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Review Article

Textile industry as a major source of microplastics in the environment

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Abstract

This review brings together data on the impact of (micro)plastics, on the environment. Critically evaluates studies on the use of various techniques for recycling textile plastic, which is a major polluter of the environment. In this review, let's focus a bit more on industrial waste in the textile industry since it would be easiest possible to capture and recycle it again. We also discuss LCA studies, bottlenecks, and future perspectives, for a lower impact on the environment. The main challenges which make further recycling progress difficult are discussed, such as the lamination of textile fibers with metal, new textile fibers that appear as a result of rapid development, the difference in the density of textile fibers, low recycling efficiency, etc. Finally, the possible uses of more environmentally friendly polymers are shown, which can be an alternative to the current synthetic polymers.

The results of the literature review showed that for the development of a sustainable textile industry, which would mitigate the impact of microplastics on the environment, from a long-term perspective, the integration of more intensive, complex decisions into the business models of manufacturing companies is necessary.

The environmental consequences will be even more intense due to the massive releases of textile microfibers into the environment and excessive accumulation, therefore, in order to achieve the specific goals of sustainable development, a reduction in the production of microplastics is first required, which is only possible with a global partnership of all countries to achieve a specific goal on a global level.

Abbreviations

UV: Ultraviolet; PES: Polyester; PET: Polyethylene Terephthalate; PA: Polyamide; PVC: Polyvinyl Chloride; Tg: glass transition Temperature; SBS: Poly (styrene-b-butadiene-b-styrene; ICT: Information and Communications Technology; AI: Artificial Intelligence; IoT: Internet of Things; *QR* code - Quick-Response code; LCA: Life Cycle Assessment

Introduction

Plastic production and the impact of micro-plastic on the environment

In the last 70 years, we have witnessed extremely rapid economic development, which in turn causes dangerous degradation of the natural environment [1,2]. We can see this in the excessive release of emissions into the environment [3], the warming of the earth's surface [4] and the associated extreme weather phenomena, the growing amount of waste [5], the depletion of the ozone layer [6], the occurrence of acid rain, the depletion of natural resources [7], and so on. With rapid economic development, the amount of produced plastic materials is also increasing, i.e. products, semi-finished products, raw materials, additives, etc. from various polymers [8,9].

From 1950 to 2021, the global production of plastics (polymeric materials) increased 1.5 million tons to 390,7 million tons per year [10,11]. Textile production is the world's second most polluting industry after the oil industry accounting for approximately 1.2 billion tons of greenhouse gas emissions (more than for international flights and maritime shipping combined) [12]. A Zion Market Research report on the global textile plastics market states that by 2025, the global market value of textile plastics production is expected to reach $1,207 billion [13]. The textile industry is ranked second in terms of land use and fifth in terms of greenhouse gas emissions [14]. Such systems should reuse resources and empower companies and their consumers to choose to reuse textiles [15]. Globally, most textile waste still ends up in landfills and incinerators, and less than 1% of all textile waste is recycled into fibers for use in new textile products [16]. Moreover, when plastic objects land in the natural environment, they are affected by weathering processes [17], including ultraviolet (UV) radiation [18-20], temperature fluctuations and increased humidity [21], biodegradation [22], as well as physical abrasion [23], and chemical oxidation [22]. Aging and weathering affect the physicochemical properties of plastics, which ultimately results in the breakdown of micro- and nano-plastics [24,25], which are invisible to the eye but affect the entire ecosystem [26,27]. The degradation of plastic largely depends on the type of polymer (for example, size, type, color, origin), and chemical additives [28]. In order to understand the life cycle of plastics and plastic products, it is important to know that they can have very different lifespans [29,30]. Well known is the so-called primary microplastic [31,32], which is added in production [33] to various products (e.g. abrasives industry,...). Another source of microplastics is t. i. secondary microplastics [34], which are produced by the breakdown of larger pieces of plastic, due to mechanical action or chemical decomposition [35]. The third source of microplastics is e.g. synthetic clothing, in which the fibers are released into the sewage during the washing of the clothes, pass through the sewage network into the treatment plant, and thus end up in rivers and seas [36-41].

