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The role of bio-based textile fibres in a circular and sustainable textiles system

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1 Introduction

The global supply and demand for textile products continues to rise (EEA, 2022a; ETC/CE, 2022a). This is fuelled by factors such as fast-fashion business models, the growth of the world's population and economy, rising income per capita and increasing urbanisation.

Inevitably, and as a result of global supply and demand, the textiles industry is facing huge challenges regarding its resource use, and environmental and climate impacts, which remain largely unsustainable, as shown in briefings by the European Environment Agency (EEA) and underpinning reports by its European Topic Centre on Circular Economy and Resource Use (ETC/CE).

Over the last two decades, global textile fibre production has almost doubled from 58 million tonnes in 2000 to 109 million tonnes in 2020 and is projected to grow to 145 million tonnes by 2030 (Textile Exchange, 2021). The EEA briefing *Textiles in the environment: the role of design in Europe's circular economy* (EEA, 2022a) and its underpinning ETC report ([1]) (ETC/CE, 2022a) highlighted that EU's textiles consumption ranks third in terms of land and water use – food is the frontrunner – and fifth in terms of greenhouse gas (GHG) emissions and raw materials use. It was estimated that in 2020 the production of textile products in the EU consumed 4 000 million cubic metres (m^3) of water and generated 121 million tonnes carbon dioxide equivalent (CO_2-eq.) (ETC/CE, 2022a; EEA, 2022a).

As stated by the European Commission, "*the growing demand for textiles is stimulating the inefficient use of non-renewable resources, including the production of synthetic fibres from fossil-fuels*" (EU Strategy for Sustainable and Circular Textiles, 2022). The new EU strategy for sustainable and circular textiles aims for impact reduction and a deviation from fast fashion, by stating that "*fast fashion is out of fashion*". Spurred by the aspiration to reduce the use of fossil resources and emissions of greenhouse gases, the search for alternative fibres, based on renewable (bio-based) resources, is gaining momentum.

It is a common assumption that by changing the origin of carbon in the fibre backbone to a renewable source, the environmental and climate impacts of the obtained product will be reduced. However, it is important to acknowledge that a fashion and textile industry relying more heavily on bio-based fibres will face its own sustainability challenges. The impacts of textile fibres are multifaceted and while certain alternatives may appear sustainable and circular at first sight, they may bring unintended consequences. To assure true sustainability, a careful assessment of the environmental and social impacts of bio-based fibres is in order.

While bio-based fibres are gaining interest, comprehensive literature on the many different fibres and their impacts is scattered and rather scarce. Some of the main environmental concerns associated with bio-based fibres include their environmental impacts, water and land use, feedstock competition, agricultural intensity, recyclability and microfibre release. These aspects, along with others, need further consideration and require both a systemic and a tailored approach to better understand the merits and drawbacks of bio-based textiles before bolder upscaling actions are undertaken.

The aim of this paper is to provide an overview of important aspects that need to be considered within the context of bio-based fibres and shed light on the environmental sustainability aspects related to bio-based alternatives. Furthermore, social impacts are critical for a sustainable textile industry as well, however, these lie beyond the scope of this report.

While the impacts of fossil-based synthetic textiles were analysed by the EEA and ETC (EEA, 2021; ETC/WMGE, 2021), this paper aims to provide a brief but comprehensive overview on the current state

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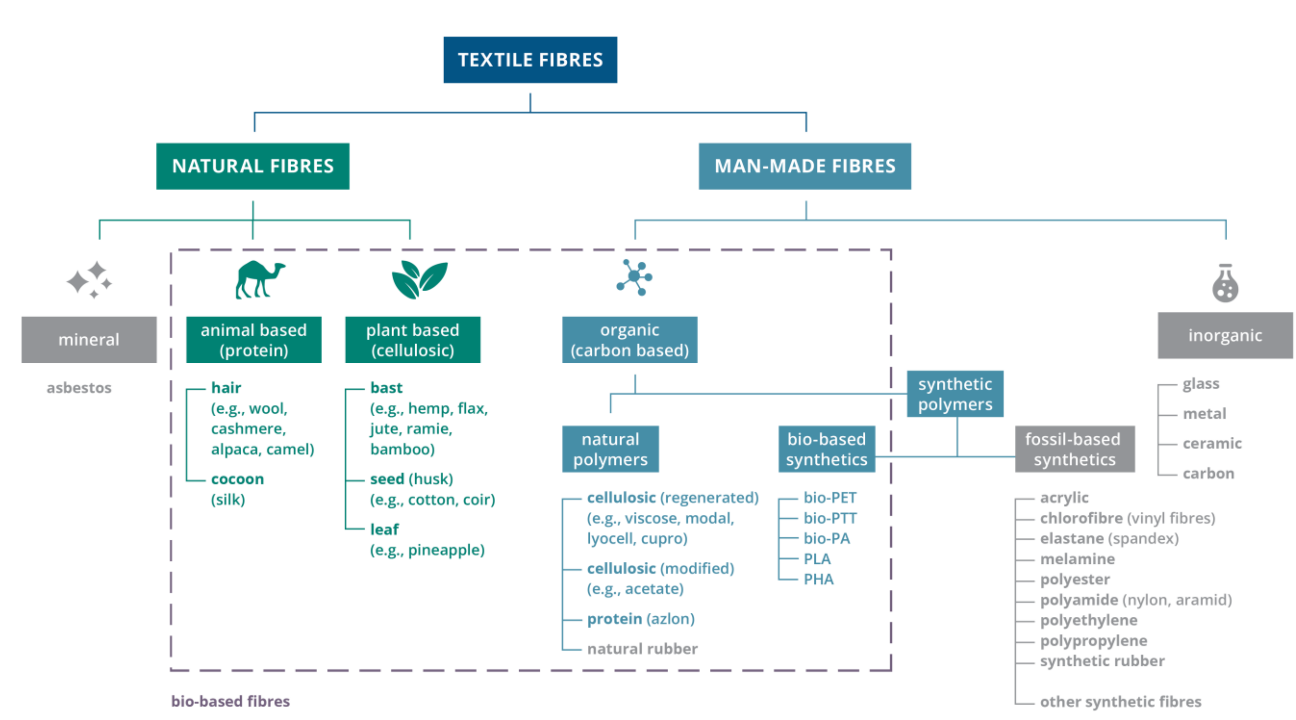
[1] Eionet Report No. ETC/WMGE 2022/2 *Textiles and the environment: The role of design in Europe's circular economy*

and knowledge of bio-based fibres, both natural and synthetic, with special attention for sustainability considerations. First, an overview is provided on the most used bio-based fibres in Europe and worldwide, based on market share as well as on innovation potential. Second, trends concerning the production and consumption of the most significant bio-based fibres are described. Thirdly, a subset of environmental pressures associated with fibre production are discussed, as well as issues related to agricultural intensity, durability and biodegradability, recyclability and microfibre shedding. Finally, the main conclusions are provided along with some future perspectives.

2. Types of bio-based fibres

This chapter provides an overview on the most used natural and man-made bio-based fibres, while at the same time shedding light on the definition and classification of bio-based fibres and summarising their properties and applications (Table 1 and Table 2).

Figure 1 Scope of this paper



Source: EEA and ETC/CE

For textiles, the term "bio-based" refers to the origin of the carbon backbone of the fibre polymer and whether this comes from a renewable source. For example, the carbon content of conventional synthetic fibres such as polyester, is derived from non-renewable fossil fuels – petroleum, gas, coal – while fibres derived from natural polymers such as cellulose are made from 100 % renewable carbon content. Due to a lack of standardisation, the term "bio-based" is often misused and misunderstood. This is currently being considered by the European commission within the context of the Regulation on Ecodesign for Sustainable Products. Throughout this paper, bio-based fibres are defined as fibres with a carbon backbone that is fully derived from a renewable, natural source, whether natural or man-made (Figure 1).

2.1. Natural fibres

One major group of bio-based textile fibres are natural fibres (Table 1). As the name implies, natural textile fibres are made from natural resources. These can be animal fibres, thus protein-based, such as silk and wool; or plant fibres, and therefore mainly derived from cellulose, for example, cotton, linen, hemp and ramie. Cellulose is one of the main structural components of plants and therefore the most abundant polymer found in nature (Ganster and Fink, 2021). Natural textile fibres, such as hemp and linen, are among the oldest textile fibres used.

Wool and **silk** (Table 1) are the best-known natural protein fibres. As a versatile fibre, wool is the most widely and commonly used animal fibre. Even though its production is rather limited, high-value wool and wool blend products, such as suits, sweaters and carpets, still hold prominent economic and social value (Erdogan et al., 2020). Sheep produce the highest amount of wool fibre per unit of pasture area. Wool fibre diameters can range from 11 micron for fine Australian Merino to 100 microns for wool from sheep originating in the northern hemisphere (Kuffner and Popescu, 2012). Wool fabrics are breathable and can absorb and release moisture. Wool has excellent insulation properties and is naturally flame retardant. In contrast to synthetic fibres, wool can regulate body heat by offering warmth when it is cold, while releasing heat and moisture when temperatures increase (Erdogan et al., 2020; Kuffner and Popescu, 2012). Moreover, wool fibres absorb odours, hence garments made out of wool(blends) remain fresh for much longer, reducing washing cycles (Swan, 2020; Wang et al., 2019). Due to these properties, wool is used in a wide range of textile applications, namely (protective) apparel, sportswear, home textiles, medical textiles, geotextiles, transportation and military textiles (CSIRO Textile and Fibre Technology, 2017).

Another natural protein fibre is **silk**, which is obtained from insects. This highly valued natural fibre has been used in textiles for at least 5 000 years (Babu, 2012). Even though many insects produce silk, more than 90 % of commercially produced silk is derived from the extrusion spun by the silkworm *Bombyx mori* that exclusively eats mulberry leaves (Astudillo et al., 2014). Silkworm fibre is a relatively strong, lustrous fibre that contributes to the softness and comfort of fabrics (Padaki et al. 2015). Silk is the only natural fibre available in a filament form (Padaki et al., 2015). Prolonged exposure to higher temperatures leads to strength loss and with the action of abrasive force, fibrillation can occur, damaging the silk fibre (Padaki et al., 2015). Even though silk has encountered competition from synthetic fibres, it has maintained its dominance in the production of luxury clothing. It has good absorbency and contributes to the drapability of fabrics. For these reasons silk is used in a wide variety of textile applications, ranging from pyjamas and wedding gowns to skiing garments and summer wear, as well as home textiles and medical uses (Babu, 2012).

