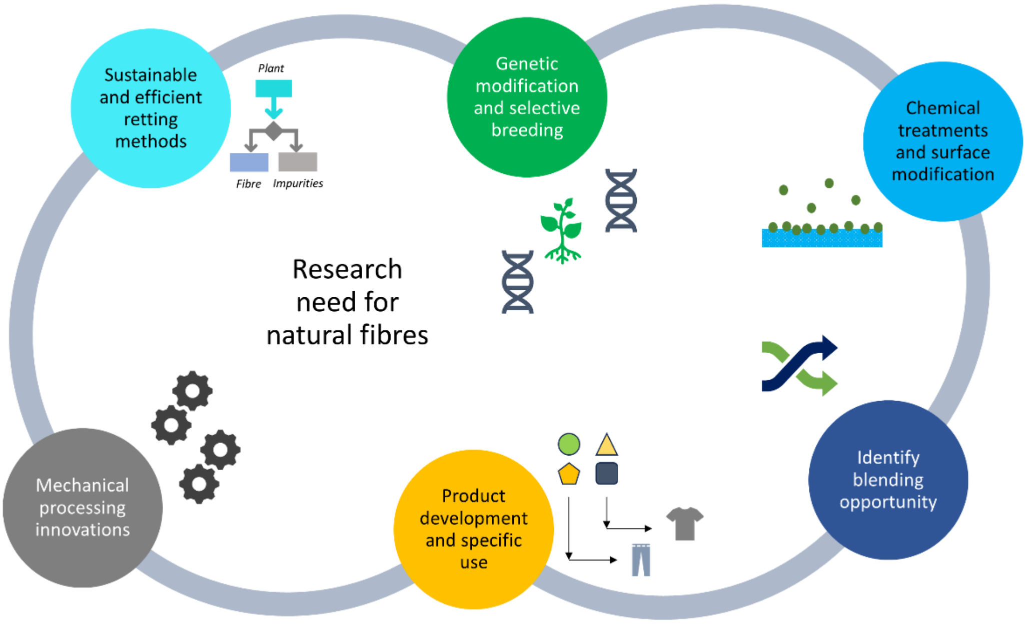

Figure 4.2: Research opportunities with natural fibres to meet Future Textiles.

These efforts can put plant-based fibres one step forward and make them more competitive in the market, contributing to a more sustainable and diverse range of textile materials.

4.2.2. Regenerated materials

Given the importance and advantages of 'cellulose' in textiles, cellulose regeneration is the future in the regenerated materials segment. The current production of regenerated cellulose fibre is 7.2 million tonnes of which the majority (5.8 million tonnes) is viscose rayon [1], and its production process is highly unsustainable [70]. An indirect but key reason behind this is the current sources used for regenerated fibre production that contain a comparatively lower amount of cellulose though high in lignin and other impurities. Therefore, hazardous chemicals and processes are often required to get rid of those and extract pure cellulose. For example, common current resources for regenerated cellulose production are wood pulp which is sourced from hardwood (31–64 % cellulose) or softwood (30–60 % cellulose) and has a significantly lower cellulose content than the common plant-based fibres mentioned before [191]. Thus, their regeneration needs intensive processing to remove lignin and other impurities. This is also true for the emerging bamboo fibre (which is also a regenerated cellulose) as bamboo contains 23–57 % of cellulose. A way to adopt sustainability in these processes could be choosing the correct materials for regeneration which are purer in terms of cellulose. One of the streams of such resources could be agricultural wastes, which could minimise the raw material cost. For example, cotton motes, a frequently generated cotton industry by-product should be useful in this regard which has a high cellulose content (>67 %) and [195], similar to cellulose content in different bast fibres. It is estimated that approximately 200,000 tonnes of cotton motes are produced annually in the United States (USA), but the country accounts for only 11.7 % of the world's total cotton production [196]. Hemp and flax are also fast-growing plants that are excellent sources of cellulose and can also be harvested more sustainably than traditional timber as alternative resources for cellulose regeneration. Besides, recycling cellulose from discarded paper products, old textiles, and other cellulose-containing waste can create a sustainable loop.

Though yet not popular in textile use, bacterial cellulose through the fermentation of sugars is also a great candidate for fibre regeneration due to its purity as cellulose, i.e., free from lignin and other impurities that are present in plant-derived cellulose. Although the production of bacterial cellulose is expensive, researchers are looking for low-cost raw materials with high sugar content to provide substrates for the synthesis of bacterial cellulose including agro-wastes, food wastes and industrial wastes [197].

Other emerging sources for fibre production include algae, fungi, and slime moulds. Algae can be cultivated in marine or freshwater environments, often requiring less land and freshwater than traditional crops. Certain types of algae, particularly those in the group of green algae can produce cellulose in their cell walls. Both microalgae (like *Chlorella* and *Spirulina*) and macroalgae (seaweeds such as *Ulva* and *Laminaria*) contain cellulose. However, their cellulose content is typically low. For example, in raw form, the portion of cellulose in most algae is below 20 % while only in some species it was reported over 40 % [198, 199]. However, an advantage of them is they commonly have low or undetected lignin content which is the most undesirable part in fibre production.

While fungal mycelium (the vegetative part of fungi) has been explored as a sustainable alternative for textile fibres, it is not cellulose-based like bacterial cellulose. Instead, mycelium-based textiles involve the use of the fibrous network of fungal mycelium, which is primarily composed of chitin and other polysaccharides. Mycelium-based textiles, also known as 'mushroom leather' or 'mycelium leather,' are produced by growing fungi in a controlled environment on organic substrates such as agricultural waste. The mycelium forms a dense network of fibres that can be processed into various materials with 'leather-like' properties [200]. Fungal mycelium-based textiles are still in the early stages of development and require further exploration for possible integration as a regenerated fibre.

Myxomycetes, a slime mould, particularly in their plasmodium stage, produce flexible natural substances that could be harnessed to create biodegradable textiles. Three fundamentally distinct types can be identified in the plasmodium stage of this slime: protoplasmodia, aphaneroplasmodia, and phaneroplasmodia. The phaneroplasmodia of certain myxomycetes species can extend to over a metre in length. This is the most robust, highly pigmented type, and is the one typically seen in natural settings [201].

Such alternative materials could offer a sustainable alternative to synthetic fibres, reducing environmental impact. Overall, the research requirement in coming years in the regenerated fibre segment is illustrated in Figure 4.3 and summarised as follows:

- *Agricultural resources and residues:* Investigate the use of plant-based resources and by-products that are rich in cellulose. This includes optimising pre-treatment processes to maximise cellulose yield and quality.
- *Adoption of bacterial cellulose:* Engineer bacterial strains for higher cellulose production and easier extraction. Explore the potential for bacterial cellulose to be used directly in fibre-spinning processes cost-effectively.
- *Alternative sources:* Investigate non-traditional sources of cellulose such as algae and fungi. Understanding the cellulose yield, quality, and extraction efficiency from these sources can

help diversify the raw material base. Research should be focused on scalable and cost-effective production methods. Equally important is the exploration of unconventional bio-material sources that could be valuable in developing new recyclable textile materials, beyond just fibres.

- *Sustainable use of chemicals:* Continuous adoption of sustainable chemical processes to replace the current use of hazardous chemicals in cellulose regeneration to process eco-friendly.
- *Scaling Up:* Develop scalable production methods that maintain fibre quality while reducing costs. This involves pilot projects and industrial-scale trials to ensure processes can be economically viable at larger scales.
- *Materials that suit sustainable processes:* The proposed materials must be compatible with sustainable processes, such as additive manufacturing and nonwoven techniques, ensuring minimal waste generation during production and cost-effective transformation into textiles.

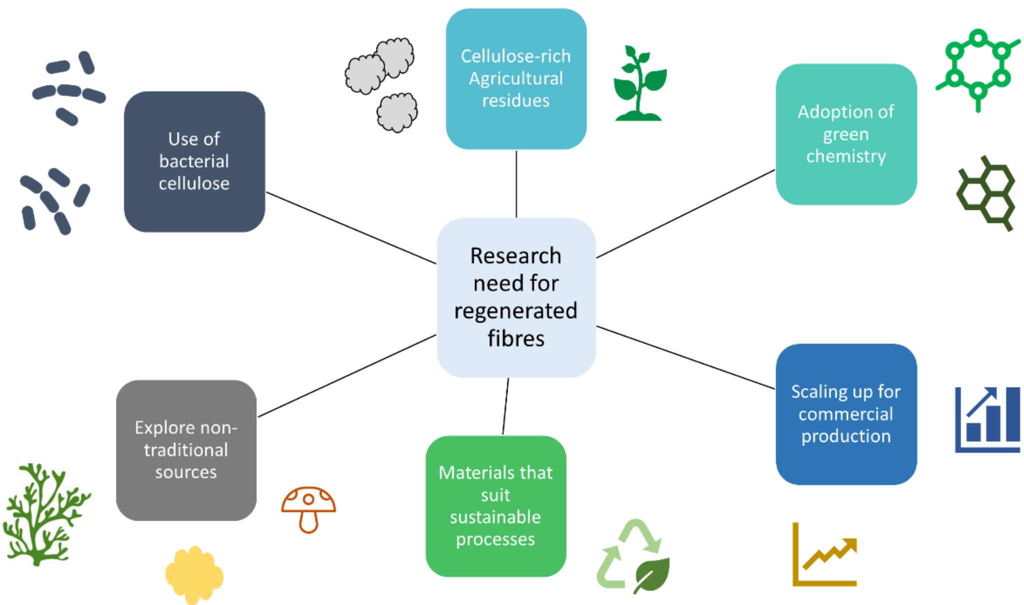

Figure 4.3: Research needs in the regenerated fibres sector to meet Future Textiles.