In the 1970s, the presence of plastic residues in coastal waters was discovered for the first time [42]. However, the quantities were not alarming until the beginning of the century, when, unfortunately, it was realized that microplastics pose a threat to the environment, organisms, and human health. Research on the potentially harmful effects of microplastics on organisms (e.g. behavioural changes, immune responses) and the potential link to altered ecosystem functioning has been very intense in the last decade [43-45]. Numerous studies show that human influence in this area is enormous, even in uninhabited, remote places, as microplastics have not only been discovered in recent years in the sea but also high in the Swiss Alps and in the Arctic [46]. Among other things, researchers from Newcastle University have found plastic in drinking water, human excrement, and the digestive tracts of deep-sea animals [47,48].

The global consumption of textile fibers is also increasing every year, where polyester (PES) accounts for more than half of the total amount of fibers [49]. Considering that the volumes of PES produced for textile purposes (55 million tons) are twice as high as polyethylene terephthalate (PET) produced for packaging purposes, textile recycling is heavily underdeveloped, and new solutions are needed. Every year more than 100 million m^2 of coated and uncoated textile products are produced for the automobile, construction, footwear, and furniture industries. The amount of technical scrap from production and clothing of them is more than 10.000 tons/year. In addition, between 30.000 – 50.000 tons of recyclable and already-used products can be collected each year. Studies on the recycling of textile polymers (PES, PET, polyamide (PA), etc.) are, hence, highly relevant.

The reason for such large-scale production of plastic is mainly its excellent properties, such as impermeability to water, resistance to microorganisms, low density, as well as favorable mechanical properties, and low production costs [50-52].

Attempts to mitigate the impact of manufactured plastics on the environment by introducing recycling and reprocessing of plastics and bottlenecks in dealing with this issue

The European Green Deal has the grand vision of Europe becoming a climate-neutral continent by 2050 [53]. For the industry and the community, this is both a threat due to the slowness of emerging technological changes and an opportunity due to the search for new solutions. There are roughly two ways of reusing industrial textile waste fibers, i.e. textile-to-textile recycling, as called closed loop technologies [54-57], or textile-to-non-textile recycling, as called open loop technologies [58-60] (Figure 1). Many researchers are looking for closed- or open-loop technology, as part of the circular economy, and the possibility to respond favourably in this situation.

Not all possibilities of the circular (recycled) economy have been exhausted in industries. The same is in the textile industries, which are still one of the big polluters of the environment, and complementary industries for circular technology which try to enable products with high added value through innovative solutions and findings, through the development of sustainable and circular solutions [62,63]. Although, as mentioned above, recycling processes already exist, faster progress is hampered by factors such as high recycling costs or high costs of further integration, poor availability (organized collection) of waste textile fibers, and the lack of a comprehensive systematic approach to textile recycling on a global scale [64-66]. The heterogeneity of shed fibers causes additional difficulties in sorting and separating different types of fibers from each other and possibly from impurities. Additional bottlenecks are also the flood of chemically different fibers, unequal sizes and distribution of fibers, unequal shapes, and new processing of textile fibers as a result of development leading to inefficiency of reuse processes [67,68]. There are many open questions for which scientific solutions need to be found to be able to properly recycle the secondary waste of plastic textile fibers and helped to solve the resulting problem of plastic/microplastic environmental impact more widely. For example, synthetic PES fibers containing metal treads [69], a mixture of PES and PP [70], or non/impregnated non-woven