Among the natural fibres, plant-based fibres comprise the largest group accounting for approximately one third of the global textile market, which is dominated by **cotton** (24 %) (Textile Exchange, 2021). Cotton fibres are seed-derived and consist mainly of cellulose (95–99 %). This natural fibre is water absorbent and can contribute to the softness and lightness of fabrics, cotton fibres are used in a wide range of textiles, such as clothing, home textiles and furnishing (Table 1) (Krifa and Stevens, 2016).

Cotton is, by far, the most used natural fibre. However, with the projected stagnation of cotton production and rising demand, there is a strong need for alternative fibres, such as bast fibres or man-made cellulosic fibres (Felgueiras et al. 2021; Paulitz et al., 2017).

Bast fibres (Table 1) are typically derived from the stem of the vegetative stalk of the plants such as jute, flax, ramie and hemp.

After cotton, **jute** (Table 1) is the next most-used natural fibre in terms of global production (Textile Exchange, 2021). Even though it is coarse, rigid and inelastic, its strength, low cost and good friction and insulation properties make it suitable for the manufacture of twines, ropes, matting and packaging materials (Muzyczek, 2020; 2012; Kozłowski et al., 2012). Another natural fibre with a relatively large market share amongst the alternative natural fibres is **coir** or coconut fibre (Textile exchange, 2020). This is a thick natural fibre and has high microbial resistance, making it a suitable fibre for (geo)technical applications. The main uses of this seed-husk fibre include sacking, floor-coverings, mattresses and geotextiles (Banerjee, 2020; Mishra and Basu, 2020). In combination with rubber, coir is used in mattress fillings, automobile seats, sofas, etc.

Hemp (Table 1) is derived from the stem of the fast-growing plant *Cannabis sativa L.* that provides high fibre yields and displays low pest-susceptibility (Duque Schumacher et al., 2020). It has been cultivated in Europe for centuries, mainly intended for producing textile, ropes, paper, and sails. The plant can grow under versatile weather conditions and almost everywhere in Europe. It provides both long and short fibres, that can fit different applications in various sectors, including textile. It offers high moisture absorbency, ultraviolet (UV) protection and contributes to fabric breathability. Moreover, hemp fibres are typically hypo-allergenic (Ahmed et al., 2022). While long hemp fibres are most desirable in terms of the favourable characteristics mentioned above, short hemp fibres obtained after decortication, have a high "cottonisation" potential, meaning that lignin content can be reduced to obtain soft and workable textile fibres that can be processed using available cotton and wool systems. While textiles made of cottonised hemp can be more resistant to wrinkling, some of the beneficial features like high tensile strength, cool touch and bioactivity are lost (Zimniewska, 2022). Nevertheless, an important bottleneck associated with hemp, as well as with some other natural fibres, is the lack of homogeneity concerning repeatability of fibre properties. This creates difficulties in terms of fibre processing. At the same time, hemp spinning is not an attractive direction for machinery producers, resulting in the lack of specialized machines required for the completion of the technological line, improved productivity and economic viability (Zimniewska, 2022). Therefore, technological development is essential for the successful production of hemp textiles in Europe (Zimniewska, 2022; van der werf 2008).

Another bast-fibre is **flax** (Table 1). This fibre is derived from the *Linum usitatissimum* plant which grows up to 60 cm tall and has slender but very fibrous stems. This food and fibre crop has been cultivated for millennia for different uses including paper, oil, composites and textiles, typically linen (Dhirhi et al., 2015). Due to its high moisture absorption, low heat retention, durability and comfort, linen fabric is highly valued by designers and used both in casual and luxury wear (Muzyczek, 2012). In general, flax is grown in areas where the daily temperature remains below 30 °C. Flax cultivation requires about 700 mm of rain per year, ideally evenly spread throughout the year. This accounts for the success of this crop in temperate and maritime areas such as coastal Western Europe (Turenen and van der Werf, 2006).

In addition, linen maintains a strong niche in high quality household textiles. Both flax (linen) and hemp are fibres of interest in a European context as they grow well in temperate climates, while cotton cultivation is restricted to the most southern European countries (van der Werf and Turunen, 2008). In this sense, their economic and social value should be duly considered in the framework of a possible repatriation of the fibre and textile value chain to Europe.

Ramie fibre (Table 1) is one of the oldest natural textile fibres and is mainly grown in China. Similar to other bast fibres, ramie fibre is extracted from the stems of *Boehmeria nivea*. Ramie is adapted to a wide range of latitudes and can be grown in tropical, subtropical and temperate regions. Under optimal growth conditions, this perennial plant can be harvested up to six times a year (Roy and Lutfar, 2012a). This white coloured bast fibre, also known as China grass, is very strong (Roy and Lutfar, 2012a). Strikingly, ramie has a high cellulose content which can range up to 90 %, approaching the cellulose content of cotton (Lyu et al., 2021). The amount of cellulose positively affects the mechanical properties and application value of natural fibres (Lyu et al., 2021). In addition to being one of the strongest and longest natural fibres, ramie has great thermal stability and is resistant to losing its shape, shrinking and microbial attack. In appearance, ramie fabrics are lightweight, shiny and similar to linen (Rehman et al., 2019). Ramie is often appreciated in summer clothing and used in very fine upper garments, but also in home textiles. The coarser ramie fibres are used in twines and threads and are very useful for making fishing nets. Blended with wool, ramie reduces shrinking and it can be used to improve lustre and strength of cotton (Roy and Lutfar, 2012a). On the other hand, ramie has very low elasticity, low abrasion resistance, stiffness, brittleness and requires degumming ([2]) (Roy and Lutfar, 2012a).

The potential of bast fibres, such as ramie, flax and hemp, has not, however, been fully exploited due to various techno-economic reasons. The use of these fibres is mainly limited by their unfavourable spinning properties, i.e., their thickness, low uniformity, stiffness and low elongation, which bring higher costs and

[2] Degumming, also referred to as retting, is a necessary step in bast-fibre processing that separates the cellulose from non-cellulose parts (Lyu et al., 2021).

require more skill (Muzyczek, 2012; 2020; Roy and Lutfar, 2012a). Hence, technical innovation is required to efficiently extract the fibres from gathered crops and further research is needed to improve the understanding and methods of retting (degumming ([2])) these materials to achieve consistent fibre grades. The West-European flax sector, for example, has worked intensively for the last decades to maximise the yield of long fibres and is now harvesting the fruits of this development (van der Werf and Turunen, 2008).

A summarizing overview of the main natural fibres is presented in Table 1.

Table 1 Overview of examples of characteristics and applications of the main natural fibres

Fibre	Carbon backbone	Examples of favourable characteristics	Examples of unfavourable characteristics	Applications	Examples of main producing countries	Source
Cotton	Seed	breathable[1] moisture absorbency strong soft[1], comfort[1]	photoyellowing photodegradation prone to creasing[1] slow drying[1] susceptible to mildew	apparel baby clothing home textiles furnishing	**Long staple cotton:** Egypt and USA **Medium staple cotton:** Central Asia, Europe (Greece, Spain), West Africa, USA, Brazil, Middle East, Pakistan **Short staple cotton**: India, USA, Central Asia	Krifa et al., 2016 Salleh et al., 2021 Dochia et al., 2012
Jute	Bast	strong low cost sound and heat insulating[1] dimensional stability[1]	coarseness stiffness[1] harsh feel[1] high fibre shedding photoyellowing creasing[1] low extensibility poor washability[1]	packaging furnishing upholstery carpets home textiles geotextiles automobile textiles	India Bangladesh China Nepal Myanmar Thailand Brazil	Banerjee, 2020 Roy and Lutfar, 2012b
Coir	Seed husk	microbial resistance sound and heat insulating[1] high elongation	short fibre length low stretchability thickness low tenacity at break	sacking floor coverings mattresses geotextiles automobile seats sofas	India Sri Lanka Vietnam	Mishra et al., 2020 Banerjee, 2020
Hemp	Bast	moisture absorbency hypoallergenic[1] heat regulation[1] UV protection[1] microbial resistance resistant to deformation breathable[1]	stiffness[1] thickness heterogeneity low elongation	apparel (socks (antibacterial), denim, etc.) ropes canvas sails	China France Netherlands Lithuania Romania	Ahmed et al., 2022 Muzyczek et al., 2012 Schumacher et al., 2020

Flax	Bast	strong breathable[1] moisture absorbency durability[1] lustre smooth[1], soft[1] resistant to deformation[1] heat regulation[1]	low elongation low stretchability heterogeneity (colour, strength) rigidness	casual wear luxury wear summer wear belts straps cords threads	Europe (France, Belgium, Netherlands) Belarus Russia China (main importer of raw European flax for processing)	Kozłowski et al., 2012 Muzyczek et al., 2012
Ramie	Bast	strong lightweight[1] breathable[1] long fibre moisture absorbency resistant to shrinkage[1] quick drying[1]	very low elasticity low abrasion resistance stiffness[1] brittleness[1]	apparel (suits, shirts, dresses, etc.) home textiles twines threads fishing nets	China	Roy and Lutfar, 2012a Rehman et al., 2019
Wool	Hair	breathable[1] moisture absorbing flame retardant good insulation[1] heat regulating absorbs odours	low abrasion resistance moth infestation	apparel (suits, sweaters, winterwear protective apparel, sportswear, etc.) home textiles medical textiles	Australia, China New Zealand, India, South Africa Argentina, UK Mongolia Uruguay	Kuffner and Popescu, 2012 Wang et al.,2019 Erdogan et al., 2020 Swan, 2020
Silk	Cocoon	strong comfort (soft feel)[1] heat regulating durability[1] drapability[1] lustre	photoyellowing and degradation water damage insect infestation microbial infestation high cost static	apparel (luxury wear, fine garments, wedding gowns, etc.) home textiles medical textiles	China India	Babu et al., 2012 Padaki et al., 2015

[1] Fibre characteristics can contribute to this fabric characteristic
[2] Nonwoven applications such as hygiene and medical materials, filters, wipes, etc.