In general, continued research is required in the fibre regeneration segment to improve the share in worldwide fibre consumption by making more use of abundant natural resources.

4.2.3. Biosynthetic materials

Biosynthetic materials, such as fibres derived from biosynthetic polymers are also a great option to explore for textile industries as a replacement for current synthetic fibres. Considering their flexibility and durability, they could be an ideal replacement for polyester fibres in textile use solely or as a blend, only if their biodegradation is guaranteed.

There are rooms to work with bio-based biodegradable fibres (such as PLA and PHB) as well as synthetic biodegradable fibres, such as (PCL and PBAT). PLA, despite its popularity in different applications including textiles, is still a threat due to its composting requirement. Even though PLA has the proven ability to be extruded into fibres and subsequent textile use, at the end of life it needs certain industrial composting conditions which are not met in natural environments such as landfills or marine environments. This can lead to accumulation of them in nature and potential environmental pollution. Another major concern is that PLA breaks down more quickly into microplastics than petroleum-based non-degradable polymers [202]. PLA recycling can also be complicated by contamination from other types of plastics. Therefore, research is needed to improve the biodegradation of PLA and polymers in a similar category (e.g., PBS) so that they do not necessarily pose a threat to the environment by any means. Some of the key research requirements in this area could be summarised as:

- *Microbial and enzymatic degradation and kinetics:* Identify and engineer microorganisms or enzymes that can efficiently break down polymers like PLA and PBS under various environmental conditions (e.g., soil, marine environments, home composting). Study the kinetics of degradation to understand the rate-limiting steps and improve the efficiency of the biodegradation process.
- *Copolymerisation and blending:* Develop copolymers or blends with other biodegradable materials to enhance biodegradation rates without compromising mechanical properties. Copolymerisation can reduce crystallinity and increase the proportion of amorphous regions, making the material more flexible and easier for microorganisms to penetrate and degrade.

Unlike these polymers, there are other kinds of biodegradable bio-based polymers (such as PHB) that do not have any issue with their biodegradation but are not feasible for spinning into a 'fibre', which is the fundamental element in textiles [170]. This category of polymers is highly promising from the sustainability point of view though needs research progress on their proper adoption in fibre preparation suitable for textile making. The areas that need attention in this regard are:

- *Thermal stability improvement:* These polymers have a relatively narrow processing window and can degrade at high temperatures required for melt spinning. Therefore, it is required to develop advanced thermal stabilisers and processing techniques to enhance their thermal stability, making them more suitable for high-temperature melt-spinning processes. Producing polymers with a higher molecular weight can also be an option to improve the thermal stability.
- *Melt spinning techniques:* Refine melt spinning parameters, including temperature control, extrusion speed, and cooling rates, to achieve consistent fibre quality and diameter. Study alternative spinning methods such as solution spinning and electrospinning for producing fine fibres from them.

The third category of polymers that needs attention is petroleum-based yet biodegradable in regular environments or at least compostable at home (such as PCL and PBAT). The research demand for them is to find an alternative way to source them completely from renewable sources. This does not seem impossible as one encouraging study came out very recently where PBAT was reported to be completely sourced from molasses gained from sugar manufacturing [203], although PBAT is generally sourced from petrochemical products. Studies are required in coming years to confirm the true feasibility of such potential as summarised below:

- *Identification of renewable feedstocks:* Investigate and identify suitable renewable feedstocks for producing these polymers. These could include plant-derived sugars and lignocellulosic biomass.
- *Biotechnological pathways:* Develop efficient microbial fermentation processes to convert renewable feedstocks into the monomers needed. This involves engineering microorganisms like bacteria and yeast to optimise production pathways. Improve enzymes used in the bioconversion processes to enhance their efficiency, stability, and specificity for desired reactions.
- *Speed up biodegradability:* Despite these polymers being biodegradable, the speed of degradation is often claimed slow. Research could be conducted to improve their degradation speed so that their environmental impact is minimised.

Overall, there is a great potential for biosynthetic polymers to be successfully adopted in textile industries in future. It is possible that with the innovations in the future, current or new types of polymers could be directly printed into a garment, eliminating the need for traditional processes like spinning, weaving, or knitting. By addressing the research needs as described above and summarised in Figure 4.4, the development of truly biodegradable fibres from renewable sources is possible in future. This could contribute to the reduction in reliance on fossil fuels and promote sustainable textile production, without worrying about fibrous microplastic generation or other environmental pollutions.

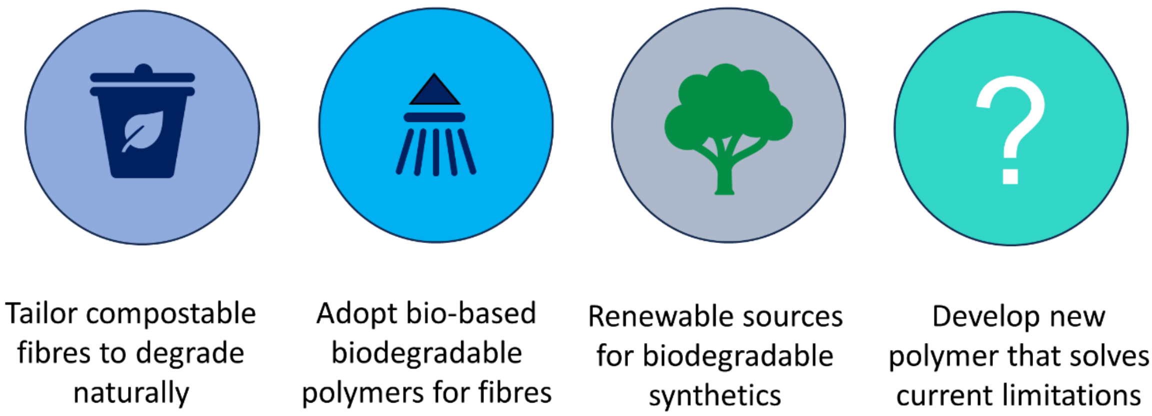

Figure 4.4: Three key areas of research to progress biosynthetic polymers for Future Textiles.

4.3. Sustainable colouration

Embracing sustainability is the key criterion in shaping the future of textile colouration processes. This includes adopting eco-friendly dyeing methods and exploring alternative dye sources such as bacterial or natural dyes. Overcoming the current limitations of natural colourants to make them suitable for bulk use can help minimise pollution and reduce the demand for synthetic dyes, i.e., slow down the consumption of fossil fuels. With increasing awareness of environmental and social issues, there is a growing demand for sustainable and eco-friendly products, leading some consumers to prefer natural and bacterial colourants over synthetic alternatives.

Among natural options, bacterial colourants can potentially offer a wider range of colours compared to some traditional natural dyes, providing more flexibility for textile designers and manufacturers. Besides, production of bacterial colourants production can be optimised and controlled in laboratory settings, potentially leading to more consistent colour quality and production efficiency. This has made them a more practical option to work with (over other sorts of natural dyes) for replacing synthetic dyes. Their easy growth, resilience to temperature and pH variations, diversity, and non-toxicity/eco-friendliness make them a strong candidate in the present pigment business [204]. The development of recombinant DNA technology has further solidified bacteria's position in the pigment business. This is the capacity to biosynthesise any natural pigment using a bacterial host cell so that bacterial culture can accomplish the same goals as cultivating quintals of plants to produce their colours [205]. Though limited studies are available, it is also evident that bacterial colourants can be applicable in both natural (such as cotton, silk, and wool), synthetic (such as polyester, nylon, polypropylene and acrylic) and regenerated fibres (such as viscose and acetate) [206, 207].

Added to that, bacterial colourants also provide extra functionality and medicinal properties. For example, pigments produced by living things can aid cells in many ways including photosynthesis, UV protection, defence against invading species, and even the creation of molecules that store energy [208]. Extensive study is being conducted on the potential use of bacterial colourants in modern medicines as well. Figure 4.5 shows some advantages of using bacterial colourants in textiles.