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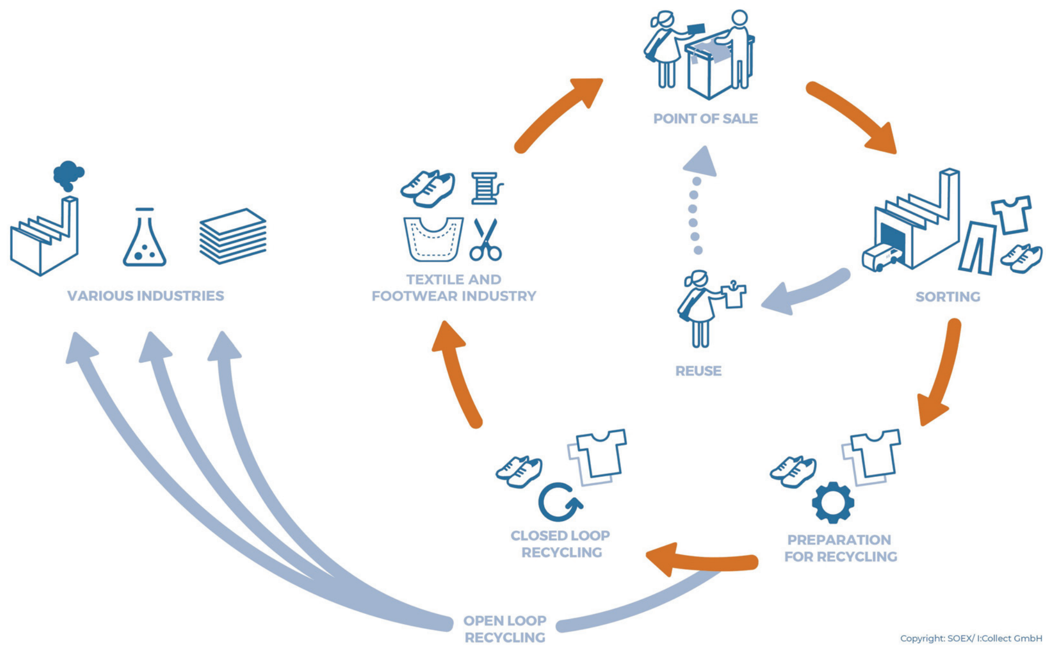

Figure 1: Schematic representation of the open and closed cycle of textile recycling [61].

materials made from them [71], as well as materials laminated with synthetic polymers (acrylic, polyurethane, PVC, ethylene-vinyl acetate) [72-75], which cannot yet be (massively) recycled or are difficult to recycle, especially in the field of secondary waste from the industrial textile industry. In the case of laminated textiles, is the rule that the coating is removed by relevant physical/chemical treatment (dissolution in solvent, and precipitation) or thermally by swelling (Tg related) and/or extracted and evaluated as a base material (additive, glue) to be used in the new lamination process.

The materials of similar densities, and Tg, need to be first mechanically separated from each other without changing the chemical structure of fibers or their composition and then cut, crush, or grind and used directly (pelletized if necessary) in a thermoplastic process, the metal thread, if exist, need to be removed [76,77]. The multifilament and coated materials could be also chemically activated (by alkaline/acid hydrolysis, hydrothermally, or enzymatically) [78,79] into smaller (micro-to-nano size) fragments of different microstructure (crystallinity), depending on the type of the polymers used, before or after cutting, and fully characterized related to the morphology, crystallinity and surface/interface properties (surface charge, hydrophobicity, roughness). Newer methods are also used such as simultaneously adding all the necessary additives for compatibilization (polyurethane, styrene, polyethylene, and polypropylene-based compatibilizers) [80,81] and dispersion in the other polymer matrix. The additives can be e.g. poly (styrene-b-butadiene-b-styrene (SBS) block-copolymers, acid and/or alkaline treatment for example with sodium hydroxide, hydrochloric or phosphoric acid, silane-, siloxane- or isocyanate-treated fibers [82]. With the novel solutions, the researchers expect benefits from the more reliable management of textile fiber waste, the acceleration of the use of recycled polymers, and other secondary raw materials for the development of new products, thereby protecting natural resources, having a strong impact on environmental protection (prevention of microplastics in water and soil) and consequently on the health of people and animals is expected.

The researchers' novelties are, of course, welcome because by upgrading the knowledge, we will have no textile landfills in the environment in the long term, no burning of textiles and the release of gases, and we will reduce the carbon footprint with friendly technologies, we will reduce the number of microplastics in water and soil, and we will influence the utilization of the zero-waste philosophy.

In order to be able to integrate all these advanced technologies as best as possible into the entire life cycle of a textile product and thereby reduce the release of microplastics into the environment, the big challenge will be to more intensively involve all (different) stakeholders who are active in the sector along the entire value chain. Insufficient literature was found in the field of innovative textile waste management solutions (e.g. high-quality separate collection, advanced sorting of used textiles and textile waste, tracking (maybe QR) of textile products, support for textile repair and reuse organizations, and public awareness) and in the field of symbiotic and sector-linked circular economy, including recycling, reuse, reduction, restoration, and processing. All of the above would enable the support and optimal functioning of the textile industry, which is currently not the best organized for an advanced circular economy that would limit the spread of microplastics.

