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SCIENCE FOR POLICY BRIEF

Bio-based products

The European Commission's Knowledge Centre for Bioeconomy

Bio-based textiles in a sustainable and circular bioeconomy

HIGHLIGHTS

→ Bio-based textiles can be made of natural, semi-synthetic and synthetic fibres. They can help reducing the use of virgin fossil-based synthetic materials, along with other strategies such as increasing textile-to-textile recycling and limiting overproduction. This is challenging, as fossil-based synthetic textile fibre production has grown significantly, reaching 67 % of the global market in 2023.

→ Although cotton is the second most produced fibre at global level, the EU holds a minor share of the cotton market and it is expected to remain a net importer in the near future.

→ Flax, hemp and wool are important sources of natural fibres that can be produced and processed fully within the EU. However, their value chains are fragmented with small production volumes, resulting into a limited market share. For flax and hemp, in addition to a general up-scaling, the steps which have main room for improvements are retting /degumming, spinning, modification and treatment of fibres and yarns. For wool, increasing production and use in Europe requires rebuilding a European infrastructure for collection and processing.

→ Semi-synthetic fibres are obtained by a chemical conversion of cellulose. They are, after cotton, the most common bio-based fibre type. In addition to certified wood, important sources of cellulose with high untapped potential are agricultural residues, miscanthus and switchgrass from degraded lands, reallocated wood cellulose from paper to textile industry and end-of-life textiles.

→ Polylactic Acid (PLA) is the only synthetic bio-based polyester fibre on the textile market. Although biodegradable, PLA has inferior performances than fossil polyesters and higher costs are often associated. Other fully bio-based synthetic fibres are still in early developments. The bio-based synthetics production requires reliable and sustainable sources of bio-based monomers, as well as sufficient and efficient production infrastructure and logistics. Knowledge gaps on sustainability of bio-based synthetics should be addressed.

Policy context and scope of this brief

The bioeconomy in the EU is a key enabler and outcome of the green transition. It contributes to the European competitiveness while reducing strategic dependencies and with a potential of enhancing sustainability. The 2018 update of the **Bioeconomy Strategy** and its **Action Plan** strongly support the development of a flourishing European bio-based textile sector.

The **EU Industrial Strategy,** updated in 2021, identifies textiles as a key product value chain with an urgent need and a strong potential for the transition to sustainable and circular production, consumption, and business models. The strategy puts forward the co-creation of transition pathways across relevant industrial ecosystems. The 'Transition Pathway for the Textiles Ecosystem' underlines that the production and uptake of (new) bio-based, recycled, and renewable fibres is one of the areas where investments are most needed. It also acknowledges the importance of research and innovation, remarking the medium technology readiness level of key technologies such as textile-to-textile recycling of post-consumer streams, the (increased) use of bio-based raw materials and phasing out of fossil-based resources.

The **EU Strategy for Sustainable and Circular Textiles**, adopted in March 2022, supports the reduction of the textile industry's dependence on fossil sources with bio-based innovations. The Strategy lays down a forward-looking set of actions, which include setting ecodesign requirements for textiles under the Regulation on **Ecodesign for Sustainable Products** framework, developing Green Public Procurement requirements, and revising the EU Ecolabel criteria for textiles. In parallel, the European Commission has proposed to introduce mandatory and harmonised Extended Producer Responsibility schemes for textiles in all EU Member States.

Such converging policy efforts aim to leverage the untapped environmental, economic, and social benefits that the bio-based textile sector can bring to the European citizens. The EU research and innovation programmes currently support its high innovation potential. Understanding opportunities and knowledge gaps is crucial to support further investments.