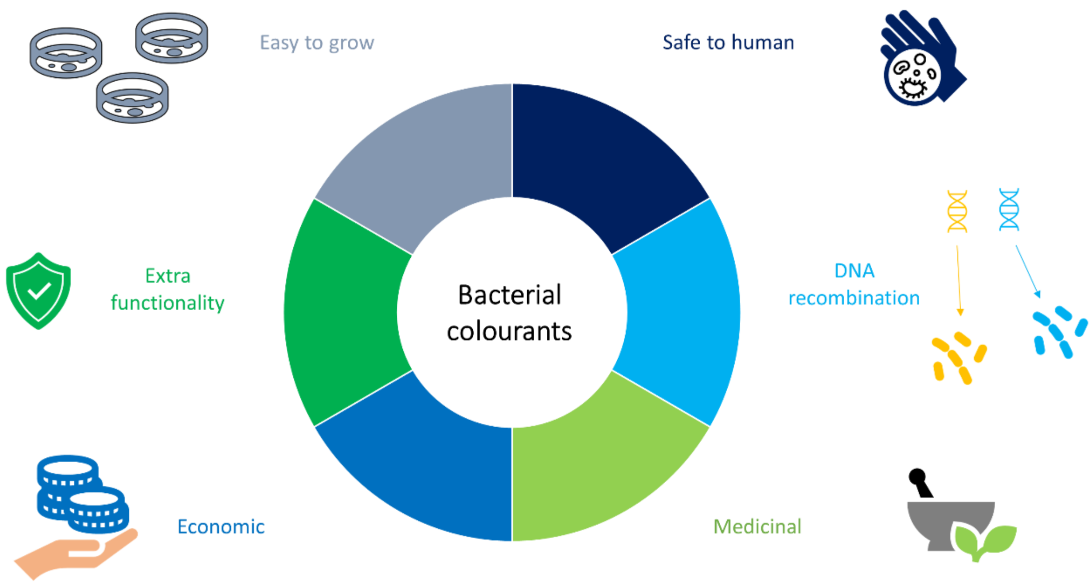

Figure 4.5: The advantages of using bacterial colourants in textiles.

Research into bacterial colourants holds promise for sustainable and eco-friendly alternatives in textile dyeing. The future research requirements to further advance this field could be summarised based on the following aspects:

- *Optimisation of bacterial strains:* Further research is needed to optimise bacterial strains for efficient and high-yield production of pigments suitable for textile dyeing. This includes exploring genetic engineering techniques to enhance pigment production, stability, and colour range.

- *Colour stability and fastness:* Improving the colour stability and fastness properties of bacterial colourants is essential for their practical application in textiles. Future research should focus on enhancing the light fastness, wash fastness, and rub fastness of these dyes to ensure the durability and longevity of dyed fibres.
- *Adoption in printing:* Aside from textile dyeing, 'printing' is an important segment of textile colouration where dyes are applied precisely to specific locations with the help of binders. To achieve success with bacterial colourants in textiles, their adoption is also required in the printing section. This can be progressed into digital printing (maybe in a desktop environment as we do for papers) that will offer precise dye application reducing waste and costs associated with excess dye and water use with the help of natural binders. Further research can be done to increase speed, precision, and colour reliability and minimise energy consumption.
- *Scalability and production efficiency:* Scaling up bacterial colourant production to industrial levels requires overcoming challenges related to production efficiency, repeatability, and cost-effectiveness. Research efforts should aim to develop scalable production processes and reduce production costs to make bacterial dyeing economically viable for large-scale textile applications.
- *Waste utilisation and valorisation:* Exploring alternative feedstocks and waste materials for bacterial colourant production can further enhance the sustainability of this approach. Future research should investigate the use of agricultural residues, food waste, and other organic substrates as renewable sources for bacterial colourant production.
- *Application and compatibility:* Studying the application and compatibility of bacterial colourants with different textile fibres, dyeing and printing techniques, and finishing processes is essential for their adoption in the textile industry. Research should explore the dyeing and printing performance, colour consistency, and compatibility of bacterial colourants with various types of natural and biosynthetic fibres, as well as evaluate their suitability for different textile applications.

Addressing these research requirements will contribute to advancing the development and adoption of bacterial colourants as sustainable alternatives in textile dyeing, paving the way for a more environmentally friendly and socially responsible textile industry.

4.4. Green chemical processes

Apart from the fibre manufacturing stage and textile colouration (which are discussed in Section 4.2 and Section 4.3), the main other sectors where chemicals are employed include textile pretreatment, finishing, washing, and binding for nonwoven preparation. The key progresses required in these sectors are summarised in Figure 4.6 and are discussed henceforth.

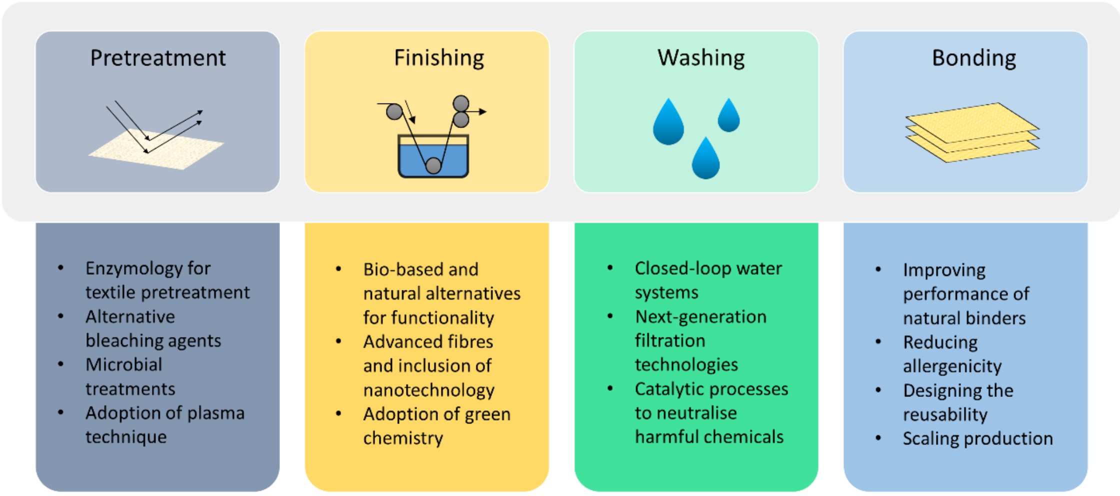

Figure 4.6: The key areas to work on in textile pretreatment, finishing, washing and chemical bonding in nonwoven.

4.4.1. Textile pretreatment

Regardless of whether we are applying colours to the fabrics, yarns or fibres, the pretreatment stage is required to make the substrate ready for colour absorption. Common pretreatments use hazardous chemicals such as caustic soda, acids, and hydrogen peroxide to remove impurities and improve absorbency [209]. However, there are encouraging findings on using alternative pretreatment methods for textiles. For example, enzymes can replace harsh chemicals in de-sizing, scouring, and bleaching processes, e.g., amylases for de-sizing and cellulases for bio-polishing [210]. Ozone can be used instead of chlorine-based bleaching agents, significantly reducing water and chemical consumption [211]. There is also a proven physical process, such as plasma treatment on textiles that significantly can increase the absorbency of fabrics, limiting the need for water and chemical use [123]. However, the initial setup cost still limits its use in large-scale production. Overall, research on the following aspects could be considered for a sustainable textile pretreatment process in future:

- *Advanced enzymology:* Research into more robust and efficient enzymes for textile pretreatment that can operate under a wider range of conditions (temperature, pH) to reduce energy and water use.
- *Non-toxic bleaching agents:* Development of alternative bleaching agents, such as activated peroxide or ozone systems, that are effective at lower temperatures and reduce environmental impact.
- *Microbial treatments:* Exploring microbial-based treatments to naturally degrade impurities and prepare fibres without the use of harmful chemicals.
- *Plasma retrofit solutions:* Developing retrofit solutions that allow existing textile production lines to incorporate plasma treatment with minimal disruption. This includes modular plasma units that can be easily integrated into current setups.

4.4.2. Textile finishing

The finishing sector uses chemicals to provide specific properties to the fabric, such as water repellence, flame retardancy, or wrinkle resistance. Common chemicals include formaldehyde resins, fluorocarbons, and softeners. Research into natural and bio-based alternatives to traditional chemical finishes can help create fabrics with desired properties without harmful effects. Some of the examples could be, more use of silicone-based softeners replacing traditional softeners that release formaldehyde, the use of bio-based water repellents derived from natural sources, such as waxes or oils, replacing fluorocarbon-based repellents, use of chitosan (derived from chitin in crustacean shells) for antimicrobial and wrinkle resistance properties and so on. The finishing sector is highly versatile and is more dependent on the specific customer requirement for a specific product. Therefore, there are numerous possibilities within this sector and countless room to incorporate sustainable alternatives. Some of them could be listed as:

- *Bio-based and natural alternatives:* Research into bio-based chemicals and natural compounds that can provide desired fabric properties. These could be derived from natural substances coming from renewable resources (e.g., plant-based dyes, oils, and natural resins). Exploring biodegradable alternatives that break down into non-toxic byproducts.
- *Advanced fibres and nanotechnology:* Developing fibres with inherent properties such as antimicrobial, flame retardant, or water repellence, reducing the need for additional chemical finishes. Investigating nanomaterials that can provide enhanced properties with minimal chemical use and improved safety profiles.
- *Green Chemistry:* Research into green chemistry principles to develop safer, non-toxic chemicals for finishing that can replace hazardous ones without compromising effectiveness.

4.4.3. Textile washing

The laundering of textiles often involves detergents, softeners, and bleaching agents that can be harmful if not managed properly. Research is required into closed-loop systems and advanced filtration techniques for recycling water and chemicals in textile processes. Developing technologies for the efficient use and recovery of water and chemicals can significantly reduce waste and pollution. Some of the areas to work on include:

- *Closed-loop water systems:* Recycling water within the production process reduces overall consumption and pollution.
- *Advanced membrane filtration:* Research on next-generation filtration technologies, such as nanofiltration and reverse osmosis, to effectively recycle and purify wastewater in textile processes, and filtrate microfibres released from garments.
- *Catalytic processes:* Developing eco-friendly catalysts that can degrade and neutralise harmful chemicals in wastewater, making recycling more efficient and less energy intensive.