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Life cycle assessment studies

Nano- and micro-particles have always been present among us and are natural materials in themselves. The harmful impact of these particles on the environment and organisms occurs where human activity, and consequently also the waste materials produced by these activities, is greater than the self-cleaning capacity of the environment and where the development of new synthetic materials, which are created with the development of society and to achieve a more comfortable life they go beyond a healthy relationship between man and the environment [83]. The production, consumption, and waste of plastics have been rapidly growing worldwide in the last decades. And it also should be emphasized that already the processes for the production of textiles require large amounts of various chemicals [84] and that chemicals and microplastics are also released in the wastewater during the preparation and cleaning/laundering of textile products [85]. Therefore, the textile industry affects our natural ecosystems in all stages of its production processes [86]. Very often, textiles are exported to a developing country, incinerated or landfilled, as recycling is still very low [87,88].

A basic tool used to support decision-making for sustainable development in all fields and which nowadays due to excessive human impact on the environment plays one of the very important roles is Life cycle assessment (LCA). The LCA technique, which is conducted in accordance with the principles defined in the international standards [89,90] can be used to assess how the recycling processes contribute to environmental protection [91], e.g. impact on water, air, soil, green energy, etc. Throughout their life cycle, textiles produce 5–10% of global greenhouse gas emissions and consume the second-largest amount of the world's water with polluting microplastics and chemical agents released to waterways [92].

As previously stated in the article, the mechanical recycling approach is the most feasible for the industry but it is not the only way to a successful circular economy. Life cycle assessment studies indicate that mechanical recycling of plastic materials is, in general, preferable to other management procedures in terms of optimizing overall energy use and minimizing the emission of gases that contribute to global warming [93]. Opposite, the main challenges are chemicals, purity, efficiency, and the amount of microfibers release [94]. As mentioned above the textile fibers can be recovered and recycled through sorting, washing, and remelting for use in new products, or by chemical reactions [95], then purified and converted into new applications. However, problems arise as the life cycles of textiles and clothing are unsustainable, due to the use of harmful chemicals, excessive consumption of water and energy, generation of large amounts of solid and gaseous waste, huge consumption of fuel for transportation to remote locations where textile units are located, and use of non-biodegradable packaging materials [96], and are expensive and lack process flexibility. Recent results showed that the main barrier facing these companies is technology [97], which accounted for 25%, while legislation and environmental issues were minor barriers, accounting for 15.7%.

According to the European Union's (EU) "Waste Framework Directive", which will come into force in 2025, textiles will have to be collected separately and compulsorily throughout the EU in the future (Figure 2). It is thus assumed that within a few years, the separately collected quantity of used textiles in Europe will increase to approx. 5.5 million tons [98]. Furthermore, future laws will also oblige companies to take care of recycling their post-industrial and post-consumer wastes.

As highlighted here, the recycling of polymers and textiles and the search for new sustainable sources will continue to be hot topics in this field. As the depletion of natural resources, population growth, and other changes that cause excessive consumption of raw materials continue, and not least EU legislation changes, interest in recycling and sustainability continues to grow rapidly. Thus, the survey showed that 83 percent of the Europeans questioned are aware of the impact of plastic/microplastics on the environment and believe that pan-European legislation is needed to protect the environment, which is also related to climate change. The European Barometer 2020 survey on the attitude of Europeans to climate change shows that environmental protection is important to 94 percent of citizens in all EU member states and 91 percent of citizens believe that climate change is a serious problem in the EU [99].

But in this century, i.e. the last 20 years, a lot has changed in the field of recycling [100-102]. The whole world is working to reduce the amount of plastic waste. The reuse of materials as secondary raw materials and recycling is increasingly emphasized [103,104], also with the help of new or improved value chain procedures, such as the example shown in Figure 3. Of course, with greater awareness and development, more and more alternative materials to classic plastics are coming to the market, such as biodegradable plastics, bio-based plastics, and recycled plastics. Today, there is a bioplastic alternative for virtually all polymeric materials and related applications [105-108].

The main challenges which make further recycling progress difficult were discussed in this review, such as the lamination of textile fibers with metal, new textile fibers that appear as a result of rapid development, the difference in the density of

Figure 2: Waste hierarchy - Preventing waste is the preferred option, and sending waste to landfill should be the last resort [98].