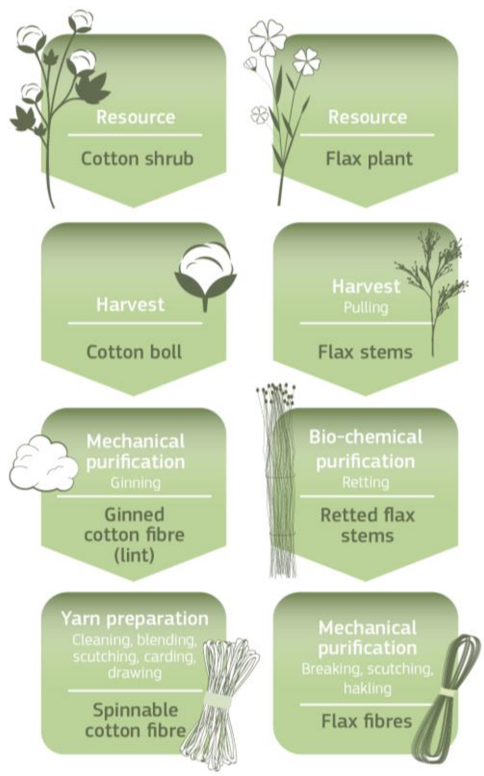
The bio-based textiles value chain

Textile fibres can be used for a broad range of applications, from apparel (clothing, fashion, work wear), to home textiles, furniture and technical uses (e.g. insulation material for construction, composite reinforcement, protective barriers in agriculture). They can be divided into three types that are produced through significantly different value chains: **natural fibres**, **semi-synthetic fibres** (also called Man-Made Cellulose Fibres or MMCFs), and **synthetic fibres**. Each fibre's value chain has its own resources, technologies, opportunities, and knowledge gaps. Once the fibres are converted into a yarn, this distinction is less pronounced. Natural fibres as well as semi-synthetic fibres are considered bio-based and largely renewable, while synthetic fibres are still mainly fossil-based.

Natural fibres

Natural fibres are obtained from plants (e.g. cotton, flax, hemp) and animals (e.g. wool). Their value chain includes multiple labour-intensive steps, involving mechanical and sometimes chemical purification. The production process starts with farmers that breed animals for their hairs or cultivate fibre crops, requiring several agricultural inputs.

Figure 1: Cotton and flax fibres production processes



Source: adapted from Harmsen et al. [1]

The cultivation of widely used natural fibres like **cotton** raises environmental challenges in terms of water, land, fertilisers, and pesticides consumption. Organically grown cotton can mitigate these impacts, whereas its certification is still complex. Cotton is by far the most used natural fibre for apparel. Favourable characteristics include softness, strength, and comfort. Before the arrival of cotton, **bast fibres** like flax (linen) and hemp were the main natural fibres used in Europe. Bast fibres need to be separated from the stems of the plant, making their processing more complex. In addition, they are stiffer and rigid compared to cotton, and wrinkle more. The cultivation and harvesting phase are followed by seeds rippling and retting/degumming of the stems. Highly mechanical and labour-intensive fibre processing (hackling, carding, spinning) is required to produce a yarn (Figure 1). Hemp can be applied for textiles in two ways: short fibres and long fibres. Short hemp fibres undergo a cottonising process and are added in small percentages to fibre blends within the cotton-system spinning. Their cultivation and processing are currently in the industrial stage. Long hemp fibres can be used in textiles, alone or blended with other (natural) fibres. All plant fibres are breathable and have a high moisture absorbency.

Wool requires a cleaning process before it can be spun into yarn. It is characterised by high breathability, heat regulation, insulation, and flame-retardant properties.

Semi-synthetic fibres (MMCFs)

Semi-synthetic fibres are man-made fibres of biological origin obtained from plants (mainly trees) containing **cellulose**, a natural polymer. Cellulose pulp used for textiles, of higher quality than paper cellulose, is called dissolving cellulose pulp. It is converted into fibres by either chemical derivatisation or direct dissolution; regeneration in a solvent allows to obtain continuous filaments and to produce the cellulose fibres (Figure 2).

Figure 2: Cellulose fibres

Source: (c) Curie stock.adobe.com

The quality and properties of the dissolving pulp are critical to produce MMCFs, and it is crucial to remove most of the non-cellulosic components of wood.

