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Towards Sustainable Textiles for a Safer Planet: Main Topics

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Abstract: The textile branch traditionally uses a surplus of energy, consuming an enormous amount of water, and is responsible for the deterioration of the environment. New solutions are formally focused on a circular economy with an impetus on sustainable development and a world with zero waste. In reality, the aims of circular economy often do not coincide with sustainability issues, and sustainability is, in fact, narrowed to nature-created products (especially fibers) and not renewable resources. The main aims of this article are to critically discuss sustainability aspects of fiber development, textile design, production, use, and recycling or waste treatment. It is demonstrated that despite improvements in sustainability, comprehensive solutions need focused action of specialists from different disciplines with the same target, i.e., real sustainability for a future world. New machinery for the production of textiles without limitations to their thickness is one typical example of the approach to better sustainability. One of the key issues is the selection of sustainable fibers for future textile applications. The benefits and problems of replacing synthetic fibers with natural ones are discussed in detail. The recent techniques of textile waste treatment are presented, and problems with microplastics releasing from textiles are shown.

Keywords: sustainability in textile branch; textile raw materials; design; machinery development; technology requirements; waste treatment

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1. Introduction

The textile industry is unique in that it uses hierarchical fibrous structures composed of fibers with unique properties [1,2]. These structures, which have been developed by the long-term trial/error method, are suitable for clothing applications, as they combine mechanical resistance with durability, formability, comfort during use, and easy maintenance. It has been shown that fibrous structures have applications in the fields of composites, medicine, electronics, and a number of other technical disciplines, where they replace compact metallic and non-metallic materials [3]. Fibrous structures (prepared by textile technologies) are also increasingly being used to solve basic societal problems, such as health care and quality of life, reduction in energy needs, and efficient use of waste [3]. A new branch of "fiber engineering" is gradually emerging, which combines achievements of textile science combined with advanced textile production technologies and the functionalization of products to obtain the effects needed in various areas of the industry while preserving the unique properties of fiber structures [2].

The current state can be briefly characterized as often not sustainable, oriented towards partial benefits without a comprehensive solution covering the entire life cycle, including waste treatment. There is either a complete or a partial lack of focus on multifunctionality, reduction in energy and process media consumption, renewable sources of raw materials, economy of production and use, environmental protection, processing of production waste, processing of products after the end of the use cycle, and user-friendliness or humanization of products [4,5]. This is reflected in the practically limited applicability of a number of interesting research results, as they require a number of additional solutions, materials, or

technologies. It should be noted that the current trend in the production of textile fibers and mainly textile structures is standardization aimed at the production of mass products with high production capacities, mainly without a focus on future societal needs.

The development of the textile branch will be critically dependent on the following factors [6]:

- Serious financial imbalances;
- Recession in the US and Europe;
- Oil price volatility;
- Energy and water costs increasing;
- Sustainability and environmental awareness;
- China and India becoming dominant economic players;
- Africa and certain Asian and Subcontinent countries gaining importance;
- Slower textile consumption internationally, with less than 2% growth forecasted through 2020.

Typical for today's society is gradual environmental degradation, shrinking of non-renewable resources, and lower quality of life directly or indirectly arising from snowballing production/consumption [6].

Only isolated steps oriented to locally positive solutions have been carried out, without considering global aspects. The environmental, social, and economic points of view are separate and competing. Consumers have no chance to directly affect the necessary changes and are informed about only positive parts of new products and technologies [7].

The textile value chain, which consists of "selection of raw materials, textiles production, maintenance during use, and waste treatment at the end of life", has constantly been evolving by introducing new concepts, products, and technologies [2]. The invention of new materials, design methodologies, novel manufacturing processes, and marketing strategies has found a strong foothold. Creative ideas in the design process impact the work of fashion designers. New consumer patterns and rapidly changing preferences have arisen, showing a bias toward e-commerce instead of the traditional "brick and mortar" approach to marketing and extracting value [1].

In this article, the components of sustainability aspects of raw materials (mainly fiber) selection, advanced design tools, production, maintenance during use, and recycling are critically evaluated [4,5].