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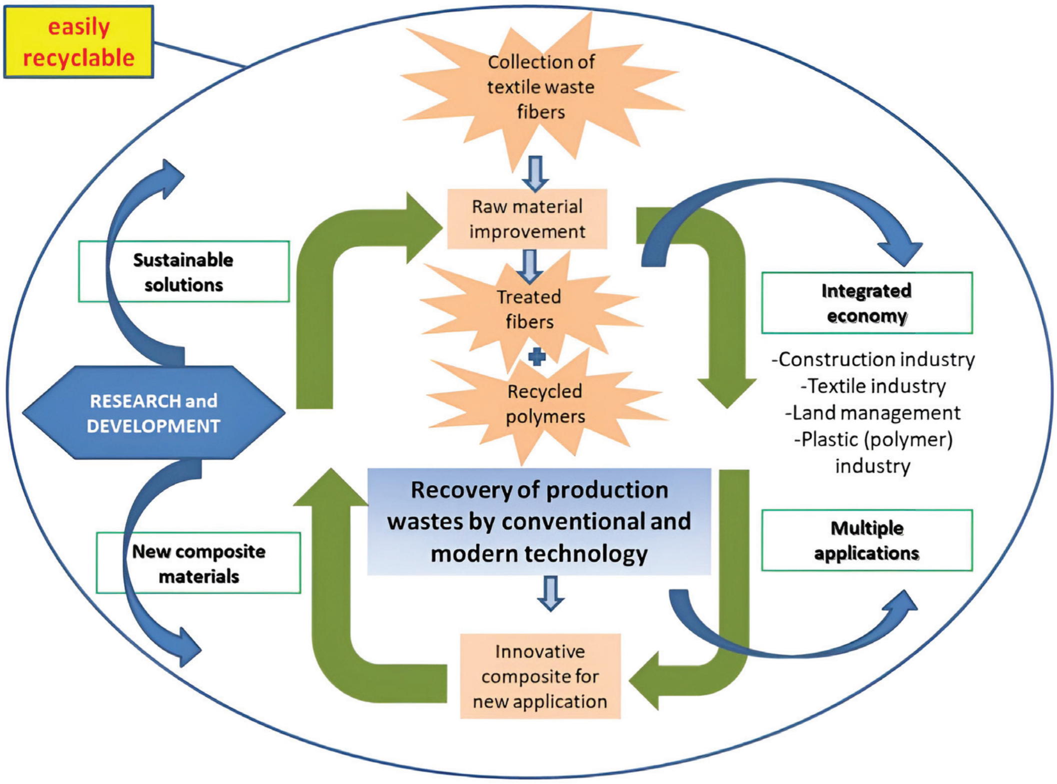

Figure 3: Possible way of textile (fibres) value chain.

textile fibers, low recycling efficiency, etc., and thus worsen the LCA assessment. Therefore, it remains a large "playground" for textile research activity and future perspectives for a lower impact on the environment.

Biodegradable and bio-basic polymers for textile industries

There is still confusion about the word "bioplastics", a common, incorrect belief that if something is derived from biomass then it must also be biodegradable. Biobased plastics are not always biodegradable and vice versa. Bioplastics are biodegradable, biobased, or both [109].

Nowadays, there are recyclables and biobased and biodegradable alternatives (Figure 4) for almost all types of polymers on the market [110,111], and the bottleneck of their use is based on three reasons: (i) the transformation of materials, where conventional polymers are replaced by new ones, requires knowledge about recycling, which is still at a lower level than conventional feedstocks, (ii) research and development of new materials based on recycled or bio-polymer matrix is required, which is expensive, and (iii) lack of knowledge on how to monitor and control synthesis variations, which can be greater in the use of recycled materials, as in the case of pure raw materials. However, the EU (2020a) suggests that textile material producers should use eco-design and sustainability measures to ensure that they participate in closed or open-loop systems (circular economy) [112].