Dissolving pulp can be derived from multiple sources:

- **Hardwood and softwood** are the main ones. The production of dissolving pulp from wood is well integrated in the paper and pulp industry in Europe.
- **Cotton linters and bamboo** are also common. The latter grows very fast and can be harvested annually. Bamboo viscose fibres are quite often used in apparel and clothing.
- Widely available **agricultural residues** (e.g. wheat straw, switchgrass, sugar cane bagasse, pruning from fruit trees, cotton stalks and the woody residues from flax and hemp), could also be used. Conventional pulping applied to agricultural residues does not ensure a good quality dissolving pulp, while the organosolv process gives a better output [2]. Residues differ also greatly regarding cellulose content and fibre yield, which must be considered. A viable production route (cultivation, harvesting and collection, high quality pulping) is still to be established.
- **End-of-life cotton and viscose** textiles have a good potential as feedstock. They can be fibre to fibre recycled by using the same chemical processes applied to native MMCFs. This has been addressed in many R&D projects, part of which are entering the commercial phase[1].

MMCFs can be classified according to the chemical manufacturing process applied [1]. The first MMCF, **viscose**, was introduced in 1893. It revolutionised the textile fibre production, as it resembles silk (produced by silkworms) but it is stronger, more easily washable and much cheaper. The viscose process requires large volumes of water and harmful chemicals. In the past, chemicals were directly released into the environment, resulting in significant environmental pollution. Today, the viscose process is improved with much less pollution [3].

The **modal** fibres are made in a modified viscose process with similar reactants. They have very good mechanical properties under wet conditions, are soft and have a good drying capability.

The most used direct dissolution process, the **lyocell** process, avoids the formation of intermediate derivative cellulose and gives high quality fibres. The used solvent and the water are recovered and recycled in a closed system. The industrial production started in 1980 and it is one of the latest innovations in the production of textile fibres.

The cuprammonium (or **cupro)** dissolving process was invented in 1890. Today it is only rarely used due to the copper release and the high cost.

Cellulose **acetate** fibres were produced for the first time in 1923. 80% of the global cellulose acetate production is for cigarette filters. The textile fabric properties are not outstanding, and the fibres are mainly blended with other fibres when used in apparel and clothing or applied as lining.

In addition to established manufacturing processes, there are **new developing cellulose regeneration methods** based on dissolving cellulose in ionic liquids, carbamate derivatisation and cold alkaline dissolution. These processes are especially used for recycling of end-of-life cotton and viscose textiles.

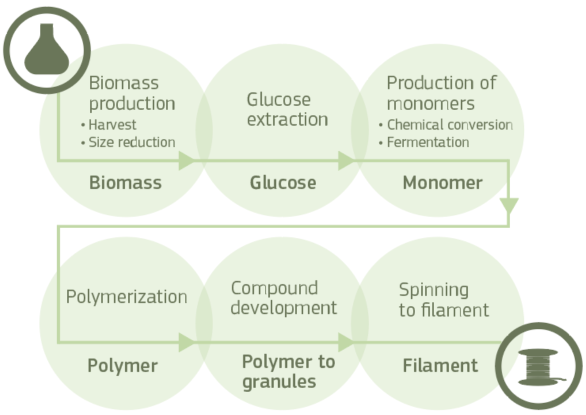
[1] See for example, New Cotton or RegioGreenTex projects.

Synthetic bio-based fibres

Synthetic fibres are produced by the petrochemical industry from fibre-forming polymers, like the ones used for plastics. In a polymerisation reaction, small building blocks called monomers are converted into a polymer, a long molecule that consists of repeating monomer units. The reaction produces solid polymer granulates that are first mixed with additives and colorants, and then converted to fibres and filaments by melt spinning (Figure 3).

Monomers can be both fossil and bio-based. Bio-based monomers, often referred to as bio-based platform chemicals, are typically produced in biorefineries through biomass pre-treatment and further conversion. Sugar, starch, lignin, plant oils and proteins are possible feedstock options for the extraction of bio-based monomers.

Figure 3: Synthetic bio-based fibres production; from bio-mass to filament



Source: Harmsen et al [1]

Bio-based monomers reacting similarly to fossil monomers can be easily integrated into the existing petrochemical production infrastructure to produce **drop-in polymers.** Drop-ins present the same structure and properties of conventional fossil polymers. They can be converted into fibres in the same way as their fossil counterparts, and directly substitute fossil polymers in the fibre production.