2. Circularity and Sustainability

Typical for today's society is the realization of only isolated steps oriented to locally positive solutions without considering global aspects. The environmental, social, and economic points of view are separate and competing. Consumers have no chance to directly affect the necessary changes and are informed about only the positive parts of new products and technologies.

Growing consumer awareness of the importance of environmental care leads to increased demand for products fabricated with minimal impact on polluting our planet. The demand for textile products that have the epithet "bio" is growing despite their significant environmental problems (e.g., the creation of polluted water). These "bio" products are not in themselves automatically safer from the point of view of human health (as some "pseudo-expert" sources try to inform, but during their production or the preparation of fiber raw materials, it is necessary to consider the requirements of preservation and protection of the environment. It is, therefore, not about protecting the health of an individual but about promoting a good state of the environment, which is important for all of society.

Nowadays, the replacement of the classical linear economy with a circular economy is supported by EU initiatives [1]. Circularity is mainly oriented on resources, especially secondary ones (wastes), via the 6R principles (reduce, recover, reuse, recycle, re-design, remanufacture) [8]. Some visions of a future economy transformed from being circular to sustainable [9] were published, where the battle for resources will be replaced by resource sufficiency.

Sustainability is therefore oriented towards the needs of future society (such as scarcity of fresh water and agri-lands, environmental friendliness, use of renewable energies, and viable technologies).

The use of reprocessed and recycled raw materials usually leads to a reduction in the consumption of natural resources, whether renewable or fossil. It can also reduce energy consumption, reduce the production of carbon dioxide (CO_2) and other emissions, and reduce the volume of waste placed in landfills.

3. Specific Characteristics of the Textile Discipline

The production of textiles is one of the oldest and highest-volume industries globally. The total production is related to the magnitude of the population. Furthermore, it is influenced by the technical sophistication of society (technical textiles and composite structures, among other examples). This impacts the development of new products and processes via new technologies for innovations that consumers desire on the one hand versus utilization of progressively harder-to-obtain resources/feedstock. The industry requires large quantities of water and energy consumption for the transformation of raw materials into products, with a high volume of waste and environmental desecration [10]. The main limitation of traditional textile structures is their low thickness, which has considerable influence on their selected properties, e.g., thermal resistivity, and is overcome by using multiple-layer garments.

New technologies and machines have overcome this problem. Examples are vertically laid nonwoven manufactured textiles using STRUTO and ROTIS technologies, which provide higher insulation and sound absorption [7].

For the production of 3D-layered fabrics composed of two woven layers (distance between layers 12–50 cm) connected by binding threads, the jet weaving loom DIFA was developed (see Figure 1) [7].



(**a**) (**b**)

Figure 1. (**a**) Air jet loom DIFA; (**b**) structure of DIFA fabric [2,7].

Traditional aspects of fashion, style, silhouette, drape, and comfort still prevail in the apparel segment. However, it is also necessary to ensure:

- The management of transport processes (water, air, water vapor, other liquids);
- Protection against deleterious environmental influences, which include microorganisms, UV radiation, extreme climatic conditions, and ecological production;
- Ease of care, including washing and ironing;
- Ecological processing of wastes (recycling, new structures, biodegradability);
- Achieving new effects (cosmetic, self-cleaning property, health care support, etc.);
- Controlled active identification during limited visibility.

The development provides multifunctional attributes, overcoming limitations of shorter life cycles associated with use and aging [4,7].

For technical textiles, the situation is simpler. The requirements for their properties can usually be defined precisely based on the intended application. The general requirements of industrial use and composites are to have a high strength and initial modulus for application with applied stress in tensile mode, bending, and torsion. In addition, other critical properties that are desirable are:

- Low deformation to break and low creep;
- Resistance to environmental influence (e.g., UV radiation, moisture, temperature, etc.);
- High abrasion resistance;
- Possibility to withstand long-term exposure to heat or cold;
- Resistance to cyclic stress and exposure to chemicals;
- Low degradation while stored and slow aging under the condition of use.

Easy decomposability at the end of the product's life (in composting conditions, etc.) is advantageous [2,5].