The low cost and excellent properties of petroleum-based synthetic fibers [114] have limited the use of biopolymers in the textile industry. Although the transition from synthetic fibers to bio-based materials is rather slow, mainly due to technological barriers, it is inevitable due to the depletion of oil resources and the growing concern for the environment [115] and, as mentioned several times in the article, due to the political directives of the EU. The use of biopolymers not only leads to the production of a more environmentally friendly product but also can have various advantages such as low-weight fabrics and in some cases low manufacturing costs [116]. Even more, so far, the recycling of textile fibers has been focused on the chemical and mechanical processes. Opposite, bio-based processes for textile production and recycling have received little attention. Fermentation and enzymatic processes have been demonstrated for the production of all types of textiles, which in combination with an enzymatic deconstruction of end-of-life cellulosic textiles could allow them to be recycled indefinitely. Within the context of the circular economy, bio-based processes could extend mechanical and chemical textile recycling mechanisms in the technical cycle, enabling greater circularity of textiles in the biological cycle before composting takes place [117].

The requirements for the development of sustainable biopolymers used in the textile industry are continuously increasing and biopolymers attracted considerable attention as a new generation of smart textile materials produced from renewable sources, e.g., cellulose, chitosan, alginates, and poly(lactic acid) [118].

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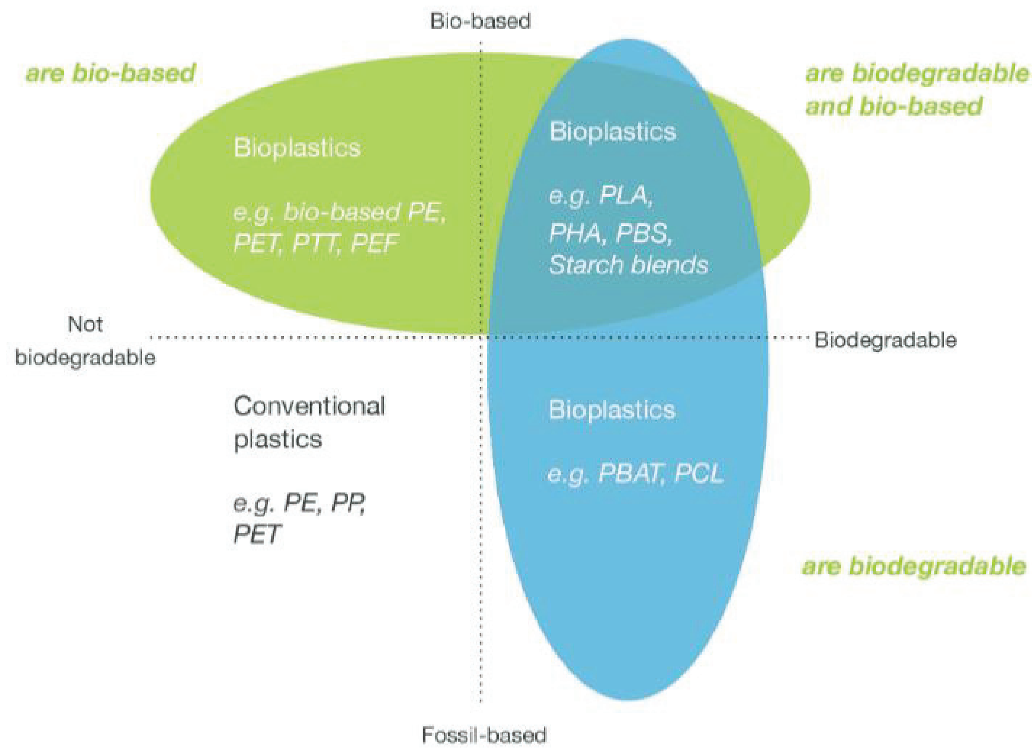

Figure 4: The material coordinate system of bioplastics [113].

Discussion

As mentioned in the introduction textiles are the fifth for greenhouse gas emissions, the second in terms of land use, the fourth highest-pressure category for the use of primary raw materials and water, and a major source of microplastic pollution in the production and use phases. Thus, in the textile industry, the impact of plastic and, consequently, microplastics on the environment is still a big challenge, as the production of industrial textile fibers has been increasing over the years with a constant offer of new trendy, better, more durable, innovative products, including fashionable ones at low prices, and thus emphasize/stimulate global growth in various sectors, e.g. in the automotive, agricultural, footwear, furniture industry, aviation, fashion, as well as in the field of other industries, such as the production of filters, geopolymer fabrics, etc.