2.2. Man-made bio-based fibres

Over the past decades, many different types of man-made fibres have been developed and mass produced, outweighing natural fibres. Most man-made fibres used in textiles are organic, meaning their backbone is made of carbon-based polymers. These carbon-based polymers can be chemically synthetised or be derived from natural polymers. For example, regenerated cellulose is obtained from a natural polymer that is processed into textile fibres via chemical dissolution of plant parts into dissolving pulp and subsequent fibre regeneration through spinning. That is why regenerated cellulose fibres are considered man-made fibres, but they are still of natural origin. Synthetic polymers, on the other hand, are obtained through chemical synthesis. The input materials for this polymer synthesis are mostly fossil-based resources such as oil and natural gas, but they can also be of bio-based origin, such as sugars or starch. Polyester (polyethylene terephthalate (PET)) is the most used synthetic fibre (EEA, 2021; ETC/WMGE, 2021). While conventional polyester is fossil-based, its carbon backbone can also be derived from biomass, such as maize starch. These so-called bio-based synthetics can be defined as a separate category within bio-based textile fibres (Figure 1) (Textile Exchange, 2022).

While fossil-based synthetic fibres, such as polyester and nylon, make up most of the man-made textile fibre market, bio-based synthetics and especially regenerated cellulosic fibres are gaining attention as renewable alternatives.

Regenerated or man-made cellulosic fibres (MMCFs) include fibres such as viscose, modal and lyocell, which are mainly derived from dissolving wood pulp and are in certain regions known as rayons. Man-made protein fibres are regenerated from protein sources such as milk waste, gelatine, peanuts, soybeans and eggshells. These protein-based fibres, historically named azlons, were mainly developed in response to wool shortages during World War II. In general, the main issue concerning these man-made protein fibres is their lack of favourable mechanical properties – they are less durable than wool and have very low tensile strength under wet conditions (Stenton et al., 2021).

In terms of characteristics, regenerated cellulosic fibres are often viewed as fibres that combine the best of natural and synthetic fibres (Table 2). These fibres are smooth and fine with the inherent attributes of cellulose, including unique characteristics in moisture management. More specifically, regulation of absorption and release of moisture can contribute to fabric breathability, supporting the body's natural thermal regulation.

Man-made cellulosic fibres (Table 2) were the first man-made fibres, initially termed artificial silk and later named rayon. Today, rayon is sometimes used as a generic name for MMCFs that are developed using the viscose process, referring to the viscous solution obtained after chemically dissolving plant-derived pulp (Parajuli et al., 2021; Chen, 2015). Conventional **viscose** rayon is the dominant MMCF in terms of market share. This versatile fibre is often used in drapey summer dresses and soft blouses. Viscose fibres have high elongation but are not as strong as cotton fibres and other MMCFs. Viscose fibres can contribute to the drapability and soft feel of fabrics. In contrast to polyester, this regenerated fibre is exceptionally moisture absorbent. While MMCFs are often considered greener alternatives to synthetic fibres, the conventional viscose process is not necessarily environmentally friendly, as it involves the use of hazardous solvents and chemicals, such as carbon disulphide and the formation of toxic chemicals and gasses, which highlights the need for proper chemical management (Fashion for Good, 2020; Mendes et al., 2021). Nowadays, discharge of hazardous substances can be avoided using state-of-the-art closed loop production systems that recirculate solvents and chemicals (Mendes et al., 2021; Chen et al., 2015). The application of fibre and dissolving pulp production processes according to the EU-BAT (Best Available Techniques), which are compulsory in the EU, minimise process emissions (Suhr et al., 2015).

An alternative viscose fibre, **modal**, is produced using a modified viscose process, generating fibres with improved tensile strength and stability compared to viscose (Mendes et al., 2021; Chen, 2015), which contributes, amongst other things, to better washability of the obtained fabrics. Modal is used in the production of different woven and knitted fabrics, sportswear, underwear and household textiles. Fabrics made from modal and viscose have a softer hand feel compared to cotton fabrics, while fabrics made from lyocell have a softness that lies in between cotton and viscose.

Driven by technical and environmental concerns, more sustainable methods have been developed for cellulose processing. A new generation of rayon fibre is **lyocell** (Table 2). This fibre, mainly derived from dissolving wood pulp, is produced using a cellulose solvent N-Methylmorpholine N-oxide (NMMO) ([3]) which is recycled through a solvent recovery system. Compared to conventional viscose, lyocell fibre production is more environmentally friendly as it reduces toxic chemical use and substantially decreases water use and air pollution (Mendes et al., 2021; Chen, 2015). Lyocell has improved properties compared to viscose and modal. More specifically, the strength and tenacity of lyocell fibre is higher compared to conventional viscose and modal and is similar to cotton. In addition, lyocell is moisture absorbent as well, making it suitable for applications that require skin contact (Parajuli et al., 2021). Furthermore, the higher crystallinity of the fibre contributes to the dimensional stability of lyocell which is superior to that of other MMCFs.

Another, more niche MMCF, is **cupro** (Table 2). This fibre is a modified viscose rayon that requires the dissolution of cellulose derived from cotton lint in a reagent containing ammonia and copper (Parajuli et al., 2021; Mendes et al., 2021). Cupro fibres are characterised by their fineness and strength and are mainly used in sheer fabrics to produce underwear, dress fabrics and linings. However, due to the high costs and environmental concerns associated with the need for high-quality cotton cellulose and the use of copper salts in the production process, only a few manufacturers still produce this niche fibre (Mendes et al., 2021).

The remaining 13 % of the market share of man-made cellulosic fibres is occupied by **acetate**, a fibre mainly used in non-textile applications such as cigarette filters. Only 5 % of the acetate fibres put on the market are used for textiles applications (Chen, 2015; Textile Exchange, 2021). Although cellulose is the original source of acetate, cellulose acetates are classified as derivative or modified cellulose fibres since their chemical composition is built around an ester of cellulose rather than cellulose itself (Chen, 2015; Parajuli et al., 2021).

[3] N-Methylmorpholine N-oxide is used as an organic solvent that enables the direct dissolution of cellulose in the lyocell process, omitting chemical derivatization.

Table 2 Overview of examples of the characteristics and applications of the main man-made cellulosic fibres

Fibre	Carbon backbone	Examples of favourable characteristics	Examples of unfavourable characteristics	Applications	Examples of main producing countries	Source
Viscose	Cellulose	moisture absorbency breathable[1]	shrinkage after washing[1] low wet tensile strength	apparel home textiles nonwovens[2]	China, Indonesia, India, Austria	Chen, 2015 Mendes et al. 2021 Parajuli et al., 2021 Lenzing, 2023
Lyocell	Cellulose	breathable[1] moisture absorbency strong (dry and wet) dimensional stability[1]	fibrillation under wet mechanical action	apparel home textiles nonwovens[2]	China Austria, Thailand, India	Chen, 2015 Mendes et al. 2021 Parajuli et al., 2021 Lenzing, 2023
Modal	Cellulose	moisture absorbency good washability[1] better dimensional stability[1] compared to viscose stronger than viscose breathable[1]	lower water retention compared to lyocell and viscose lower dimensional stability[1] compared to lyocell	apparel (knit material, sportswear, underwear, etc.) home textiles	China Austria, Indonesia, India	Chen, 2015 Mendes et al. 2021 Parajuli et al., 2021 Lenzing, 2023
Cupro	Cotton linter pulp	lustre fineness breathable[1] moisture absorbency higher tensile strength than viscose	lower tensile elongation compared to viscose high production costs	apparel (sheer fabrics, underwear, linings, sportswear, etc.) home textiles	Japan	Mendes et al. 2021 Parajuli et al., 2021 Lenzing, 2023

[1] Fibre characteristics can contribute to this fabric characteristic

[2] Nonwoven applications such as hygiene and medical materials, filters, wipes, etc.

Another group of bio-based man-made fibres are **bio-based synthetics**. These fibres are produced from sugars and starch by chemical synthesis processes. Examples include bio-based PET and polylactic acid (PLA) (Box 1). In contrary to what is often assumed, bio-based synthetic fibres are typically not biodegradable. While bio-based PET is chemically identical to conventional PET, PLA is an alternative bio-based synthetic with different characteristics.

Box 1 Polylactic acid as bio-based alternative for polyester

Polylactic acid is a polymer with a 100 % bio-based carbon content, which was developed at the beginning of this century as a crop-derived and presumed biodegradable alternative for conventional polyester (Gupta et al., 2007). While its alleged biodegradability has facilitated its widespread use in applications such as disposable items, packaging, medical equipment and clothing, the degradation rate of PLA under ambient conditions is low and therefore does not adhere to the definition of biodegradation ([4]) (Rosli et al., 2021). As degradation of PLA requires temperatures above 50 °C it can only be considered industrially compostable (Rosli et al., 2021).

The production of PLA typically starts with the extraction of sugar or starch from various crops. In the case of starches, these are first converted to fermentable sugars prior to bacterial fermentation. The latter will generate lactic acid using bacteria form the *Lactobacillus* genus. Subsequently, the obtained lactic acid is polymerized to form PLA. Nowadays, the most popular production route of PLA is fermentation of corn starch, however PLA can also be derived from molasses, a by-product in sugar mills, potato starch, rice, wheat, etc. (Yang et al., 2021; Gupta et al., 2007). Although PLA is derived from crops rather than fossil fuels, its agro-based nature does not necessarily make it a greener alternative and its environmental impact is largely defined by the agricultural intensity and practices (Ivanović et al., 2021) (Section 4.2).

[4] Implies the degradation of substances through the action of micro-organisms under natural conditions without posing environmental hazards.

In comparison to MMCFs, this strong and stretchy fibre has low water absorbency, similar to polyester, while its UV resistance its much higher than polyester (Farrington, D. W. et al., 2005). As other synthetic fibres, PLA fibres contain fewer impurities than natural fibres. At the same time, as PLA has a low melting temperature (165–180 °C), these fibres are sensitive to heat. Hence, caution should be taken when ironing PLA at high temperatures as this can damage the fibre and the PLA fabric will harden. To avoid ironing problems and wrinkling, knitted PLA fabrics are recommended instead of woven ones (Yang et al., 2021).

2.3. Summary

Overall, it can be stated that bio-based fibres offer potential as alternatives for conventional synthetics and conventional cotton. The development of an improved, ecologically sustainable production chain for high quality alternative fibres in parallel with an integrated quality system for raw and processed fibres based on eco-labelling criteria could contribute to the development of a competitive, innovative and sustainable bio-based textile fibre industry in the EU. While in chapter 4, we look more closely at the environmental impacts of the different bio-based fibres, the next chapter will discuss trends in production, trade and consumption volumes.

3. Trends in production, trade and consumption of bio-based fibres

From a global perspective, synthetic fibres dominate the market with a share of around 62 % (Figure 2), followed by cotton, 24 %; and other natural plant fibres, 6 %; while animal fibres account for 2 %, half of which is wool (Textile Exchange, 2021). The remaining 6 % encompass regenerated fibres. This chapter provides an overview of the trends in production, trade and consumption of the main alternative bio-based fibres. In terms of **natural fibres**, it focuses on flax and hemp, which are the most relevant within a European context. For the group of **man-made bio-based fibres**, it focuses on the production and consumption of the main regenerated fibres, i.e., man-made cellulosic fibres.