The polyester polyethylene terephthalate (PET), commonly used in beverage bottles, dominates the textile fibre market. PET is a fossil synthetic polymer made from ethylene glycol and terephthalic acid. PET fibres are also made from recycled PET bottles (rPET). **Bio-PET** is a **partly bio-based** alternative to PET, where the ethylene glycol drop-in component is made from bio-based feedstock. PET, whether fossil-based or partly bio-based, is highly resistant to biodegradation, causing environmental problems mainly due to microfibres release that accumulate in nature. Among the **bio-based synthetic fibre polymers** without a fossil-based analogue, polylactic acid (**PLA**) is the main commercially available 100 % bio-based polyester. PLA is a biodegradable polyester that has been actively developed since the 1990s for applications in single-use plastics such as food packaging and cutlery. PLA has a different chemical structure than PET, and especially thermal properties for textile applications are inferior compared to PET. Other examples of new, fully bio-based polyesters are PEF (polyethylene furandicarboxylate) and PBF (polybutylene furandicarboxylate), which are still under development, and far from the marketing stage. Of these, PEF is a potential fibre polymer candidate due to its promising fibre material properties.

Fibre properties

Natural, semi-synthetic and synthetic fibres are produced from different resources and in different value chains, resulting in various properties, largely determined by the type of polymer they are made of, as well as by the additives used. Table 1 illustrates the fibres properties as a rule of thumb.

Table 1: Main properties of the different fibre types**.**

Parameter	Natural	Semi-synthetics	Synthetics
3D-structure	Complex	Simple	Simple
Fibre length	2-5 cm	Infinite	Infinite
Fineness	10-40 µm	Adjustable	Adjustable
Affinity for water	High	High	Low
Breathable	Yes	Yes	No
Resistance to degradation	Low	Low	High
Thermoplastic	No	No	Yes

Source: own elaboration, based on qualitative assessment by authors

Fibres produced from the same polymer have comparable properties. Plant-based natural fibres (cotton, flax, hemp) and semi-synthetic fibres (viscose, lyocell, cupro) are all based on the natural polymer cellulose. Cellulose has a strong affinity for water, and this is the reason why these textiles take up water, do not dry quickly, are comfortable to wear, and are biodegradable (as cellulose is biodegradable). Synthetic fibres like polyesters and polyamides are composed of polymers processed by melting into fibres and are therefore thermoplastic. Thermoplastic polymers can be reprocessed by melting, which is a huge advantage in a material recycling process.

Different fibre production chains include different processing steps, and large variations in production scale and production rates exist (Table 2). Investment costs can vary significantly, and environmental impact is different and related to different steps of the value chain. Value chains can be manual, labour intensive or highly automatised; process technology level can vary from rather simple to advanced. The fibre production process can be self-standing or integrated in other industrial value chains.

Table 2: Main features of bio-based fibres' production chains.

	Natural	Semi-synthetics	Synthetics
Production rate	Medium	High	Low
Complexity	Medium	Medium	High
Investment costs	Medium	Medium	High
Environmental impact	Low	Medium	Medium
Automation level	Low	High	High
Technology level	Mature	Mature	Immature
Industrial integration	High	High	Low

Source: own elaboration, based on qualitative assessment by authors

The bio-based fibre market

Global fibre market[2]

Textile fibre production (Figure 4) is a global scale business and takes place largely outside Europe. The sustainability of the textile sector is hindered by:

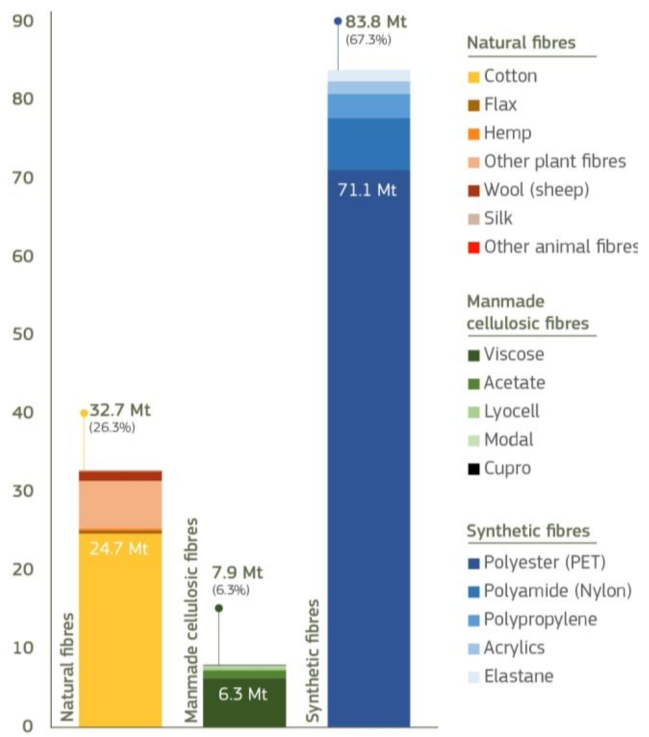
- **Increasing demand and production volumes**, from 58 Mt of textile fibres produced in 2000 to 124 Mt in 2023. Following this trend, the annual production could grow to 160 Mt by 2030.
- **Increasing reliance on virgin fossil-based synthetic materials**, which dominate the market thanks to low prices, thus fuelling fast-fashion.
- **Low textile-to-textile recycling**, resulting in low share of recycled fibres. Pre- and post-consumer recycled textiles account for less than 1 % of the global fibre market.

In 2023, **PET** held a 57 % share of the global fibre[i] production, equivalent to 71.1 Mt, while rPET fiber production is around 8.9 Mt. The market share of bio-PET is still very low, around 0.02 % of global PET fibre production. The total production of **PLA** is in the range of 0.5-0.7 Mt and a 40 % annual growth (for all PLA applications, not only the textile) is expected.

The annual production volume of clean sheep **wool** fibre is approximately 0.9 % of global fibre market (1 Mt). Recycled wool accounts for 6 % of the global wool market. Australia, China, and New-Zealand are the biggest producers of wool for textiles and apparel [4]. Of the other animal fibres, **silk** production covers 0.07 % of the global fibre market.

Cotton is the most produced bio-based fibre (24.7 Mt in 2023), representing 20 % of global fibre production. Recycled cotton holds a significant potential and accounts for 1 % of the total cotton production. Most of the world's cotton is grown in the United States, Uzbekistan, China, India, Brazil, Pakistan and Türkiye. Besides cotton, **other plant-based fibres**, mainly **jute** and **coir**, contribute to the global production. In 2023 they accounted for 6.7 Mt. 6 % of this total was covered by **flax** fibre production, estimated around 0.4 Mt. 64 % of the flax used for fibre in 2023 was grown in Europe, mainly in France. Significant flax production takes place also in Belarus, Russia, Ukraine, and China. **Hemp** fibre production was estimated 0.2 Mt in 2023 (4 % of the other plant-based fibre market). France contributed for almost 50 % of global hemp fibre production in 2023, followed by China, North Korea, Netherlands, Australia and Unites States. Its advanced manufacturing infrastructure allows China to produce large volumes of hemp textiles. More and more countries are allowing hemp production.

Figure 4 : Global fibre production 2023 (Mt)



Source: Textile Exchange [4]

Global **MMCF** production has more than doubled since 1990, reaching 7.9 Mt in 2023 (6 % of the total global fibre production). Viscose is the main MMFC fibre. Its production volume in 2023 was 6 Mt (80 % of the global MMCFs production, 5 % of all textile fibres). Modal fibres, lyocell and cellulose acetate cover respectively a 3 %, 4 % and 13 % share of the total MMCFs market.

[2] Global market data are sourced from Textile Exchange [4].

EU bio-based fibre market[3]

In 2021, in the EU-27 almost 700 000 people worked in the bio-based textile sector. Its value added was EUR 25 billion, 3.5 % of the total value added of biomass producing and converting sectors [5].
The average annual **cotton** production in the EU-27 over the last 10 years was 0.35 Mt [6], meaning 1.4 % of the global cotton production, with Greece and Spain being the main producers. Within the EU, cotton certified to the EU Organic Regulation is grown in Greece (2048 t in 2020/21), Spain (23 t in 2022/23), and Italy (33 t in 2022/23) [4]. Since 2019, both cotton production and cultivated area in the EU-27 show a decreasing trend which is partially compensated by the increasing prices and EU cotton trade balance.