Furthermore, increased amounts of separately collected textile waste are expected because of the Waste Framework Directive's obligation to separately collect textiles as of 2025. It is necessary to prepare even better for this deadline, as there are still many open ways for improvements in the field, such as increased diffusion of new circular business practices, in particular in cutting-edge technologies, novel tracking reuse, and remanufacturing, and also the introducing of sector cooperation economy practices. A good way could also be the involvement and empowerment of citizens that would allow environmentally informed purchases and organized textile collections, maybe improving the knowledge about opportunities and challenges of textile waste recycling technologies, and provide policymakers with an in-depth analysis of existing regulatory barriers and present alternative policy options.

An overview of the field of textile materials shows that the textile industry and experts are aware of the importance and influence of textiles on the environment, as much research, as mentioned above, has already been carried out and the perspective is to continue this trend. In the literature itself, however, there was insufficient connectivity between different industries (sectoral cooperation) and a lack of symbiotic projects or research, for example, Information and Communications Technology (ICT), including the field of advanced digital solutions, which are practically inevitable in our future. These are, for example, Artificial Intelligence (AI), robotics, the Internet of Things (IoT), and blockchains, which will be challenged to connect efficiently and effectively in different circular business processes. Of course, the aforementioned represents a limitation both in controlling/restricting the release of microplastics into the environment, as well as in the speed of response to the negative impacts of microplastics on the ecosystem. In addition to the recent advances in the textile fiber industry both in the field of fiber surface treatment, the use of biopolymer fibers, and also in the field of innovation in recycling processes such as the addition of compatibilizers into industrial recycling processes, we should also consider more advanced comprehensive processes such as the eco-designed recyclable material sourcing product. This could be a recommendation and challenge in the early stage of the search for innovations and the design of product manufacturing, which would enable the expansion of the involvement of stakeholders and a more tangible impact on reducing microplastics in the

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environment. This literature, which should demonstrate the sustainability of raw material extraction, material production, and end-of-life management with the possibility of reuse, recycling, and/or biodegradability of bioplastics (an entire value chain), is only partially accessible and not fully addressed, which is the limitation in the knowledge transfer. Moreover, as can be seen from the reviewed literature, the production of a lot of polymers/plastic materials from renewable and biological sources has already been proven, but additional challenges are needed in order to make bio-based products and the related value chains at least partially competitive in terms of functionalities, costs, and sustainability, in comparison with the current fossil-based solutions. Nevertheless, the offer of bio-based polymer fibers and useful raw materials for their production needs to be expanded on the market. It was difficult to find literature showing the possibilities of using more environmentally friendly polymer fibers/textiles, which can be an equivalent alternative to the current synthetic polymers/ textiles.

However, new biopolymer fibers/biomaterials would contribute to increased use of recycled material and increased recycling rates and to new higher value products, which would be very perspective. It would certainly also have an effect on increasing circularity in plastic value chains and reducing the content of microplastics in the surrounding waters and soil. The challenge will be to demonstrate efficient production routes and consider that the safety, quality, and purity of new bioproducts must comply with commercial and/or regulatory requirements and standardization activities. In addition, it is also necessary to take into account technical and economic feasibility, since the market attractiveness of biological products should not only be based on the expectations of manufacturers but also on the needs of end users in various applications. Certainly, this is also a unique challenge when entering the market, both technically and financially.

Conclusion

The brief of key aspects

1. The textile is a major source of microplastic environment pollution both, in the production and use phases and also at the end of its Life-cycle.
2. The production of industrial textile fibers has been still increasing over the years with a constant offer of new trendy, better, more durable, innovative products.
3. The increased amounts of separately collected textile waste are expected also because of the Waste Framework Directive's obligation to separately collect textiles as of 2025.
4. Today's challenges of the "circular and sustainable" textile industry are mainly in comprehensive business models that will connect different industries with cutting-edge technologies and thus contribute to strengthening industrial competitiveness, independence from resources, and reducing the negative impact on the environment, by reducing the release of microplastics into the environment and with a friendlier environmental footprint.
5. Bio-based polymers and biodegradable polymers will replace environmentally non-degradable and non-recyclable polymers, and product recycling processes are increasingly present or almost unavoidable today.
6. However, the only effective way to reduce and prevent plastic/microplastic pollution is to produce and use much less plastic.

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