4.4.4. Binder for nonwoven

Binding agents used in nonwoven can be hazardous, but there are safer alternatives available to work on. Binder is estimated around 10–40 % of a whole nonwoven [212]. The traditional agents include synthetic resins, adhesives, and chemical binders, some of which can pose health and environmental risks [86, 88]. The safer alternatives could be the biodegradable binders coming from natural polymers such as starch, cellulose, or proteins (e.g., soy-based adhesives) as they are also generally non-toxic and safe for human health. Natural latex derived from natural rubber is also biodegradable and generally safe for human health, although some people may have latex allergies [213, 214]. Another example could be the use of biodegradable polymers or the modification of bio-synthetics using enzymes to enhance their binding properties and environmental performance. While designing a safe binder for constructing nonwoven, it is also important to allow for its deconstruction ability probably by a different solvent or chemical so that the manufacturing process retains the circularity and ease of reuse again and again. The research needs in this area could be summarised as:

- *Performance of natural binders:* Research into enhancing the durability, water resistance, and adhesive properties of natural and biodegradable binders to match those of synthetic counterparts.
- *Reducing allergenicity:* For natural binders like latex, research into reducing allergenic proteins can make them safer for a broader range of applications.
- *Designing reusability:* Development of an ideal system that can deconstruct the nonwoven by dissolving the binder and then regenerate the binder to be used for the construction of the nonwoven again and again.
- *Scaling production:* Developing cost-effective methods for large-scale production of safer binding agents to ensure they are economically viable.

4.5. Separation and reuse

Technology for sorting and separating textile fibres is a pressing need given the urge for efficient reuse of current fibres that have been consumed. Currently, only 1 % of old textiles are recycled to new textiles globally [130]. However, the quality of fibres only degrades by 30 % when they are thrown away into landfills [128]. Theoretically, there is a great potential for these fibres to be utilised again in textiles if not solely, at least in combination with fresh virgin fibres. This could significantly reduce or control the need for new fibres. However, the major obstacle to this is the lack of technology. As discussed in Chapter 3, the mechanical method of disintegration of old textiles is currently possible in the bulk phase but is not suitable for maintaining the fibre quality and indeed harms the quality significantly. The chemical process of separation is a better option than mechanical, though it still poses a risk of fibre degradation and loss. Considering polyester and cotton are the two major streams of fibres in apparel production, the separation technique for these two is a key requirement. However, most of the solvents used for separation are particularly harmful to cotton and there is very little evidence of getting chemically separated intact cotton fibres that are suitable for textile making again.

One of the major issues in the chemical separation process is the presence of dye in the textiles. Commonly, they need to be removed by pretreatments before the separation is occurred. The removal of colour provides more customisability in producing new textiles to be started from a fresh white tone. The chemical process is the only way to remove colours currently used in textiles, but they also come with the cost of partial fibre degradation. Besides, the chemicals needed are mostly hazardous. If we imagine a domestic scenario where textiles are remanufactured again and again with different colours, the use of hazardous chemicals every day for either separation or colour removal is not feasible.

A promising idea to use domestically is the dry separation technique of fibres which already got some light in recent years. Fibres can be electrically charged based on their surface properties and can be separated [215]. This is also theoretically possible to separate fibres of more than two types probably in multiple steps. This technique is not only chemical-free but also can retain the fibre quality which is not possible either in chemical or mechanical processes. Within this triboelectric separation technology, instead of removing colours from fibres, it is possible to make use of the colours and limit new colourant production. This is no different from the concept of Lego, where different coloured fibres can be sorted and can be reused again and again to make a new textile of a new design. Figure 4.7 shows a perception of sorting and separating fibres of different compositions (molecular tagging by integration of other technologies) and colours ready to be used in new textiles. Such triboelectric separation could be integrated with optical technologies such as the use of infra-red to know the composition of fibres and possibly fibre length, grades, and quality to make the whole process more efficient and useful. For example, the technology could be further advanced to detect the fibre grades and separate the fibres that would be deemed unfit for the next cycle.

This should be noted that the presence of yarn and fabric (in either woven or knitted form) will first need mechanical disintegration into the fibres to be used within this technology which is likely to negatively impact the fibre quality. Therefore, the use of nonwoven structures for this kind of garment remanufacturing will be more practical at home, given their easy disintegration possibility. However, the separation and use of coloured fibres of different compositions is still feasible for woven and knitted fabrics (on a large scale) where a pre-process of yarn preparation is involved, and those yarns can be designed to be made as per the coloured fibres sorted. Therefore, the dry or triboelectric separation of textile fibres has great potential in textiles, regardless of the ultimate method of textile manufacturing.

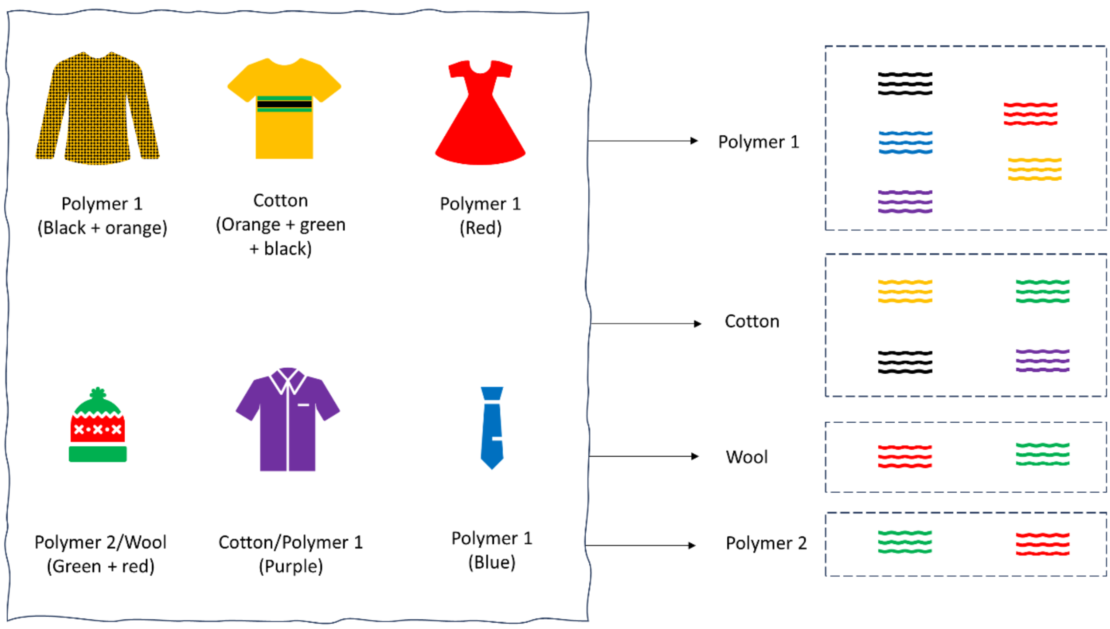

Figure 4.7: A concept of sorting the textile fibres based on colour and types ready to be used again.

Future research into triboelectric separation of textile fibres could focus on several key areas to advance this technology for viable applications. These can be summarised as below points:

- *Understanding triboelectric properties of textile fibres:* Research is needed to comprehensively understand the triboelectric properties of different types of textile fibres, including natural fibres (e.g., cotton, wool, silk) and synthetic fibres (e.g., current polyester, nylon, acrylic and biosynthetic fibres). This includes studying the surface charge generation mechanisms, charge transfer characteristics, and factors influencing triboelectric charging behaviour (e.g., fibre morphology, surface roughness, moisture content).

- *Optimisation of separation parameters:* Further research is needed to optimise the parameters involved in the triboelectric separation process, such as contact pressure, contact area, separation speed, and environmental conditions (e.g., humidity, and temperature). Systematic studies can help identify the optimal conditions for achieving efficient and selective separation of different types of textile fibres based on their triboelectric properties.
- *Development of separation devices and systems:* Future research could focus on designing and developing efficient separation devices and systems tailored for the triboelectric separation of textile fibres. This includes exploring different separation geometries, electrode configurations, and material combinations to maximise separation efficiency and throughput.
- *Characterisation techniques:* Research is needed to develop reliable characterisation techniques for evaluating the effectiveness of triboelectric separation in terms of fibre purity, separation efficiency, and output. This may involve developing novel measurement methods, such as imaging techniques, spectroscopic analysis, and electrostatic measurements, to quantify the distribution and properties of separated fibres.
- *Scalability and integration:* Future research should address the scalability of triboelectric separation technology for industrial-scale applications in textile recycling and waste management. This includes exploring strategies for scaling up separation processes, integrating triboelectric separation into existing recycling systems, and assessing the economic feasibility of large-scale implementation.
- *Separating different grades of fibre:* This technology could also be potentially implied to separate different grades of fibre, to provide more customisability in the next step. Besides, when new textiles are made from the same fibres time and again, this is more likely that the properties of some of them will be degraded at some point and will be unsuitable for next use. Within this technique, those fibres could be efficiently removed.

Addressing these research needs can help advance this technology for textile fibres, contributing to the development of more sustainable and efficient solutions for textile reuse and waste management.