3.1. Natural fibres

Before the arrival of cotton, flax (linen) and hemp were the main natural fibres used in Europe. In the late 1990s, the market share of cotton was surpassed by the dominant synthetic fibre, polyester, which is still the frontrunner today.

In 2019, the annual world natural fibre production was estimated at 33 million tonnes, cotton contributed almost 70 % by value, and wool 25 %. This corresponded to the production of 26.5 million tonnes and 1 million tonnes of cotton and wool, respectively (Townsend, 2020). The European Man-made Fibres Association (CIRFS) estimated that Europe and Türkiye consumed 205 000 tonnes of wool and 1.54 million tonnes of cotton in 2021 (Dufloucq C., 2022). About 1% of global cotton production is situated within the EU, corresponding to approximately 350 000 tonnes (European Commission, 2018). Other natural plant fibres, such as jute, coir, flax, ramie, hemp, sisal, kapok, kenaf and abaca, accounted for a global production volume of approximately 6.5 million tonnes in 2020 (Textile Exchange, 2021).

Europe is one of the main producers of **flax** used for fibres and, in particular, for high-quality linen. More specifically, more than 90 % of the global flax fibre and tow ([5]) production of around 940 000 tonnes in 2020 was in Europe (FAOSTAT, 2022). Top producers and exporters of flax fibres are Belgium, France and the Netherlands, while Italy is the main exporter of linen fabrics in Europe (C.E.L.C. Masters of Linen, 2010). Furthermore, approximately 10 000 companies in 14 EU countries are involved in the European linen industry (C.E.L.C. Masters of Linen, 2010). Globally, China is the main importer of flax fibres (The Observatory of Economic Complexity, 2020) and today most of the processing of flax into linen fabrics happens outside Europe.

Another fibre crop grown worldwide is **hemp**. As mentioned in the previous chapter, this versatile crop can be cultivated in both temperate and tropical regions and is possibly the oldest known multipurpose crop. Along with flax, hemp was one of the main fibre crops grown in Europe until the arrival of cotton and synthetic fibres (Horne, 2020; 2012). While exact numbers differ among sources, around 200 000 tonnes of hemp fibres were produced globally in 2020 (FAOSTAT, 2022; Textile Exchange, 2021). In 2020, some of the top exporters of hemp fibres in Europe were France and the Netherlands and the global hemp trade was estimated to be worth EUR 46 million (The Observatory of Economic Complexity, 2020). Between 2015 and 2019, European hemp production increased by 62.4 %, from 94 120 tonnes to 152 820 tonnes. Approximately 70 % of this European grown hemp was produced in France; followed by the Netherlands, 10 %; and Austria, 4 %. Overall, the hemp cultivation area in Europe increased by 70% from 2013 to 2018, while the number of hectares has increased more than sixfold since 1993 (Zimniewska et al. 2022). In addition, China produces a huge amount of hemp textiles due to its optimised manufacturing infrastructure (Ahmed et al., 2022).

Jute cultivation is primarily restricted to India and Bangladesh, respectively accounting for approximately 67 % and 30 % of the world’s jute production of 2.7 million tonnes in 2020 (FAOSTAT, 2022; Banerjee,

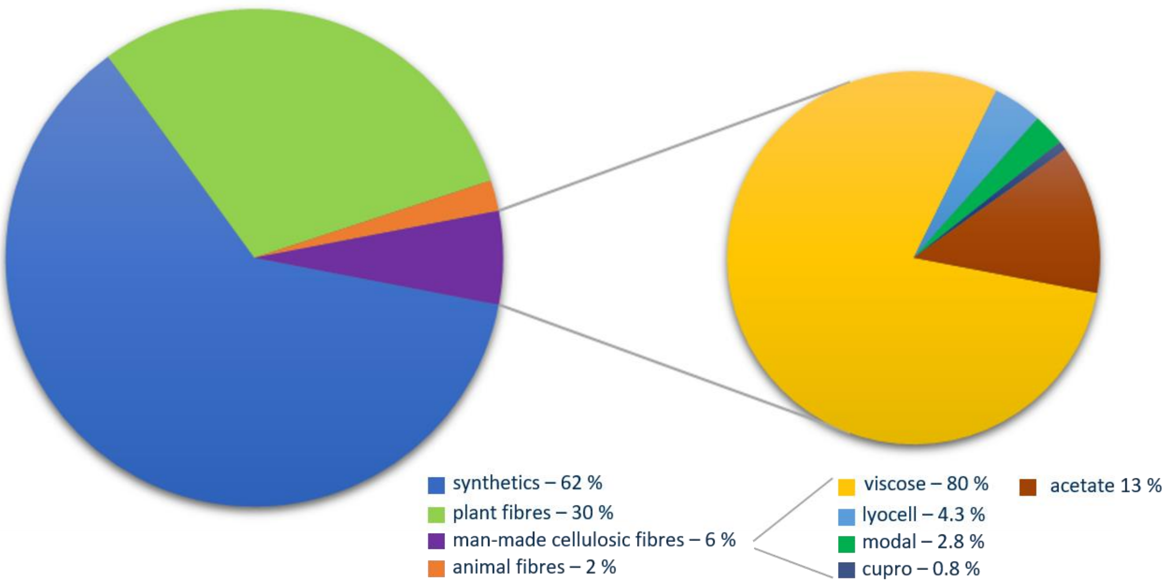
[5] Tow is a short or broken fibre that is used for yarn, twine or stuffing.

2020). With a production volume of 60 935 tonnes in 2020, **ramie** is mainly produced in Asia (FAOSTAT, 2022) where China leads the world in the production and export of ramie. In spite of its unique characteristics, ramie is of secondary importance in world trade largely because of a lack of suitable large-scale fibre extraction equipment and the high cost of degumming, spinning and weaving the fibre. Only a small portion of the ramie produced is available on the international market and is mainly imported by Germany, France, Japan and the UK (Rehman et al., 2019; Roy and Lutfar, 2012). **Coir** ranks third in terms of global natural fibre production, valued at almost EUR 300 million in 2019 (Townsend, 2020). India as the main producer, was responsible for the production of around 600 000 tonnes in 2020, which corresponds to 45 % of global coir production (FAOSTAT, 2022).

3.2. Man-made cellulosic fibres

Man-made cellulosic fibres (MMCFs) have been on the market for a long time, but competition from natural and synthetic fibres, mainly cotton and polyester, has limited their market share. The global production volume of MMCFs reached 7 million tonnes in 2019 (Fashion for Good, 2020). The market share of MMCFs is about 6.4 % of the total fibre production volume (Figure 2) and is expected to increase in the coming years. More specifically, the production value of MMCFs is forecast to reach almost EUR 24 billion by 2025 and to reach a volume of 8.6 million tonnes by 2027 (Research and Markets, 2021).

Figure 2 Global fibre production with a focus on different man-made cellulosic fibres, 2021, per cent



Note: Percentages may not sum to 100 % due to rounding.

Source(s): Textile Exchange, 2021

Viscose is the dominant MMCF with a market share of around 80 % (Figure 2) and a production volume of around 5 million tonnes in 2020 (Textile Exchange, 2021).

Cellulose-derived **acetate** has a market share of around 13 %, however this fibre is largely use in non-textile applications (Textile Exchange, 2021).

With a market share of 4.3 % in 2020, **lyocell** is the third most used MMCF, after viscose and acetate and its production is expected to grow faster than the other MMCFs (Textile Exchange, 2021).

Modal had a market share of around 2.8% of the total MMCF market in 2019 (Textile Exchange, 2020), while **cupro** had a market share of less than 1 %. In 2019, there was only one supplier of cupro, producing 17 000 tonnes of this niche fibre (Textile Exchange, 2020).

It was estimated by CIRFS that in 2021 the EU produced 468 000 tonnes of MMCFs and consumed 377 000 tonnes of MMCFs – for comparison, Europe and Türkiye produced 515 000 tonnes of MMCFs and mill consumption was 731 000 tonnes. The EU produces a substantial share of MMCFs, accounting for 9% of the world market. For the intermediate product, i.e., dissolving pulp, the market share is 22% (Lenzing, 2023).

In Europe and Türkiye, the main end-uses of these fibres were in apparel, 53 %; industrial applications, 41 %; tyres, 4 %; and household goods and furnishings, 2 %. It should be noted that a little less than 300 000 tonnes of MMCFs were imported into Europe and Türkiye in 2021 (Dufloucq, 2022).

4. Environmental impacts and concerns associated with bio-based fibres

In recent years, the search for more sustainable, alternative fibres has become an important trend, aiming to reduce the environmental and climate impacts of textiles and fashion.

The environmental impact of textile products is, besides the use phase, defined to a large extent by the production phase. More precisely, the production of garments contributes to about 80 % of the total climate change impacts, mainly through the use of fossil fuels in the production processes. Of this 80 %, fibre production accounts for 16 % of the climate change impacts. For conventional cotton, the cultivation phase dominates in terms of water scarcity impact (87 %) (ETC/CE, 2022a).

Consequently, some developments aim to break fossil-fuel dependency by replacing synthetic fibres with renewable alternatives, while others aim to replace cotton with alternatives that use less water and land.

Identifying superior fibre types in terms of reducing environmental and climate impacts is, however, very challenging, if not impossible, as textile production involves one of the most complex supply chains and environmental and climate issues arise at all life-cycle stages and may not always be directly visible as many issues may take place outside Europe.