Europe is one of the main producers of **flax** (Figure 5) used for fibres and high-quality linen [7]. The average production of flax fibres in the EU-27 from 2015 to 2023 was 0.74 Mt[4] [6].

Figure 5: Mown flax on a field before harvesting

Source: © zmitry_2014 stock.adobe.com

Belgium, France, and the Netherlands are top producers and exporters of flax fibres, while Italy is the main exporter of linen fabrics in Europe. Approximately 10 000 companies in 14 countries are involved in the European linen industry [8]. Globally, China is the main importer of flax fibres and today most of the processing of flax fibres into linen fabrics happens outside Europe. The European **hemp** production area increased from 20540 ha in 2015 to 28020 ha in 2023 (+40%). In the same period, the production of hemp increased from 0.09 Mt to 0.16 Mt (+67%) [6]. Some of the top exporters of hemp fibres in the EU are France and the Netherlands. The EU-27 exports peaked in 2022/23, reaching 0.07 Mt, thanks to the high demand from U.K. and China. The EU-27 imports of hemp from third countries have also increased in the last years.
Annual shearing, which is necessary for the well-being of sheep, produces 1.5-3 kg of coarse wool per animal, meaning over 0.2 Mt of wool in Europe [9]. European **wool** could in theory contribute to 20 % of the total wool production. The volume of European wool used in textiles is unknown, but it is probably not much, as the coarse wool from the European dairy and meat industry is currently seen as a valueless by-product. It is of little interest to the textile industry due to cheaper fossil-based alternatives, neither for clothing nor for interior design products, and must be disposed of, at a high cost to small breeders. To avoid these costs, coarse wool is often left to sink into the soil illegally with manure instead of being landfilled. More often, it is burnt, producing dangerous air and soil pollution. Many activities are initiated now to apply this valuable source of natural fibres in various applications [10].
In 2017 the global production of dissolving **cellulose pulp** was 9.5 Mt, and the European share was 1.7 Mt. A major part of the global dissolving pulp is for MMCFs production, but it is also used for cellulose acetate, cellulose ethers, and nitrocellulose [11]. The EU production of MMCFs is estimated to be around 1.5 Mt [11]. European producers of MMCFs are exporters, dealing with competitiveness issues with respect to extra EU producers of fossil based fibres.

Sector outlook and recommendations

The market share of bio-based textiles is dependent on the overall textile **consumption patterns**, and on the success rate of textile recycling. There are many opportunities for increasing the share of bio-based textiles, but these will not reach the fossil fibres' production volumes mainly due to economic and biomass availability constraints. Given the prominent role of fossil-synthetic fibres, their phase out is a medium to long-term process and continuous effort is needed both at the level of R&I but also systemic. Over the last decades, consumers became accustomed to the characteristics of fossil-based textiles such as wide availability, affordability, elasticity, moisture repellence, stain resistance etc. These characteristics are not easily met by bio-based fibres, and consumers might be less inclined to accept changes. On the other hand, improved awareness about the benefits of bio-based textiles and circular economy principles could foster their market uptake.

Natural fibres

Although cotton is by far the most produced fibre within the bio-based textile sector, and it is expected to keep a prominent role especially in apparel applications, it is not expected that cotton production in the EU will grow. It will remain a net importer of cotton. On the other hand, the production of **bast fibres** (hemp, flax, nettle) in the EU could grow. Historically these were the main fibres for textiles in Europe, with many spinning mills and weavers. Bast

[3] The brief focuses on EU data; when not available, European data was used.

[4] Data are referred to the amount of harvested crop.

fibre crops fit well in the (mostly north-western) European ecosystems and are useful rotation crops that contribute to biodiversity and healthy soils. For example, hemp can be double cropped with grain production and hemp shives can be used to replace peat as a growth medium for horticulture. An increasing role of bast fibres like flax and hemp, as well as alternative plant-based fibres from bast, leaf or grasses could alleviate the pressure on cotton demand, as main source of natural fibres for textile applications. Small production volumes from fragmented supply chains represent an obstacle to such development. Investments in technologies, aimed to **strengthen supply chains,** could stimulate production volumes while keeping low environmental impacts. In addition to a general up-scaling, the steps which have the main space for improvement are retting/degumming, optimised spinning processes and modification and treatment of hemp and flax fibres and yarns.