4.6. Circular garment production

Let’s consider we have reached all prior milestones; we have sustainable new materials (e.g., fibres or other forms if suitable for textiles) in hand that are fully biodegradable, we have developed a sustainable colouration technique for both dyeing and printing and we also have established green chemical processes for pretreatment, finishing, washing and binding (and disintegrating) the components, we also have an effective method for separation and reuse. Now what more must be done to envision circular garment production at home in the future? Figure 4.8 shows a design for developing the circular process of garment production, considering all the materials to be used (either natural, regenerated or biosynthetic) are biodegradable in natural conditions, definitely not requiring any composting facility.

The process starts from the nature of materials production. For example, the materials can be natural fibres, regenerated fibres or biosynthetic fibres that will be derived from renewable resources. Industries will process them, pretreat and colour them by use of sustainable dyes and chemicals as projected in previous sections. Industries are supplying coloured fibres to users to build their clothes, like the coloured Lego pieces we buy for building Lego blocks. There will be other industries, such as solvent suppliers and manufacturers of external components such as buttons and zippers. Apart from building cloths from combinations of plain coloured fibres, the users will also have access to optionally print on a local part of their cloth (such as putting a picture of a bird or a company logo). Users can also optionally buy finishing ingredients to provide the desired finishing on the prepared cloth. All of these materials need to be eco-friendly and preferably bio-based.

The user will have 4 input chambers for fibres, chemicals, non-fibre components and old cloths. The user can control the production process through computer or mobile devices where an AI-integrated Master Planner will be unified. Users can collect innovative designs from textile designers, adopt the available designs in the community, or even create their designs themselves. Based on the design, the AI will calculate the values needed for different fibres and solvent and non-fibre components and will signal these to the respective chambers. Then the accurate amount of raw materials will be progressed to the cloth manufacturing compartment or the Master Chamber.

The Master Chamber should be designed in such a way so that it can follow the additive manufacturing principle, i.e., use the raw materials precisely and no waste in the process. As mentioned before, ideally, if we consider the fibres to be used again and again, the manufacturing technique should be on the nonwoven pathway, rather than weaving or knitting. This is to retain the quality and integrity of the fibres in multiple cycles, ease of processing, production speed and reduction of cost and energy through cutting off the yarn production line (that would also be unfeasible in a domestic scenario). A possible example of such production could be robotic spraying fibres on a dummy and further robotic actions to include buttons and other parts. This could be encouraged by the current spray-on process but with higher perfection, automation and customisation. Or, the manufacturing process could be a multifaceted 3D melt extrusion where biosynthetic fine materials will be directly placed to prepare the nonwoven as per a given design, possibly through a hundred or more nozzles at a time. There could be independent nozzles for binder, as well as dedicated nozzles to supply natural and regenerated fibres, devised for anti-clogging. Either way, this will be more like an 'Advanced 3D-type Printing' where users can customise and make their clothes on demand. Users can choose whether they want a cloth from either natural, regenerated, or biosynthetic fibres or a blend. Adopting augmented reality (AR) and virtual reality (VR) within the process will allow them to see how a garment will look and fit before it is produced.

[*The form of fine 'fibre' is the key in textiles and without that, currently it is not possible to get a flexible structure by just extruding and shaping a polymer which is common in current 3D filament extrusion. For example, PLA, a common polymer used for 3D printing is rigid when printed. But the same polymer is also used to make nonwoven only after they are extruded into very fine fibrous form. Worth noting at this point that despite spinning (to produce yarn), and weaving or knitting may not be needed in the future, if fibres continue to play its fundamental role, Future Textiles may still need 'melt spinning' to produce those fine fibres from the biosynthetic polymer chips or 'wet spinning' to produce regenerated fibres from natural resources. Within this design, the material (e.g., fibre) preparation/cultivation, and colouration steps are saved to the industries, to help users get a simpler but highly tailorable experience*.]

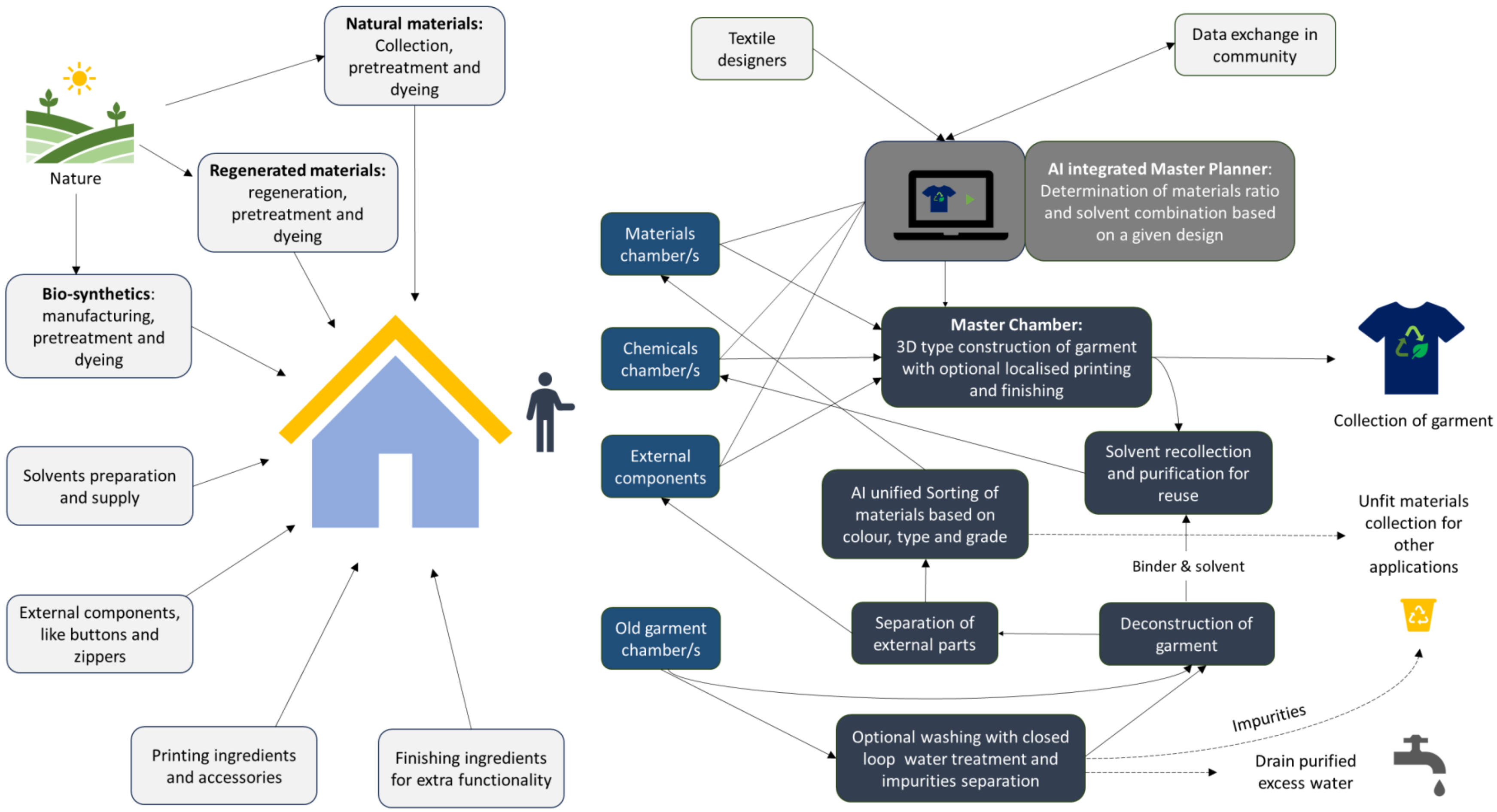

Figure 4.8: A design for home-based circular garment production probable in the future.

The Master Chamber should also have the facility for localised printing and finishing from which the users can choose one, both or none. Aside from common printing, this can also integrate conductive print to produce functionalised textiles or smart fabrics. For example, textiles that respond to environmental changes, such as temperature or moisture, like clothes that adjust their insulation properties based on the weather. This could be integrated with the finishing part where the unification of diverse functionality as per users' choice, such as stain protection to reduce the need for washing the garment. The Master Chamber will be connected to a further chamber which will collect, purify, and send the solvents back to the raw chemical chamber/s for future cycles.

The last input chamber is for old clothes, where users can put the cloth and switch on the machine with the optional function of washing, which may often be avoided if a suitable finish was used in the Master Chamber. The washing chamber will be a closed loop system for water and able to purify before discarding excess water. It will also have a microfibre filtration facility and the separated microfibres (not microplastics, as they all are biodegradable) will find their way into new applications. Currently, the microfibres generation rate is high for nonwoven but as expected within the scientific progress over future years, this will be efficiently controlled and reduced. The washed cloth (or old cloth that does not need any washing) will then be deconstructed by dissolving the binder. The binder and solvent for the binder will flow to the solvent recollection and purification chamber and be sorted towards the initial chemical chamber/s. The disintegrated fibres with non-fibre components will then progress to the next chamber where the non-fibre parts will be separated and transferred back to the non-fibre raw material chamber. The fibres will proceed into a separation process to be sorted based on types, colours, grades and quality. The sorted fibres will then be progressed to the raw fibres' chamber/s for the next cycle. The fibres that will be unqualified for further use will be directed for new applications.