Recently, studies on biomass-based wearable smart devices, such as electronic shielding, energy interaction, hygrothermal sensing, etc., have been reported [11]. The attributes suggested will provide a comprehensive regulatory benchmark for materials in the production of textiles. For the use of fiber products and their end-of-life disposal, the requirements of society should be in balance with the needs of the quality of the environment. For this to emerge, it will be necessary to consider, above all, mutual links in the key areas of the value chain.

4. New Tools for the Design of Textiles

The aim of the design of textile products is to create synergy from the aesthetic perspective, values of materials, technical requirements, and comfort during use.

Classical design elements based on geometry and color enrichment for special effects can be replaced by the use of fiber optics as a design element (an example is in Figure 2 [2]).



Figure 2. Fiber optics as a design element [2].

The complex design systems nowadays enable the prediction of the behavior of textiles during their useful life and help with the development of computer-aided physical and mechanistic models. As an example, the integration of the disciplines of chemistry, physics, and engineering is already in progress. This will help in the construction of new, environmentally acceptable, and long-term sustainable textile structures for clothing textiles. These developments are capable of adapting to changes in environmental conditions. Special technical textiles with unique properties provide for newer applications. A computer-aided systems approach is increasingly used in the design of new textile products. For this purpose, software systems combining existing software focused on fashion textile construc-

tion (visual design) with systems predicting textile properties based on their construction (similar to CAD systems in engineering) are being used.

Comfort prediction systems are gradually being adopted as well. For clothing used in protective textiles, it is necessary to include special requirements. These may lead to new designs incorporating the permeability of water vapor while maintaining impermeability to liquid water, thermal resistance, and ventilation. For optimization purposes, "soft" methods such as CBR (case-based reasoning) and special definitions of metrics are also beginning to be used [2]. If it is possible to specify the desired properties of the fabric, it is possible to define the pseudo-distance between this virtual fabric and individual variants with superior performance [2].

5. Selection of Fibrous Materials

A typical feature of the fibers is that their thickness is several orders of magnitude smaller than their length. The thickness of common fibers is usually in the range of d = 10^{-6}–10^{-4} m and the length in the range of l = 10^{-2}–10^{-1} m. The ratio l/d ~ 10^{3} shows that the predominant dimension is length [2]. In the case of natural fibers, the length and thickness are determined by the conditions of fiber growth and are only indirectly influenced by humans. With chemical and synthetic fibers, it is possible to change not only the length and thickness but also the shape of the cross-section. This is particularly important for the category of microfibers (thickness of the order of 2 μm). Thanks to this small thickness, microfibers have some unique properties. For example, the transport of moisture takes place by a microcapillary mechanism. Hence, the fiber bundles of hydrophobic fibers are able to easily transport moisture without swelling of the fibers and diffusion through their mass [3].

Fiber characteristics depend on their origin. For natural fibers, it is difficult and time-consuming to change their geometry and properties. It can be achieved through selective breeding, gene manipulation, etc., to enable good processability (such as spinning and processing of fibrous mixtures). On the other hand, the properties of man-made chemicals (viscose) and synthetic fibers (such as polyamides, polyesters, acrylic fibers, polyolefins, etc.) can be modified with relative ease by changing the conditions of production (spinning, drawing, heat setting, etc.) or geometry (fineness, cross-section form, texturing, etc.), spinning conditions (spinning speed, drawing conditions, conditions of heat treatment, etc.), or through chemical modification [12].

The choice of sustainable fibers is not so simple. Usually, natural fibers and fibers based on renewable resources are nominated as more sustainable. For clothing purposes, cotton fibers are mainly suitable (but not sustainable). Other plant fibers are primarily used as reinforcements for composites and concrete [13]. One potentially beneficial application is the utilization of these fibers as the source for the preparation of regenerated cellulosic fibers or a source of cellulose extracted from biomass. The main limitation is the complicated preparation of cellulose solution. One promising solvent is ionic liquids despite their high price [14–16]. According to the gross energy required for the production of 1 kg of manmade fibers, one of the best choices is polyester fiber. The major limitation of polyester is the requirement to use non-renewable sources and costly processing. But in reality, the situation is not so critical. Approximate energy consumption, freshwater consumption, and CO_2 emissions for cotton, polyester, polyamide, and wool are shown in Table 1 [17].