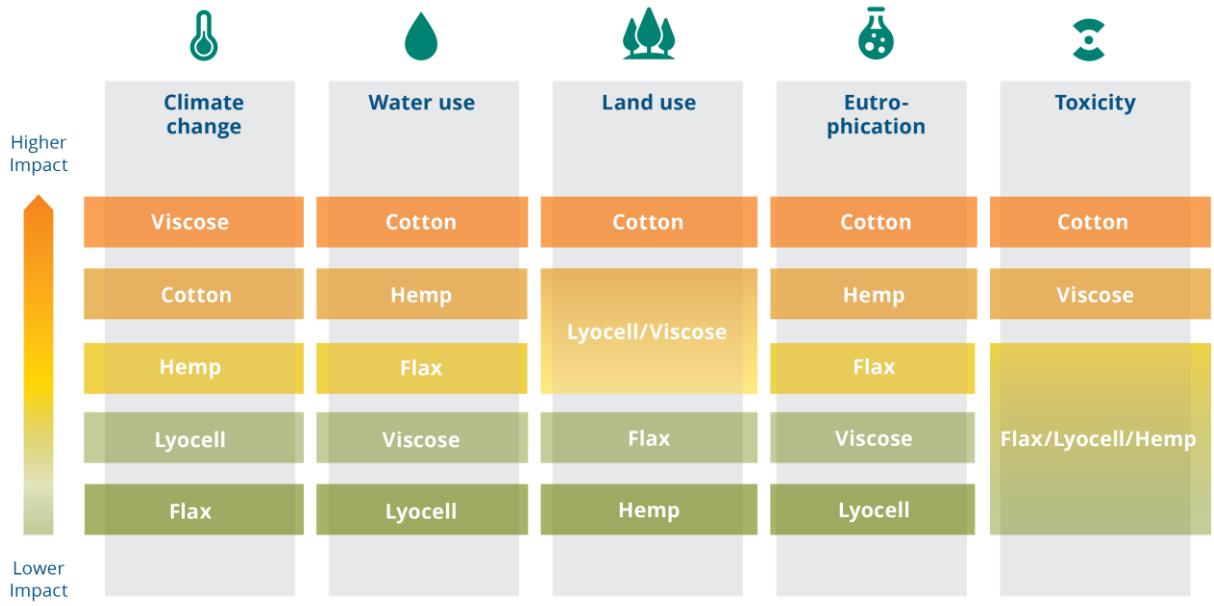
To ensure the actual sustainability of alternative fibres, it is crucial to monitor their environmental performance and identify potential unintended consequences that might arise from developing and scaling up the use of alternative feedstocks or processes. The global nature of textile value chains makes it even more complex to assess environmental and climate impacts. More specifically, the agricultural part of the textile supply chain is mainly located outside Europe. Only 8 % of the land use for textiles consumed by European households, 13 % of water use and 15 % of other resource use takes place in Europe (EEA, 2022a; ETC/CE, 2022a). Likewise, although greenhouse gas emissions have a global effect, more than 75 % of emissions related to the production of textiles consumed by EU households are released elsewhere in the world (EEA, 2019; ETC/WMGE, 2019). This underlines the need for a systemic view to prevent the shift of environmental burdens to other regions outside Europe (EEA, 2022a; ETC/CE, 2022a). Furthermore, due to the fragmented structure of the textile supply chain, the identification of environmental impacts associated with plant-based fibre production remains challenging and often spatiotemporal differences in agriculture and third-scope impacts (i.e., value chain emissions) are overlooked. More research on these impacts is greatly needed along with the collection of more accurate primary data.

4.1 Environmental impacts of bio-based fibres

In this section an overview on the impacts related to the production of the most used bio-based fibres – natural, man-made cellulosic and bio-based synthetic ones – is provided. The further processing of fibres into textile products, weaving, knitting, dying, etc., strongly impacts the environmental performance of a textile product as well, but that lies beyond the scope of this report.

To decrease climate impacts, the general focus is to steer away from fossil-based synthetic fibres. However, next to climate change, other impacts related to, for example, water consumption, eutrophication, acidification, ecotoxicity and land use are also relevant to consider. To illustrate this, Figure 3 presents a simplified overview of the relative environmental impacts of a subset of bio-based textile fibres, based on literature.

Figure 3 Comparison of the environmental impacts of plant-based textile fibres



Notes: This simplified overview is based on literature studying some of the main impacts associated with the production of different plant-based textile fibres. The ranking presents a general appraisal based on conventional production practices. Depending on region-specific climate, water and land conditions, agricultural practices, the type of processing and the used energy sources, the impacts of specific fibre brands or individual producers can strongly deviate from this ranking.

Source: EEA and ETC/CE

Natural fibres, such as cotton, are often expected to be more environmentally friendly than synthetics, since they are of natural origin and, hence, derived from a renewable source and intrinsically biodegradable. Cotton cultivation, however, can consume large quantities of water and land, and is often heavily fertiliser- and pesticide-dependent, which contributes to eutrophication and ecotoxicity. Moreover, it is a general misconception that bio-based fibres are not related to the use of fossil-based resources as these fibres often also require energy-demanding processing and transportation. In addition, fertiliser production is an energy-consuming process that contributes to 63.9 % of the carbon footprint of cotton (Günther et al., 2017).

The global production of conventional cotton is estimated to require 200 000 tonnes of pesticides and 8 million tonnes of fertiliser annually (Ellen MacArthur Foundation, 2017). Consequently, as EU cotton production represents 1 % of global production, European pesticide and fertiliser use can be estimated at around 2 000 tonnes and 80 000 tonnes respectively for European cotton production (European Commission, 2018). Organically grown cotton can, however, mitigate these impacts to a large degree. According to a lifecycle assessment (LCA) by Textile Exchange, cotton’s global warming potential (GWP) can be reduced by 46 % if it is grown organically (Textile Exchange, 2014). This reduction is mainly attributable to lower agricultural inputs of mineral fertilisers and pesticides, as well as the reduced use of machinery and irrigation (Aid by Trade Foundation, 2014). While organic cotton farmers are much less likely than conventional ones to use chemical fertilisers and pesticides, the organic cotton label does not rule out the use of agrochemicals. A study conducted by the American Institutes for Research (AIR) found that 35 % of organic cotton farmers self-reporting the continued use of chemical fertilisers and 33 % self-reporting the continued use of chemical pesticides. However, the self-reported nature of these statistics requires caution and further research (Hoop et al., 2018). A significant reduction in water use can be achieved when cotton is grown in a suitable climate. For example, Cotton made in Africa (CmiA) ([6]) is cultivated under rain-fed conditions, limiting irrigation and blue water ([7]) use is reduced by up to 90 % compared to conventional cotton production (Aid by Trade Foundation, 2014; Textile Exchange, 2014).

Other natural fibres, such as hemp and flax, are also potentially more sustainable than conventional cotton. Hemp cultivation requires only 25 % of the fertilisers needed for cotton, as well as a fewer seeds, field operations and less irrigation costs (Schumacher et al., 2020). Furthermore, compared to cotton, hemp is a high-yield crop – one cultivated hectare of hemp yields three times more metric tonnes of hemp fibres than cotton fibres. This, together with a cost reduction of 75 % due to lower fertiliser use, fewer seeds, less irrigation and limited costs associated with pest control, makes hemp a more sustainable and economic alternative to cotton (Schumacher et al., 2020).

While flax cultivation requires less fertiliser than hemp, pesticide use is higher (González-García et al., 2010). Compared to cotton, flax and hemp cultivation generally require less water and has a lower overall environmental impact (European Confederation of Flax and Hemp, 2022; Schumacher et al., 2020; Muthu et al., 2012; Turenen and van der Werf, 2006). Because other impacts are largely limited, land use is the main environmental impact contributor of flax cultivation (European Confederation of Flax and Hemp, 2022). Furthermore, while crops such as hemp and flax can be grown in temperate regions, such as Europe, and do not normally require irrigation, cotton cultivation is restricted to (sub)tropical regions, which are often water-stressed, and is thus more likely to depend on irrigation, as well as the heavy use of agrochemicals to ensure good yields (La Rosa and Grammatikos, 2019; Turenen and van der Werf, 2006).

Hemp and flax fibres, however, require more processing, i.e., degumming ([2]), involving significant water use. Nonetheless, the amount of water consumed during degumming such as warm water retting or bio-retting was reported to correspond to only 1 % of the water used in cotton irrigation (Turenen and van der Werf, 2006) – more recent data are required to further confirm this. Overall, it seems that the environmental performance of both bast fibres is better than cotton, at least throughout the fibre cultivation phase. When degumming is applied in case of bast fibres, however, this can worsen their impact depending on the type of process and energy source used. As the impact of the degumming process is mostly determined by the energy source used for heating, this impact is largely country dependent and can be reduced when renewable sources of energy are used. Consequently, there is a need for alternative degumming processes (Lyu et al., 2021).

Over the past decade, **man-made cellulosic fibres (MMCFs)**, such as viscose, modal and lyocell have received increasing attention as more environmentally friendly alternatives to fossil-fuel based synthetic textiles, such as polyester, or water-intensive crops, such as cotton (Felgueiras et al., 2021; Sandin et al., 2013). As these fibres are conventionally derived from dissolving wood pulp, the feedstocks used to produce the dissolving pulp, together with the chemicals used in the dissolving process, are both important determinants of their environmental performance. In addition, land use and forest management practices, as well as the energy use associated with the applied mill technology, are important determinants as well.

The impact of MMCFs originating from dissolving pulp derived from different sources and produced in different locations was studied by Schultz and Suresh (2017). They demonstrated that Asian MMCF production derived from boreal forest pulp and rainforest pulp had the worst environmental impacts, followed by Asian MMCFs derived from cotton linter and plantation (eucalyptus) pulp. According to their study, viscose fibres produced from recycled pulp from textile waste had a lower environmental impact than fibres from virgin pulp (Schultz and Suresh, 2017). Overall, sourcing and production practices can vary greatly among different producers and can strongly affect the environmental performance of textile fibres.

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6 Cotton made in Africa is one of the cotton standards of The Aid by Trade Foundation.

7 Concerning water consumption, a distinction is made between blue and green water. The former is surface water or groundwater that is used or evaporated during irrigation, industry processes or household use. Green water is rainwater stored in the soil and typically used for crop cultivation.

Viscose produced in Asia is typically derived from eucalyptus wood, while viscose manufactured in Austria comes largely from beechwood. Eucalyptus has a relative high yield, while European wood requires more land because it grows more slowly. However, compared to cotton, which requires 0.8 hectares per tonne per year (ha/t-year), Shen et al. (2010) demonstrated that land use is still reduced to approximately 0.7 ha/t-year for Austrian modal and viscose, to 0.3 ha/t-yr for Asian viscose and even 0.2 ha/t-yr for Tencel™ (lyocell) which is derived from imported market pulp mainly produced from eucalyptus wood.

As no irrigation is needed for the Asian and European plantations, the water use in MMCF production is dominated by water requirements during processing. Nevertheless, water use for cotton is still 10-20 times higher than for these MMCFs, while water use of synthetic fibres is lower (Felgueiras et al., 2021; Shen et al., 2010). Furthermore, the impact on climate change can be strongly reduced if process heat can be derived from municipal waste incineration instead of natural gas combustion (Shen et al., 2010).