Extensive sheep farming can play a role in nature preservation in some ecosystems. The combination of meat and fibre production could improve the economic viability and environmental sustainability of sheep farming. A joint effort from public and private sectors, and especially the agricultural sector, leveraging innovation and technology, could revitalise wool fibre production in Europe. The main target should be rebuilding a European infrastructure for **wool collection and processing**. Once this logistical system is back in place, more processing capacity will be created in Europe. The expertise is in place to do so.

Semi-synthetic fibres

There is a consensus that the European MMCFs production can increase. Several **biomass sources containing cellulose** can be used for producing MMFCs. New processes for cellulose regeneration and dissolving can further increase the production.

Wood pulp will remain a primary source due to its abundant availability and well-established processing infrastructure, supporting consistent quality and sustainable management practices. Of the grasses, **bamboo** stands out for its rapid growth, minimal water and pesticide needs, and strong, silky fibres suitable for textiles. Bamboo is not a native plant in Europe, and could be considered as an invasive species, if spread quickly. Perennial grasses such as **miscanthus and switchgrass** thrive on marginal lands and require few inputs, making them attractive biomass sources. In parallel, non-wood **agricultural residues** and lignocellulosic side streams show a high untapped potential. Efficient methods for converting them to dissolving pulp and textile fibres should be developed. In fact, these biomass sources not only contribute to reducing environmental impact but also support local textile production and circular economy practices in the EU.

There are opportunities for reallocation of wood cellulose from paper to textile industry. In favourable market conditions, paper pulp manufacturers could shift to dissolving wood pulp for textile applications.

Finally, there is significant potential for using cellulose-based (post-consumer) **end-of-life cotton and viscose textiles** as a feedstock for MMCFs. The market share of MMCFs made from recycled feedstock was 0.7 % in 2023 [4] and it is expected to increase significantly in the coming years thanks to new recycling technologies for textile waste.

Synthetic bio-based fibres

For both bio-based drop-ins and new bio-based polymers (Figure 6), the main challenge is to **substitute synthetic fibres of fossil origin.** The key targets are PET, due to its huge production volume, and elastane, as small amounts of this synthetic fibre are often added to fabric and are considered a contaminant in recycling. The microplastic and microfibre release from these fibres is of great concern.

PLA is the only bio-based and biodegradable synthetic fibre for textiles on the market. Whereas its properties are inferior to those of PET in relation to textiles, biodegradability is key added value.

Figure 6: Fabrics made of bio-based synthetic fibres

Source: © Mikael Skrifvars

Production costs also hinder competition with PET while bio-based alternatives to elastane are not available yet. Bio-based polyester PEF has a high potential, but it remains to be seen if it will succeed in textile applications. Limited bio-based monomer alternatives represent a barrier to produce synthetic bio-based fibres in high volumes. In fact, the bio-based synthetic fibres production requires reliable and sustainable **sources of bio-based monomers**, as well as sufficient and efficient **production infra-structure and logistics** to upscale the production of bio-based monomers and polymers.

In addition, preferable textile characteristics such as high strength, high thermal stability and biodegradability are hard to combine in one type of fibre, and more research is required.

Knowledge gaps

Addressing lack of data, assessing multiple impacts, and analysing competitiveness is key to support policies with sound evidence. The following knowledge gaps have been identified.

1. Environmental performance of new bio-based textiles compared to their established alternatives. In particular the performance of new bio-based synthetic fibres in terms of biodegradability, technical durability, environmental exposure, wear and behaviour in the textile finishing and dyeing, as well as disposal in waste handling systems.
2. Commercial viability of new sustainable business models in the bio-based textile sector and their competitiveness with respect to fossil-based materials, as well as consumer expectations and perceptions of bio-based textiles.
3. Role of textiles (fossil-based and bio-based) regarding microplastics generation, including to what extent biodegradability can minimise/prevent the effects of microplastics shedding on the marine ecosystem.
4. End-of-life options for bio-based textiles and how to dispose them in waste handling systems.
5. High quality and accurate data (including traceability) representing the textile sector, to ensure a good understanding of its dynamics. Quantitative data on the final destination of the produced fibres in terms of product category is particularly relevant.

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