To bring this concept into the real world, research is required on the nonwoven itself to make it suitable for everyday wear. Nonwoven fabrics generally have lower durability compared to woven or knitted fabrics. Progress is needed to enhance the strength and abrasion resistance of nonwoven to withstand regular wear purposes, though probably not as robust as the current woven or knitted fabrics since they will have a relatively short span of life within this circular process. Nonwovens typically lack the flexibility and softness of traditional fabrics. Studies should also focus on improving the tactile qualities, breathability, and moisture wicking of nonwoven to make them more comfortable for everyday wear.

Advances in technology could lead to faster production times, enabling quick turnarounds for custom clothing. Printing devices, relevant machines and technologies need to be designed and developed based on the mentioned specific purposes to succeed in the whole process. As the technology matures, the costs associated with such nonwoven preparation are likely to decrease, making them more accessible to a broader range of consumers. Economies of scale and improved production processes will drive this affordability.

To achieve the desired properties in nonwoven clothing, a blend of different fibre sizes may be used. For example, combining nanofibres with microfibres can provide a balance of strength, softness, and breathability. The size of the fibres can be tailored to incorporate various functional enhancements. For instance, smaller fibres can be used to improve moisture wicking and breathability, while larger fibres can add to the garment's durability and structural integrity. Further, integration of the technique more with Industry 4.0 technologies is required for better user-friendliness, effective and smart operation.

Research into new polymers and fibres that can be used in such manufacturing techniques could lead to nonwovens with improved strength, flexibility, and durability. Importantly, the fashion industry could embrace such nonwovens for their versatility and novelty. Designers could experiment with new forms, textures, and aesthetics that traditional fabrics cannot achieve.

In general, the research requirements in this segment can be summarised as:

- *Technology innovations:* For the multifaceted 3D extrusion, devices need to be tailored to such precision and hybridisation, and innovation is needed to design each of the components to efficiently and flawlessly handle their respective tasks. Progress is also needed to add further robotics for incorporating non-fibre parts into the garments. Based on the specific needs at different steps of the whole process (such as sorting, chemical purification, etc.), it is essential to develop future devices tailored to each of these requirements. The devices are required to be seamlessly integrated with current Industry 4.0 technologies, such as IoT, automation, and AI. This will ensure that they perform effectively and enhance overall productivity and accuracy through a streamlined, data-driven, and automated workflow. In the spray-on path, more precise and efficient spray systems are needed that can control the thickness, uniformity, and layering of nonwoven fabrics for better performance and aesthetics. Researching techniques for simultaneously spraying multiple components (e.g., different fibres, binders or additives) to create nonwovens with tailored properties. By all means, reducing waste during the production process should be the top priority.
- *Material development:* Exploring the production and integration of nanomaterials and micromaterials to improve the mechanical properties, texture, and functionality of nonwovens. Research is also needed to incorporate biosynthetic, natural and regenerated fibres, their mixture and the correct combination with bio-friendly solvents to offer enhanced strength, flexibility, breathability, and comfort.
- *Fabric properties enhancement:* Enhancing the durability of nonwovens to ensure they can withstand regular use without degrading at least for the short span of time required for this circular process. Improving the softness, drape, and overall comfort of nonwoven fabrics to make them suitable for everyday clothing. This includes their resistance to release microfibre during washing (if needed) to limit the waste of fibres.
- *Consumer acceptance and market viability:* Enhancing the visual appeal of nonwovens, including colour, pattern, and texture, to meet consumer preferences. Conducting studies to understand consumer perceptions, acceptance, and willingness to adopt such nonwoven garments that could ultimately look like woven or knitted garments.
- *Setting up pilot plant*: Before the concept can be practically operated by users, it is necessary to establish it in a pilot phase. This allows for fine-tuning and adjusting the settings, proving the competence and accuracy of the process. Additionally, such a setup will benefit users who prefer not to take on it at home but would like to get the service of reusing and remaking from local hubs.
- *Wear trials and testing:* Conduct extensive wear trials and testing to evaluate the performance, comfort, and durability of nonwoven garments in real-world conditions. Gathering feedback

from users to identify areas for improvement and to tailor the development of those nonwovens to meet user needs.

Overall, focusing on these specific research areas along with the research needs described in the previous sections, the potential of having nonwoven fabrics for regular textile use can be significantly advanced, leading to innovative, sustainable, cost-effective and highly functional garments in the future.

4.7 Summary

Imagine a future in which designing and creating your garments is as easy as a keystroke on your laptop or smartphone. Scroll through your library of likes. Choose for the occasion. See what it looks like on a 3D graphic model of yourself, then click print. Instantly, a machine in your laundry room begins the process of transforming your recently worn garments into new ones, using the materials to print and produce your next creation in mere microseconds. The best part? You have the freedom to change your mind at any moment and fashion another garment with a fresh design by simply placing your latest creation back into the machine.

Even now in some cities the service of making of new garments from old is already heading in the reuse direction, at least on a pilot scale or at some one-stop shops. People want to be part of a new solution and therefore technology will probably not be too far away from helping it become possible and even to do it in your own home.

To reach the full potential of Industry 4.0 in textile manufacturing, significant research and innovation are required. It is imperative to recognise the ultimate for Future Textiles and to move in that direction before it becomes critical, given the impending lack of materials for the production of textile fibre owing to the depletion of fossil fuels and the significant environmental costs associated with the procedures used in the manufacture of textiles today.

While current technologies allow for substantial automation in textile preparation, achieving both smart and sustainable processes necessitates further advancements. This is apparent that the path forward is encapsulated in five key elements of manufacturing textiles, i.e., sustainable material supply, sustainable colouration, green chemical processes, separation and reuse of the components, and circular garment production. By focusing on each of the elements, textile manufacturing can move towards a future where automation and sustainability go hand in hand, making the process not only efficient but also environmentally responsible. Establishing research and innovation hubs where manufacturers, academia, government and lateral thinkers can collaborate on contributing to such sustainable advancement will be a timely step forward.

Conclusions

The textile industry is heavily dependent on fossil fuel-based fibres and significantly contributes to environmental degradation, posing substantial risks to human and wildlife health. We now stand at a critical point where the need for sustainable practices and innovative solutions is more urgent than ever, as the demand for change is undeniably inevitable. The current production of textiles incurs a substantial environmental cost, and predictions indicate that fossil fuels may be exhausted within the next few decades. This depletion is expected to cause a significant shortage of materials needed for textile production.

To address these pressing issues, a coordinated effort involving industry stakeholders, policymakers, researchers, and consumers is essential. The following conclusions outline the necessary steps and key players required to navigate the path towards a more sustainable textile future.

Sustainable materials

Transitioning from fossil-fuel-based fibres to bio-based alternative materials is a crucial step towards sustainability. Innovations in bio-based materials, such as those derived from bacterial pathways or agricultural waste, algae, and other renewable resources can offer promising solutions. However, to make a significant impact, these alternatives need to be developed at scale and integrated into mainstream textile production. Additionally, widening the resource base to include underutilised natural fibres (such as hemp, flax other high bio-mass plants) can help diversify and stabilise the supply chain. Collaboration between research institutions, industry leaders, governments and lateral thinkers is vital to fund and accelerate the development and commercialisation of these sustainable materials.

Sustainable colouration

Traditional dyeing and printing processes are resource-intensive and contribute significantly to chemical pollution. Bacterial colourants, which utilise microorganisms to produce natural dyes, present a sustainable and scalable alternative. This eco-friendly technology can reduce the environmental footprint of textile manufacturing by minimising the use of harmful chemicals and water, and also reducing the dependence on synthetic dyes that are fossil fuel-based. To achieve widespread adoption, the textile industry must invest in upscaling bacterial colourants in both the dyeing and printing segments, ensuring they are economically viable and capable of meeting demands. Governments can play a supportive role by providing incentives for research and development in this area.

Green chemical processes

The use of hazardous chemicals in the pretreatment, dyeing, printing, finishing and other required areas poses significant environmental and labour health risks. Transitioning to eco-friendly chemicals and processes is essential to mitigate these impacts. This shift requires comprehensive research to identify and develop sustainable chemical alternatives that perform effectively in textile applications. Industry standards and regulations should be updated to mandate the use of eco-friendly chemicals, encouraging manufacturers to adopt greener practices. Collaboration between chemical companies, textile manufacturers, and regulatory bodies will be crucial to drive this transformation.

Separation and reuse

Fast fashion could become even more rapid, stylish, and entirely waste-free if the majority of textile and garment materials were designed to be reusable. Recycling of consumed textiles is complex but is a necessary process to reduce textile waste and promote a circular economy over the 20 years. Triboelectric separation, a method that uses electric charges to sort and recycle fibres, has shown promise in enhancing recycling efficiency. Advancements in this technology can improve the bonding and the separation and recycling of mixed fibre textiles, significantly reducing the amount of waste sent to landfills and incinerators. Beyond that and into the next 3 decades the future is more difficult to predict. However, whatever the next generation materials and/or technology is used will need to address all the challengers we have highlighted in this paper. Investment in research and development of triboelectric separation technologies and understanding the influence of different fibre characteristics, along with the establishment of efficient recycling infrastructure, are critical. Governments and private sector partnerships can facilitate the operation and scaling of these technologies and reduce the demand for manufacturing new fibres.