Taken together, Shen et al. (2010) demonstrate that man-made cellulosic fibres, except viscose produced in Asia, have a better overall environmental performance than cotton and polyester. The overall impact of Asian viscose is similar to polyester (Shen et al., 2010). These environmental impacts associated with the viscose process are strongly reduced when the lyocell process is applied, however, some environmental challenges remain. While lyocell is produced using a closed-loop system using NMMO solvent, stabilisers are required as unwanted side reactions and by-products can occur that can cause cellulose degradation, solvent decomposition and discolouration of fibres (Felgueiras et al., 2021). Therefore, new alternative processes are being developed for the dissolution of cellulose, such as the use of deep eutectic solvents, aqueous NaOH-based solvents and ionic liquids. The latter has already reached pilot scale level, for example for the Ioncell-F® process, and is close to industrial exploitation (Mendes et al., 2021).

Another effort to break fossil-fuel dependency and, possibly, the associated environmental impacts, is bio-sourcing for the production of synthetic fibres that would otherwise conventionally be made out of fossil fuels. These so-called **bio-based synthetics** can be chemically identical to their conventional fossil fuel-based counterparts, but their carbon backbone is derived from renewable sources. Bio-based synthetic fibres are frequently cited as more eco-friendly options to conventional, virgin fossil-based ones. This may be true in terms of the usage of fossil resources, but key is the sustainable sourcing of the feedstock that, preferably, does not compete with food in terms of land use and does not heavily rely on water or chemicals (ETC/WMGE, 2021). Hence, it is crucial to verify and quantify the environmental sustainability of bio-sourced synthetics and bio-based fibres in general. Moreover, Ivanovic et al. (2021) demonstrated that bio-sourcing of synthetics does not necessarily reduce environmental impacts.

This paradox mainly arises when first-generation feedstock, i.e., food crops or deliberately grown fibre crops, is used leading to eutrophication, ecotoxicity, land use and water consumption. More specifically, when crops displace the petrochemical inputs, the requirements for primary inputs strongly increase due to feedstock and process modifications (Ivanović et al., 2021). The impacts are, however, largely dependent on the bio-content and feedstock choice. For example, sugarcane-derived, bio-based polyester has an environmental performance similar to petrochemical polyester, while bio-based polyester derived from maize has a poorer environmental performance when compared to polyester (Ivanović et al., 2021). This is attributable to the fact that the cultivation of maize uses large amounts of pesticides and water, while sugarcane-derived polyester can stem from by-products produced during sugar or ethanol production, resulting in shared environmental burdens. Overall, when bio-based synthetic fibres remain predominantly agro-based, caution should be applied when considering these fibres as greener alternatives. Consequently, the need for circular strategies that enable sourcing of secondary raw materials and agricultural residues, so-called second-generation feedstock, is pressing (Box 2). To illustrate, a comparison between bio-based TPA ([8]) (derived from corn, sugar cane or orange peel) and conventional TPA showed that the lowest environmental impacts were associated with the bio-based route involving second-generation materials. This is mainly attributable to the upcycling of side-streams

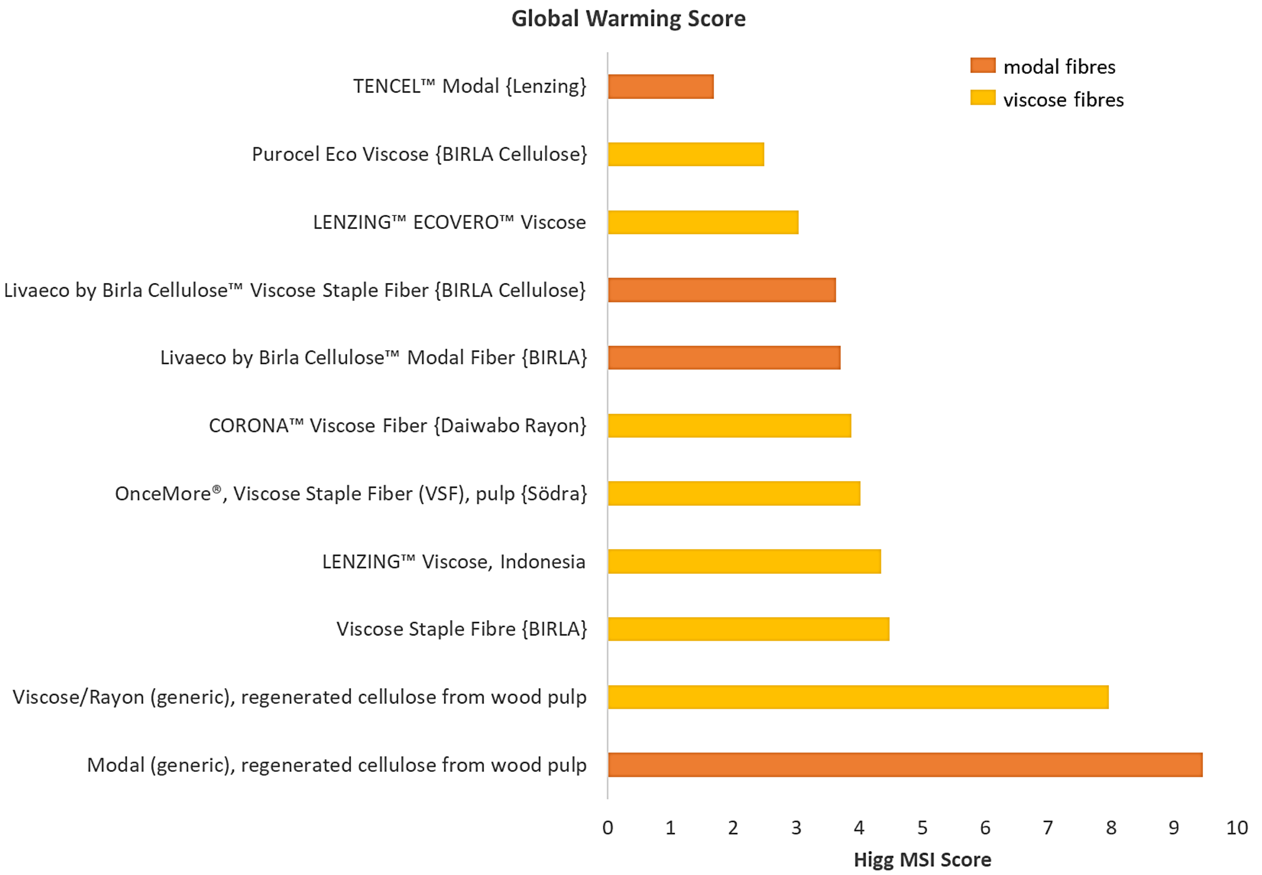
[8] Terephthalic acid, one of the building blocks of PET.

such as orange peel which avoids resource extraction and land use and prevents waste (Palacios-Mateo et al., 2021; Volanti et al., 2019).

The comparison of environmental impacts is a complex task that is associated with several limitations. These include the heterogeneity of fibre production practices which are, amongst other things, impacted by differences in production methods and technologies as well as regional variations in environmental regulations. In addition, external factors such as climate conditions and water and resource availability can affect environmental impacts. Furthermore, obtaining accurate and comprehensive data remains challenging and differences in the assumptions made regarding system boundaries can lead to variations that make it difficult to compare different impact assessment studies. There is a general need for comprehensive, up-to-date and accurate data.

As an illustration, figure 4 shows the variation that may arise between similar fibre types as a result of regional differences as well as differences in production and sourcing practices. This figure presents the global warming potential score of different viscose and modal fibres according to the Sustainable Apparel Coalition's Higg Material Sustainability Index (MSI). For example, it can be observed that the spread of global warming scores of different viscose and modal types is large.

Figure 4 Global Warming Score according to the Higg Material Sustainability Index provided by the Sustainable Apparel Coalition (SAC)



Notes MSI scores are normalized LCA results and the Global Warming Scores presented in this figure are linearly correlated to the Global Warming Potential results for these fibres. The lower global warming score, the less impact the fibre has on global warming. These results were calculated using the Higg Material Sustainability Index (Higg MSI) tools provided by the Sustainable Apparel Coalition. The Higg MSI tools assess impacts of materials from cradle-to-gate for a finished material (e.g., to the point at which the materials are ready to be assembled into a product). This figure shows impacts from cradle to fibre production gate. The Higg MSI scores were calculated based on Higg MSI database Version 3.5 (December, 2022).

Source Higg Index MSI Material Sustainability Index

Given the differences in regionally appropriate parameters, it is important to state that the ranking of fibres in Figure 3 needs to be nuanced and that the associated impacts are not intrinsic to the fibre source itself, but largely depend on the agricultural, forestry and processing practices that surround them (Lanfranchi et al., 2021). For example, monocultures make crops more susceptible to pests, while the growth of crops in water-stressed areas requires more irrigation.

Overall, it is clear from Figure 3 and Figure 4 that the ranking of environmental impacts can differ considerably depending both on the considered impact category as well as sourcing and production practices. This indicates that there is no optimal fibre choice based on impacts at the production level. Furthermore, it is important to note that the environmental impact of textile products is not only determined by the fibre, but is strongly influenced by other factors such as the addition of processing agents and dyes, manufacturing, serviceable life, use and end-of-life treatment. In addition, the textile industry is a dynamic industry that is constantly evolving with changes in technologies, production procedures and consumer preferences. Consequently, the environmental impacts associated with textile fibres can vary over time as new innovations and processes are developed.

4.2 Agricultural intensity

The increasing world population and rising affluence is driving the demand for more food and textile fibres, and thus arable land. Moreover, the annual cotton production is no longer enough to meet market demand and the limiting availability of arable land and irrigation water are likely to hinder the future expansion of cotton cultivation (El Seoud et al., 2020; Mendes et al., 2021). In addition, the need for arable land has increased deforestation worldwide. According to the Food and Agriculture Organization of the United Nations (FAO) and the United Nations Environment Programme (UNEP) (2020), deforestation is largely attributable to agricultural expansion, mainly for the cultivation of oil palm and soybeans, however among the main threats of short-term overexploitation is the conversion of land to cotton production (de Oliveira et al., 2021). This will spur a further intensification of agricultural practices. A main problem related to intensive agriculture is the excessive use of fertilisers that not only contributes to eutrophication and the production of which is energy intensive, but which are often made from phosphate rock, a non-renewable resource that will be largely depleted by the end of this century (de Oliveira et al., 2021; Lun et al., 2018). In addition, the application of nitrogen fertilisers contributes to greenhouse gas emissions (de Oliveira et al., 2021).