Circular garment production

The idea of circular garment production at a domestic level in the future is ambitious but feasible, as most of the necessary components are already available today. This is a matter of compiling all the elements together and upgrading the current technologies to fit the specific purpose. This must be done by taking advantage of Industry 4.0 technologies and with a keen focus on sustainability. It is also important to overcome the drawbacks of nonwoven to be successful in regular clothing applications. Efforts are needed from a wide array of stakeholders, starting from researchers from diverse areas, such as textiles, materials and chemistry, to machine design and manufacturers. The fashion industry can support this movement by offering innovative designs and meeting consumer preferences, enhancing the visual appeal involves improving elements like colours and patterns. Partnerships are essential among research institutions, industry leaders, and governments to plan, finance and expedite the development and commercialisation of such new technology.

Key players and their roles

- Industry leaders: Seed producers, farmers, biomass processors, and fine fibre manufacturers—must work together with textile manufacturers, fashion brands, and chemical companies to ensure a seamless, eco-friendly supply chain. They need to invest in sustainable technologies and practices, collaborate on research and development, and adopt circular economy principles. Their commitment and innovation are crucial to driving industry-wide change.
- Governments and regulatory bodies: Policymakers must implement regulations that mandate sustainable practices, provide incentives for research and development, and support infrastructure for reuse, recycling, and bio-based materials (e.g., fibre) production. Governments and regulatory bodies must also advocate for the development of standards, testing methods, and guidelines to support sustainability in the industry. International cooperation is essential to address the global nature of textile pollution and resource depletion.

- Research institutions: Academic and research organisations play a critical role in developing new technologies, bio-based materials, eco-friendly chemicals, and efficient reuse methods. Collaborative efforts between research institutions and industry can accelerate the commercialisation of sustainable innovations. When successful, the financial rewards for achieving the ultimate need will be enormous.
- Consumers: Public awareness and consumer behaviour are powerful drivers of change. Consumers can influence the market by choosing sustainable products, participating in circular fashion practices, and advocating for transparency and sustainability in the textile industry.
- Non-governmental organisations (NGOs): NGOs can raise awareness about the environmental impacts of the textile industry, advocate for policy changes, and support initiatives that promote sustainability and corporate accountability.

Conclusion: A sustainable path forward

The textile industry faces a dual challenge of environmental degradation and resource scarcity. Addressing these issues requires a comprehensive and collaborative approach involving all stakeholders. By developing sustainable materials, upscaling bacterial dyeing and printing, replacing hazardous chemicals with eco-friendly alternatives, advancing dry separation technologies, and promoting circular garment production, the industry can significantly reduce its environmental footprint and march towards a sustainable healthy future.

The journey towards sustainability is complex and requires sustained effort and innovation. However, the potential benefits—for the environment, society, and the economy—are immense. By embracing sustainable practices, the textile industry can not only mitigate its negative impacts but also become a leader in the global movement towards a more sustainable and resilient future.

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Glossary of Terms

A

Acetate	Regenerated fibre made from cellulose acetate. It is a type of rayon.
Acid dye	Type of dye that is water-soluble and typically used to colour animal-based fibre (such as wool, silk) and some synthetic fibres.
Acrylic	Synthetic fibre made from polyacrylonitrile, known for its wool-like feel.
Additive manufacturing	Process of creating objects by successively adding material layer by layer based on a digital model. This technology is known for precise use of raw materials and minimal waste generation.
Adsorption	Process used in wastewater treatment where contaminants are removed from water by adhering to the surface of a solid material, known as an adsorbent.
Aerobic process	Biological treatment method that uses oxygen to break down organic matter.
AI	Artificial intelligence, refers to the simulation of human intelligence in machines that are programmed to think and learn like humans.
Anaerobic process	Biological treatment method that breaks down organic matter in the absence of oxygen.
Azo dye	Class of dyes characterised by the presence of one or more azo groups within their chemical structure.

B

Bacterial cellulose	Cellulose produced by certain species of bacteria, such as *Acetobacter xylinum*. It differs from plant-derived cellulose in its ultrafine nanofibrillar structure and purity.
Bacterial colourants	Natural dyes obtained through fermentation processes where bacteria assist in the creation of dyes.
Basic dye	Positively charged dyes typically bond with materials that have a negative charge, such as wool, silk and acrylic fibres.
Binder	Chemical substance or adhesive used to bond fibres together during the manufacturing process (nonwoven), or pigments to fibres (printing).
Bleaching	Chemical process to prepare textile materials for dyeing or printing processes by ensuring a uniform base colour. It removes the natural colour of fibre.
Blow room	Initial processing area of fibres to open, clean and blend before being processed further into yarn.
Breathability	Ability of textiles to allow air and moisture vapour to pass through them, enhancing comfort by promoting airflow and moisture evaporation.

C

CAGR	Compound annual growth rate, a measure used to determine the average annual growth rate of an item over a specified period.

Carding	Process of aligning and cleaning raw fibres, such as cotton, to prepare them for spinning into yarn.
Carbon footprint	Total amount of greenhouse gases, mainly carbon dioxide, produced directly and indirectly by human activities.
Cellulose fibre	Fibres derived from cellulose, which is the main structural component of plant cell walls.
Chambray	Lightweight woven fabric, typically made from cotton or a cotton blend.
Cobots	Collaborative robots, designed to work alongside humans in a shared workspace or environment.
Combing	Process used to align and remove short fibres and impurities from natural fibres. This process improves the quality and strength of the yarn and deliver smoother and finer yarns suitable for high-quality textiles.
Cotton	Natural fibre harvested from the seedpods of the cotton plant, which belongs to the genus *Gossypium*.
Count	Numerical system used to express the fineness or thickness of yarn.

D

Degree of polymerisation	Number of monomer units (typically repeating units) in a polymer chain.
Depolymerisation	Process of breaking down large polymer molecules into smaller units or monomers.
De-sizing	Process where sizing agents applied to yarns or fabrics during weaving are removed.
Digital twin	Virtual representation or model of a physical object, process, or system.
Direct dye	A water-soluble dye applied under alkaline conditions in textile industries for their ease of application and bright colours.
Disperse dye	Class of synthetic dyes that are primarily used to colour synthetic fibres such as polyester, nylon, and acetate.
Down	Soft, fluffy cluster of fibres found underneath the outer feathers of ducks and geese.
Double-knit	Knitted fabric created by knitting two sets of yarns simultaneously on the same needle bed.
Drape	The way fabric hangs or falls when it is draped over or worn on the body.
Dry-laid nonwoven	Produced by laying fibres randomly or in a controlled manner onto a moving conveyor or belt. This process does not involve the use of water or solvents.
Dyeing	The process of colouring a material, such as textiles.

E

Effluent	Wastewater or liquid waste discharged from industrial processes.
Enzyme	Biological molecules, typically proteins, that act as catalysts in biochemical reactions.
Eutrophication	Situation when lakes, rivers, and coastal areas suffer oxygen depletion from nitrogen and phosphorus buildup, harming water quality and ecosystems.

Extrusion	Manufacturing process where a material, often in the form of a pellet, is forced through a die to create a continuous profile or shape with a consistent cross-section.

F

Fast fashion	Rapid production and turnover of inexpensive clothing collections by fashion retailers to keep up with the latest trends.
Felt	Textile material that is produced by matting, condensing, and pressing fibres together.
Fibre	A slender, thread-like structure or material that is the fundamental building block of textiles.
Filament	Continuous form of fibre, often made from a synthetic material such as polyester or nylon.
Finishing	Series of processes applied to fabrics to improve their aesthetics and/or functionality, such as texture, performance, or durability.
Flannel	Soft woven fabric known for its brushed surface, which creates a soft and fuzzy texture.
Flax	Fibres obtained from the stem of the flax plant. This is also known as linen fibre.
Flyer	Rotating component on a spinning machine that guides yarn onto a bobbin during the spinning process.
Fossil Fuel	Natural non-renewable energy resources formed from the remains of ancient organisms over millions of years. They include coal, oil, and natural gas.

G

GHG	Greenhouse gas, these gases, such as carbon dioxide, methane, and nitrous oxide trap heat in the Earth's atmosphere, leading to the greenhouse effect.
Gin	Machine used to separate cotton fibres from their seeds.

H

Hemp	Fibre derived from the stems of the hemp plant (*Cannabis sativa*)
Hyperspectral camera	Advanced imaging device capable of capturing and analysing a wide range of wavelengths across the electromagnetic spectrum.
Hypoallergenic	Products that are less likely to cause allergic reactions in individuals

I

Industry 4.0	Fourth Industrial Revolution, refers to the ongoing automation and digitalisation of manufacturing and industrial processes.
Injection moulding	Manufacturing process used to produce parts by injecting molten material into a mould.
Ionic liquids	Class of salts that are liquid at relatively low temperatures, often below 100°C. They are valued for their ability to dissolve a wide range of substances, including organic compounds and polymers.

IoT	Internet of Things, network of physical devices, instruments, appliances, and other items embedded with sensors, software, and connectivity that enables them to connect and exchange data over the internet.