Consequently, there is a need for fibre crops that require less fertiliser, such as flax, as well as for high-yield fibre crops such as hemp that need less arable land. Besides the environmental benefits, a more diverse matrix of fibres will also reduce future supply issues (de Oliveira et al., 2021). While the type of fibre crop for a large part determines the environmental impacts, it is important to realise that good agricultural practices are crucial. As agricultural intensity is a major determinant of a fibre's environmental performance, one should not simply aim to replace one mass produced fibre with another, as this will not mitigate the impacts associated with intensive agriculture (de Oliveira et al., 2021).

Monocultures, for instance, should be avoided as they increase the risk of disease and pest outbreaks and promote soil degradation. Furthermore, the integrity of a farm's natural ecosystem can be preserved by a regenerative agriculture, increasing its health, biodiversity and resilience. Regenerative agricultural practices include, amongst others, no tillage, permaculture and keyline land preparation. To conserve soil quality, agroforestry and crop rotation are beneficial as well (Bhattacharyya et al., 2022; de Oliveira et al., 2021). Hemp, for example, is often grown in rotation with wheat as it improves soil quality. Its long roots retain the soil and natural leaf decomposition returns vital nutrients back to the soil, which benefits wheat production (La Rosa and Grammatikos, 2019). Also, hemp effectively suppresses the growth of weeds, leading to reduced herbicide costs for the subsequent crop (Turenen and van der Werf, 2006). In general, intensive soil management practices, such as frequent tillage, the application of mineral fertilisers, drainage and lack of crop rotation should be avoided as they diminish soil quality and negatively affect soil carbon sequestration (Bhattacharyya et al., 2022; Corsi et al., 2012).

As the production of MMCFs is projected to increase strongly in the future, this will also entail environmental impacts and competition for land as dissolving pulps are primarily manufactured from woody feedstock and thus large plantation areas for wood production will be needed (Research and Markets, 2021; Kallio, 2021).

Over the past decades, deforestation has taken on alarming proportions, with the world losing around 10 million hectares of forest each year between 2015 and 2020. It was estimated by Canopy that approximately 150 million trees are felled annually to feed the world's viscose production mills and on average 2.5–3 tonnes of wood are required to make 1 tonne of rayon (Canopy, 2020). For this reason, it is essential that these plantations are sustainably managed and, preferably, certified (Wojciechowska, 2021). About 40–50 % of all MMCFs are Forest Stewardship Council (FSC) or Programme for the Endorsement of Forest Certification (PEFC) certified. For the remaining half of the global production, the risk of sourcing MMCFs from endangered or ancient forests remains high when transparency is lacking (Textile Exchange, 2020). More specifically, the non-governmental organisation Canopy estimated that 50 % of the 6.5 million tonnes viscose produced annually originates from ancient and endangered forests (Canopy, 2020). In Europe, most countries have strict and well-enforced forestry laws to ensure sustainable forest management. A large proportion of production forests are additionally certified by FSC or PEFC or both systems, yielding wood with lower impacts on land and ecosystems (Forest Europe, 2020). Furthermore, it is important to keep in mind that the comparisons of land use per ton of product does not always take into account the effects of land use intensity.

Alternatively, MMCFs derived from fast-growing plants such as bamboo (bamboo viscose) or hemp (Lyohemp™) could provide a possible route to increase dissolving pulp production while limiting deforestation (Prakash, 2020; Paulitz et al., 2017). Hemp, for example, yields more biomass than wood, offering twice as much useable fibre compared to forests. Furthermore, this fibre can consist of a maximum of 77 % cellulose which is almost 30 % more than wood (Mendes et al., 2021). This indicates that, in theory, a significantly higher amount of dissolving pulp can be produced from hemp than forests grown in the same area (Ahmed et al., 2022). Nevertheless, research and optimisation are required to overcome challenges related to the processing of these alternative materials into dissolving pulp and to develop new sustainable technologies that maintain product quality. For example, annual crop plants can contain more mineral components and organic substances that have to be removed to produce high-quality dissolving pulp. In woody plants like trees these components are mainly concentrated in the bark, which can be removed during the first stage of the process (Schuster et al., 2023).

In addition to the search for alternative crops, there is an increasing trend of using agricultural and bio-waste in manufacturing processes (Box 2).

Box 2 Bio-based textile fibres from agricultural waste

A shift towards circular strategies that enable sourcing of secondary raw materials and agricultural residues is required. Moreover, the sustainable management of agricultural residues is one of the key challenges associated with a growing agricultural sector (Institute for Sustainable Communities, 2021). As only a part of these residues can be utilised for domestic applications such as fodder, animal bedding, fuel, mulching and composting, the mass burning of these residues is the most convenient disposal route for farmers, leading to air pollution.

Nevertheless, some agricultural residues have been proven to be suitable for fibre production. These are often called second-generation feedstock and are mainly made up of lignocellulosic waste and products such as bast, stalks and leaves. Some examples are straw derived from rice, wheat and maize, sugarcane bagasse, banana pseudo-stems, pineapple leaves and oil palm (empty fruit bunches). Sugarcane bagasse and rice straw are amongst the most widely available agro-residues and are typically used for the production of dissolving pulp. Pineapple leaves or pseudo-stems of banana are best suited for fibre extraction (Institute for Sustainable Communities, 2021). Fibres derived from pineapple leaves, for example, are already being utilized for a long time by people in rural areas that refer to the obtained fibre cloth as “Pina cloth” (Hazarika et al., 2017; Jose et al., 2016). Pineapple leaf fibre (PALF) is a glossy, fine, white, strong and soft fibre that can be spun into textile fine grade yarn. It is estimated that almost 14 million tonnes of PALF are produced globally (Institute for Sustainable Communities, 2021). Fabrics made from PALF have good absorbency, are breathable, have good dyeability and are wrinkle resistant. Applications of PALF encompass conventional apparel but mostly upholstery. For example, PALF can be used in nonwovens and has gained special attention as bio-based alternative for leather (e.g., Pinatex®) (Wood, 2019). However, because of difficulties related to fibre extraction and the suboptimal fibre yield from existing spinning methods, there is no steady supply of PALF. Hence, the centralized textile sector shows limited interest in this fibre (Jose et al., 2016).

Overall, great potential lays in the development and optimisation of spinning procedures as well as fibre modification for the development of textile products derived from agro-residues. As stated in the study of the Institute for Sustainable Communities (2021) there is an ample supply of crop residues that can be channelled to fibre production, however, this is a system challenge that requires organisation, collaboration and investment.

4.3 Biodegradability of bio-based fibres

Overall, there is a common belief that bio-based inherently implies biodegradable. However, this is a misconception, as biodegradability in the first place depends on the polymer type. While natural fibres, as well as man-made fibres derived from natural polymers are biodegradable, this is not necessarily the case for bio-based synthetic polymers.

Biodegradability is the breakdown of substances through the action of micro-organisms under natural conditions without posing environmental hazards and without human intervention. Hence, the conditions under which biological degradation occurs in large scale waste management environments, such as industrial compost facilities, do not match those found in pure natural environments, such as soil and seawater.

Furthermore, biodegradability is no permit to uncontrolled disposal of textiles. Both in the case of biodegradable as well as compostable textiles, proper waste treatment is crucial to assure safe decomposition of the textiles. If, on the contrary, textile waste ends up being landfilled, biodegradable fibres can contribute to methane production due to anaerobic conditions, which is a more potent greenhouse gas than carbon dioxide. Furthermore, in a circular economy the higher value option would be to recycle or upcycle textile products at the end of their intended lifetime so the fibres can be reused in new textiles (Textile Exchange,2018; Ivanovic et al., 2021).

Another point of concern is that the biodegradability of a fibre can be negatively impacted by the presence of processing chemicals and finishing agents that can disturb the degradation process. For example, the presence of toxic metals in dyes can inhibit the bacterial growth which is essential to the biodegrading process or can contaminate the resulting compost. In addition, certain dyes can be hazardous if they leak into the environment. Since almost all textiles are processed and finished, even garments made purely from biodegradable materials often contain residues of chemicals used in fibre production and textile processing or may contain other materials in stitching, labels, buttons, etc. (Ellen MacArthur Foundation, 2017).

In order to reduce environmental impact, it is also key to retain the value of textiles for as long as possible. In this regard, fibre quality is crucial for textile longevity and the reduction of waste volumes. Furthermore, the most important determinant of the environmental performance of textile products is the useful life which is, amongst other things, affected by the longevity/durability of the textile fibre. A contradiction seems to arise when considering biodegradability and durability. Durability within the context of textiles is often defined as the ability to resist wear and tear and exist for a long time without significant deterioration. Biodegradability, on the other hand, implies microbial degradation under natural conditions. An example of the trade-off between durability and biodegradability was demonstrated by Hildebrandt et al. (2021) in the case of plant-based leather substitutes (Hildebrandt et al., 2021). This study indicated that the positive environmental benefits associated with the use of plant-based biodegradable materials were outweighed by the negative environmental impact of a decreased lifetime due to reduced durability (Hildebrandt et al., 2021). Durability of these plant-based alternatives can be increased with coatings or impregnation, the impact of which is compensated for by the environmental benefits of enhanced durability (Hildebrandt et al., 2021). Nevertheless, these coatings should ideally be natural and have a limited impact on the products' biodegradability. Taken together, biodegradability might be an interesting company target for marketing purposes, however, long-term durability, facilitating prolonged serviceable product life, is a key determinant of improved environmental performance (Klepp et al., 2022; Cooper et al., 2013). Overall, critical and case-specific assessments of the trade-off between biodegradability and durability are required to decide which feature outweighs the other in terms of environmental benefits, while taking into account a product's intended application.

4.4 Recyclability of bio-based fibres

High-quality recycling of waste textiles is a known challenge in the textiles industry, since less than 1% of waste textiles is recycled into new textile applications (Ellen MacArthur Foundation, 2017).

Until now, recycling facilities are mainly put into place for the mechanical recycling of cotton (EEA, 2021; ETC/WMGE, 2021). However, with the increasing demand for bio-based fibres, and alternative cellulose-based fibres in particular, further research related to the opportunities for and barriers to the recycling of these fibres, as well as blended materials, is required. (Bio)chemical recycling is often used for the recycling of cotton and other cellulose-based fibres, such as viscose and lyocell. Nevertheless, potential lies in the development of less destructive solvent alternatives for chemical recycling, such as the use of NMMO ([3]) or ionic liquids (El Seoud et al., 2020; Ma et al., 2020; Haslinger et al., 2019). However, research is still ongoing and further optimisation is required to improve recycling process economics as well as thorough assessments of their environmental impacts.