J

Jacquard	A weaving technique named after its inventor, Joseph Marie Jacquard. The key feature is its ability to control individual warp threads independently, enabling the creation of complex designs and patterns.
Jute	Fibre derived from the stems of the jute plant (*Corchorus olitorius* and *Corchorus capsularis*)

K

Knitting	Method of creating fabric by interlocking loops of yarn with needles

L

Latch needle	Type of needle used in knitting machines. It has a latch mechanism that allows the needle to hold and release the yarn during the knitting process.
Life cycle analysis	Methodology used to evaluate the environmental impacts of a product, process, or service throughout its entire life cycle.
Loom	Device used for weaving fabric by interlacing threads or yarns.
Lyocell	A type of regenerated cellulose with sustainable closed-loop manufacturing process.

M

Machine learning	Branch of artificial intelligence that focuses on developing algorithms and statistical models that enable computers to learn from and make predictions or decisions based on data.
Melt spinning	Manufacturing process used to produce synthetic fibres by melting polymer pellets and extruding them through spinnerets to form continuous filaments.
Microplastics	Tiny plastic particles less than 5 mm to nano sized, often smaller than the eye can see.
Mycelium	Vegetative part of a fungus, consisting of a network of branching, thread-like hyphae.
Myxomycetes	Known as slime moulds, are a diverse group of organisms that belong to the kingdom Protista or sometimes considered a group between fungi and protozoa.

N

Nanotechnology	Science, engineering, and application of materials and devices at the nanoscale, typically ranging from 1 to 100 nanometres.
Needle punching	Manufacturing process used to mechanically interlock fibres to create nonwoven fabrics or textiles.
Nonwoven	Fabrics that are manufactured by bonding or interlocking fibres together without weaving or knitting.

Nylon	Nylon is a synthetic polymer and the first ever true synthetic fibre developed.

O

Organic cotton	Cotton grown using methods and materials that have a low impact on the environment. This involves practices such as crop rotation to maintain soil health, and the absence of synthetic pesticides, herbicides, and fertilisers.
Oxidation	Chemical reaction in which a substance loses electrons, often associated with the addition of oxygen or the loss of hydrogen.
Ozonation	Process that involves the infusion of ozone (O_3) into water.

P

PBAT	Polybutylene adipate-co-terephthalate, polymer made from adipic acid, 1,4-butanediol, and terephthalic acid.
PBS	Polybutylene succinate, aliphatic polyester synthesised from succinic acid and 1,4-butanediol.
PBSA	Polybutylene succinate-co-adipate, copolymer made from the polymerisation of succinic acid, adipic acid, and 1,4-butanediol.
PE	Polyethylene, common thermoplastic polymer made from the polymerisation of ethylene monomers. It is one of the most widely produced plastics in the world.
PET	Polyethylene terephthalate, the major polyester type made from the polymerisation of ethylene glycol and terephthalic acid. It is widely used in the textile and packaging industries.
PHA	Polyhydroxyalkanoates, polymers produced naturally by microbial fermentation of renewable carbon sources like sugars or lipids.
PHB	Poly(3-hydroxybutyrate), biodegradable polymer belonging to the polyhydroxyalkanoate (PHA) family. It is synthesised naturally by bacteria.
PHBV	poly(3-hydroxybutyrate-co-3-hydroxyvalerate), copolymer within the polyhydroxyalkanoate (PHA) family. It is produced through microbial fermentation using bacteria capable of synthesising both 3-hydroxybutyrate (3HB) and 3-hydroxyvalerate (3HV) monomers.
Pilling	Formation of small, tangled balls of fibres on the surface of fabric. It occurs when loose fibres on the fabric surface tangle together due to friction and abrasion during wear and use.
PLA	Polylactic acid, aliphatic polyester derived from renewable resources such as corn starch, tapioca roots, or sugarcane.
Plasma treatment	Surface modification technique used to enhance the adhesion, wettability, and other surface properties of materials, such as fabric. Plasma generates highly reactive species like ions, electrons, and free radicals that interact with the surface.
PLC	Programmable logic controller, industrial digital computer designed for controlling manufacturing processes, machinery, and other automation applications.
Poplin	Plain-weave fabric characterised by a tight, closely woven structure.

PP	Polypropylene, thermoplastic polymer made from the polymerisation of propylene monomers.
Printing	Process of applying designs, patterns, or images onto particular areas of fabrics
Protein fibre	Natural fibres derived from proteins found in animal sources, such as wool and silk.
PVC	Polyvinyl chloride, synthetic thermoplastic polymer made from vinyl chloride monomers.

R

Ramie	Natural fibre obtained from the stem of the ramie plant, a member of the nettle family.
Rayon	Semi-synthetic fibre made from regenerated cellulose. It is produced by dissolving cellulose (usually from wood pulp or bamboo) in a chemical solution and then extruding the solution through spinnerets to form fibres.
Raschel knitting	Type of warp knitting where the fabric is created by interlocking loops vertically along the length of the fabric.
Reactive dye	Type of synthetic dye designed for use on cellulosic fibres (such as cotton, flax, and rayon). These dyes chemically react with the fibre molecules to form a covalent bond.
Regenerated cellulose	Cellulose derived from natural sources, such as wood pulp, that has been chemically processed to dissolve the cellulose fibres into a solution.
Retting	Process used to separate fibres from the woody stalks of plants such as flax, hemp, and jute.
RFID	Radio-frequency identification, technology that uses electromagnetic fields to automatically identify and track tags attached to objects.
Ring frame	Machine used in the textile industry for spinning yarn from fibres such as cotton, wool, or synthetic fibres.

S

Scouring	Process of cleaning and removing impurities such as oils, waxes, and dirt from natural fibres or fabrics using hot water, detergents, and alkalis.
Seamless knitting	Method of knitting where garments are produced without seams, using specialised knitting machines that create tubular or three-dimensional garments in one continuous process.
Short staple	Fibres in textiles that are relatively short in length, e.g., 2 to 5 cm.
Shuttle	A tool that carries the weft thread through the shed created by the heddles (devices that separate and control the warp threads) during weaving.
Silk	Natural fibre produced by silkworms to form their cocoons.
Simulation	Process of creating a model of a real-world system or process and performing experiments or scenarios to understand its behaviour or predict outcomes.
Sisal	Natural fibre derived from the leaves of the *Agave sisalana* plant.

Sizing	Process where a protective or strengthening agent, called sizing or size, is applied to yarns before weaving.
Sliver	Continuous strand of loosely assembled fibres that have been carded and sometimes combed to align the fibres in a parallel arrangement.
Spandex	Also known as elastane or Lycra (a brand name), is a synthetic fibre known for its exceptional elasticity.
Spinning	Process of converting fibres into yarn.
Spindle	Cylindrical rod or shaft used in spinning machinery to twist fibres into yarn.
Spindle picking	Mechanised method of harvesting cotton where a spindle picker machine is used to mechanically pick cotton from the plants.
Spinneret	Small device used in the production of synthetic fibres and filaments. It consists of a metal plate or tube with fine holes through which a viscous polymer solution or melt is extruded.
Spool	Cylindrical device or bobbin around which yarn, or thread is wound for storage, transport, or processing.
Spray-on cloth	Concept where liquid fabric is sprayed onto a surface and transforms into a solid fabric upon application.
Spun-laid nonwoven	Nonwoven material made by extruding synthetic fibres into a continuous web and then bonding them together through heat, pressure, or adhesives.
Stripper harvesting	Cotton harvesting involves a machine known as a cotton stripper that mechanically removes cotton from the plants.
Sulphur dye	Dyes containing sulphur atoms in their chemical structure.
Synthetic dye	Dyes that are chemically synthesised in laboratories rather than being derived from natural sources.
Synthetic fibre	Manmade fibres produced from polymers or other synthetic materials.

T

Three-dimensional	Often referred as 3D, objects or representations that have three dimensions: length, width, and height.
TPU	Thermoplastic plasticised starch, biodegradable polymer derived from starch.
Triboelectricity	Generation of electric charge through friction or contact between two dissimilar materials.
Tricot knitting	Warp-knitting that produces fine, smooth texture and distinct diagonal ribs on the face of the fabric.

U

Urbanisation	Process of population concentration and growth in urban areas, typically involving the movement of people from rural to urban areas.

V

V-bed knitting	Knitting machine configuration where the needles are arranged in a V-shaped bed.
Viscose rayon	The major type of rayon, often referred to simply as viscose.

W

Warp yarns	Set of yarns that are stretched lengthwise on a loom.
Warping	Process in weaving where the warp yarns are wound onto a beam in preparation for the loom.
Weaving	Method of textile production in which two sets of yarns, known as the warp and weft, are interlaced at right angles to create fabric.
Web of Science	Multidisciplinary citation database and research platform provided by Clarivate Analytics. It indexes and provides access to high-quality research literature across various scientific disciplines.
Weft yarn	Yarn that runs horizontally across the width of a woven fabric.
Wet-laid nonwoven	Type of nonwoven material produced by suspending fibres in a water-based solution, forming a fibre slurry or pulp.
Wet processing	Series of textile manufacturing processes that involve the use of water and various chemicals to treat fabrics or fibres to achieve desired characteristics, such as colour and finish.
Wet spinning	Process used in the production of synthetic fibres, particularly those that are dissolved in a solvent before being extruded, such as regenerated cellulose fibres.
Wool	Natural fibre derived from the fleece of sheep.
Woven fabric	Textile produced by weaving.

Y

Yarn	Continuous strand of fibres that are twisted or spun together to form a long, thin thread used in weaving, knitting, or sewing.