While the share of regenerated cellulosic fibres with recycled content is currently estimated at less than 1 % of the man-made cellulosic fibre market, the use of recycled cellulose holds a lot of innovation potential and is expected to increase significantly in the coming years (Textile Exchange, 2020). To illustrate, Canopy estimated that by recycling only 25 % of current pre- and post-consumer cotton textile waste in addition to 25 % of the rayon textile waste, all wood fibre currently used to manufacture dissolving pulp could be replaced (Canopy, 2020). Many projects are currently tackling the improvement of textile recycling, including SCIRT ([9]), Re:NewCell's Circulose® ([10]), Circular Systems™ Texloop ([11]) and Ioncell® ([12]). A large-scale industrial fibre product is TENCEL™Lyocell produced with REFIBRA™ technology ([13]) (Cao et al. 2022; Piribauer and Bartl, 2019).

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[9] System Circularity & Innovative Recycling of Textiles: an EU- funded project that aims to demonstrate a textile-to-textile recycling system for discarded clothing or post-consumer textiles.

[10] Circulose® is a branded fibre that Re:NewCell produces from dissolved pulp derived from cotton and man-made cellulosic waste, such as worn-out jeans and production scraps.

[11] Textloop technology by Circular Systems, which can mechanically recycle TENCEL™ lyocell.

[12] Ioncell is a technology developed by Aalto University (Finland), that turns used textiles, pulp or even old newspapers into new textile fibers without harmful chemicals.

[13] REFIBRA™ technology by Lenzing makes lyocell of viscose fibres with a share of recycled cotton pulp

To maximise the potential of textile recycling, including bio-based fibres, sorting is crucial. To illustrate, in plastics recycling, problems can arise when bio-based alternatives end up in established recycling processes. For example, PLA can contaminate the PET recycling process as most recycling technologies are unable to distinguish between the two types of plastics (Textile Exchange, 2018). Likewise, blending bio-based fibres with synthetic ones also hinders high-value textile recycling. This illustrates the importance of taking the end-of-life of textiles into account when making design choices (ETC/CE, 2022a).

As of 1 January 2025, separated collection of textile waste will be obligatory in all EU Member States, facilitating strategies to optimise the benefits of biodegradable and bio-based fibres in general by minimising their landfilling and incineration. In addition, as stated in the EU strategy, extended producer responsibility (EPR) will promote product design that enables circularity throughout a product's entire lifecycle, including their end-of-life management (EU Strategy for Sustainable and Circular Textiles, 2022). While closing the loop through recycling and reutilisation of materials is key, slowing down the loop through life-extending strategies such as design for durability, ease of reuse, repair and remanufacturing is at least equally important (ETC/CE, 2022a).

4.5 Microfibres

Microfibres are small, thread-like particles, released, among other routes, by the wear and tear of textiles. They are considered contaminants of major environmental concern and have been detected in substantial amounts in terrestrial and freshwater ecosystems, surface and subsurface waters, in sea ice, and deep-sea and coastal sediments (EEA, 2022b; ETC/CE, 2022b; Suaria et al., 2020). Microfibres include both plastic microfibres, shed by (fossil- or bio-based) synthetic textiles, as well as microfibres released from natural polymer fibres which include both natural fibres and regenerated fibres, such as cotton, viscose and lyocell.

Microfibres mainly enter the environment through wastewater effluent and aerial deposition (EEA, 2022b; ETC/CE, 2022b). Washing clothes and other textiles has been identified as a major route for releasing microfibres into the wastewater. The estimates for microfibre release vary widely among different sources (EEA, 2022b; ETC/CE, 2022b).

While most attention has been devoted to plastic microfibres resulting from the washing of synthetic textiles, several studies have demonstrated that 60–80 % of textile microfibres in both the environment and organisms are not plastic, but originate from natural and man-made bio-based textile fibres, such as cotton, wool and viscose, even despite many of these fibres' biodegradability (ETC/CE, 2022b; Kim et al., 2021; Suaria et al., 2020; Stanton et al., 2019; Sanchez-Vidal et al., 2018; Woodall et al., 2018; Remy et al., 2015). While microfibres released from bio-based synthetics like PLA and bio-PET are not biodegradable, even the biodegradability of microfibres released from natural and regenerated fibres can be affected by processing procedures such as dying, coating, and other fabric treatments (Lykaki et al., 2021). In addition, it should be noted that certain MMCFs are not only used in textile manufacturing but are also widely present in cigarette filters and personal hygiene products, possibly contributing to this high percentage (EEA, 2022b; ETC/CE, 2022b). Furthermore, due to characterisation difficulties, these natural polymer microfibres were wrongly considered as microplastics, plastic microfibres, by hundreds of studies, leading to disproportionately high microplastic counts and an underrepresentation of bio-based microfibres (Suaria et al., 2020; Comnea-Stancu et al. 2017).

Recently, concerns have arisen about the impact of these bio-based microfibres (Suaria et al., 2020). Often, the environmental threats associated with bio-based microfibres are underestimated as there is a general assumption that their biodegradability reduces their lifetime and thus their impact.

While microfibres from regenerated cellulosic fibres, such as viscose and lyocell, have been found to have less detrimental effects on ingestion by aquatic species compared to plastic microfibres, gut damage still occurred (Kim et al., 2021; Remy et al., 2015). The persistence of microfibres in the environment poses risks to human health as they can bioaccumulate when ingested by organisms, facilitating their introduction into the human food chain. Both bio-based and fossil-based microfibres have, for example, been found in the faeces of king penguins (*Aptenodytes patagonicus*) (Le Guen et al., 2020). Remy et al. (2015) have suggested that microfibres derived from cellulose fibres, such as viscose, are less likely to bioaccumulate than synthetic microfibres because, cellulose, even of artificial origin, is more digestible. Nevertheless, because both natural and synthetic textile fibres are typically treated with a variety of chemicals, such as dyes and finishing agents, this also raises concerns about the role of microfibres as vectors for introducing hazardous substances into the environment. Additionally, the faster degradation of certain bio-based microfibres could possibly facilitate the release of toxic additives into the environment (Liu et al., 2021).

Over the past decades, microplastics have been identified as pervasive, chronic, persistent, transboundary pollutants that pose a threat to the environment and human health (EEA, 2022b; ETC/CE, 2022b). It is evident that microplastic pollution poses a big challenge and preventive measures should be considered. At the same time, the knowledge of microfibres released from bio-based fibres remains rather limited. As indicated, however, the impacts associated with this type of microfibre should not be minimised and need further research.

5. Conclusions

Bio-based fibres include a broad and diverse range of fibres. While these can be natural or man-made, they are all derived from natural inputs, such as sugars, cellulose or proteins. Due to their natural, non-fossil origin, they are often regarded as go-to fibres in the search for more sustainable textiles. While these fibres offer great potential to steer away from the use of fossil-based fuels their bio-based origin does not absolve them of environmental burdens, such as those related to agricultural activities, forestry practices and fibre processing. Moreover, it cannot simply be assumed that all bio-based fibres are biodegradable. Even for those fibres that are biodegradable, care must be taken since processing treatments and the presence of chemicals can reduce or hamper their biodegradation. Consequently, concerns related to sustainable production practices, microfibre shedding, waste and recyclability also need to be carefully assessed with regard to bio-based fibres.

When petrochemical inputs are replaced by crops, different environmental burdens arise that are mainly related to agricultural activities such as pesticide and fertiliser use, water consumption and land use. These are well-known problems that are commonly associated with the conventional cultivation of cotton. Nevertheless, some alternative natural fibres, such as flax and hemp, show great promise as more sustainable substitutes as they often require less irrigation and fewer agrochemicals compared to conventional cotton. Further innovation, however, is required to overcome technical hurdles and minimise the environmental burdens associated with these natural fibres.

Among the man-made bio-based fibres, regenerated cellulosic fibres, such as viscose, have the largest market share and are made from cellulose, mainly originating from woody feedstock. As man-made cellulosic fibres derived from woody feedstock are widely produced without irrigation and agrochemicals, environmental impacts associated with these fibres are mostly linked to forestry practices and the emissions during chemical processing of cellulose. Sustainably managed, certified production forests in Europe can be a source of wood with lower impacts on land and ecosystems. Application of fibre and dissolving pulp production processes according to the EU Best Available Techniques (BAT), which are compulsory in the EU, minimize process emissions.

While the renewable origin of bio-based fibres is an important environmental advantage, it remains vital to minimise the environmental intensity associated with their feedstock production. Responsible sourcing practices are therefore crucial for the sustainability of bio-based fibres. This includes sustainable agricultural and forest management practices. Some research also explores the use of alternative input materials, such as hemp or bamboo. More ideal is the use of second-generation feedstock made from biowaste, which does not compete with other land uses, while, at the same time, creating an outlet for waste streams and delivering low-cost revenue streams for agricultural communities.

Sorting and recycling are a major challenge in terms of textile waste treatment in general. Hence, this also applies to bio-based textile waste. Nevertheless, the regeneration of new textile fibres from dissolving pulp derived from cellulosic textile waste offers great potential. During fibre production of both virgin or waste-derived fibres, solvent recovery systems that allow closed-loop operations are key and great potential lies in the development of less destructive solvent alternatives.

Another frequently mentioned advantage of bio-based fibres is their biodegradability. In the first place this depends on the polymer type. Synthetic polymers, even those derived from natural inputs such as sugars are, in most cases, not biodegradable. Furthermore, the biodegradability and environmental compatibility of bio-based fibres can be, negatively affected by dying, coating, and other fabric treatments.

Taken together, a systemic approach is required to better understand the trade-offs associated with bio-based fibres. This will enable the identification and tackling of pitfalls and barriers that hinder these fibres reaching their full economic and sustainable potential. Overall, the development of an improved, ecologically sustainable production chain for high quality alternative fibres in parallel with an integrated quality system for raw and processed fibres based on eco-labelling criteria could contribute to the further development of a competitive, innovative and sustainable bio-based textile fibre industry in the EU.

Nevertheless, the lack of up-to-date and accurate data concerning the environmental impacts of textile fibres and the fragmented nature of the supply chain, makes it challenging to assess the environmental performance of fibres and to develop truly sustainable ones. Hence, it is often more implementable and straight forward to focus on improving useful lifespans and reuse than aiming to choose the best fibre in terms of environmental impact. Life-extending strategies and prevention of the premature discarding of textiles may therefore present more robust and effective routes to reduce the environmental impacts related to production and consumption in general.

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