Table 1. Environmental impacts of common types of fibers [17].

Characteristic	Energy Consumption [kW per kg Fiber]	Freshwater Consumption [liter per kg Fiber]	CO_2 Emissions [kg per kg Fiber]
Cotton	48	1559	2.2
Polyester	108	21	3.3
Polyamide	160	40	8.3
Wool	120	530	17

The environmental impact of production for natural fibers (cotton and wool) requires more water during production than synthetics (polyester and polyamide). Cotton requires extraordinary water consumption. CO_2 emissions values are higher for polyamide and wool only [18]. The wastewater from cotton plants is very highly polluted. The limitation of wool is the land use, mainly.

Usually, the fibers from renewable resources (cellulosic) are automatically classified as sustainable fibers without investigation of all aspects of sustainability (time of production, energy consumption, land and water use, maintenance cost, recycling.). Most of these fibers are composed of cellulose, hemicelluloses, lignin, and other compounds. Non-cellulosic parts are removed during transformation to textile products. Pectines serve as a natural glue, joining elementary fibers to technical fibers that are spinnable [19]. The critical factor for textile processing is obviously small length or elementary (ultimate) fibers (e.g., for bamboo 4–8 mm only) [20].

In some cases, the monomers are prepared from natural sources (biomass) for the creation of synthetic polymers and then fibers. The standard approach is to prepare biobased monomers, but often more challenging is to use biopolymers available in nonfibrous forms and transform them into fibers [21–24].

Bio-based polymers can be classified according to their origin into three classes [25–27]:

Class 1: Extracted directly from cellulose-based biomasses with or without modification. Example: starch-modified polymers and polymers derived from bacterial cellulose.
Class 2: Produced directly from microorganisms in their natural or genetically modified state. Example: Polyhydroxyalcanoates (PHAs).
Class 3: Obtained with the participation of bio-intermediaries produced by renewable raw materials. Examples: PLA; bio-polyethylene (BPE) by polymerization of ethylene produced from bio-ethanol, bio nylon via diacids from biomasses, and bio-polyurethanes from polyols of vegetable origin.

According to ASTM D6866-06 [28], biopolymers are special polymers used during the synthesis of products of natural origin. In general, three basic factors influence the development of biopolymers. They are raw materials, durability, and processing after the period of use.

A. Raw materials

Most bio-based polymers are produced from corn, although cellulose from plant fibers and trees or some biomass is used for some purposes, e.g., approx. 2.5 kg of corn is needed to produce 1 kg of polylactic acid (PLA). Covering the global needs for PLA requires roughly 230,000 km^2 of agricultural land. In addition, bioethanol is mainly produced from corn. Agricultural policy will, therefore, affect the availability of this raw material for biopolymers.

B. Durability

Mostly, durability is narrowly assessed with respect to biopolymers only. Here, the service life is limited in many cases by the relative ease of degradation under conditions of use and maintenance. In general, however, it is also about issues related to the cultivation of corn, where fossil fuels, fertilizers, and pesticides are used during cultivation. Soil erosion, water contamination, and CO_2 overproduction can therefore occur. Effective genetically modified corn varieties will likely continue to encounter environmental groups and legal barriers, even if they are not intended for food use (similar to genetically modified cotton).

C. Processing after the period of use

As a number of materials are gradually replaced by polymers, landfills become clogged with materials that degrade extremely slowly. The general opinion is that degradability is a positive factor. However, landfills are built to limit degradation. They are mostly anaerobic storage conditions without access to air. If the material degrades under these conditions, methane production usually occurs. In addition, the degradation of biopolymers usually requires quite specific conditions, such as higher temperature (over 60 °C) and the presence

of moisture. This can be ensured in special landfills and composts, but it will have little effect on ordinary solid waste outside of landfills, which is increasingly dangerous for the environment. In general, waste from biopolymers is more voluminous and lighter, and it can be used in the construction of equipment for collection and processing.

By processing biomass, it is possible to obtain some important monomers and intermediates for the synthesis of advanced biopolymers [29] (see Figure 3).

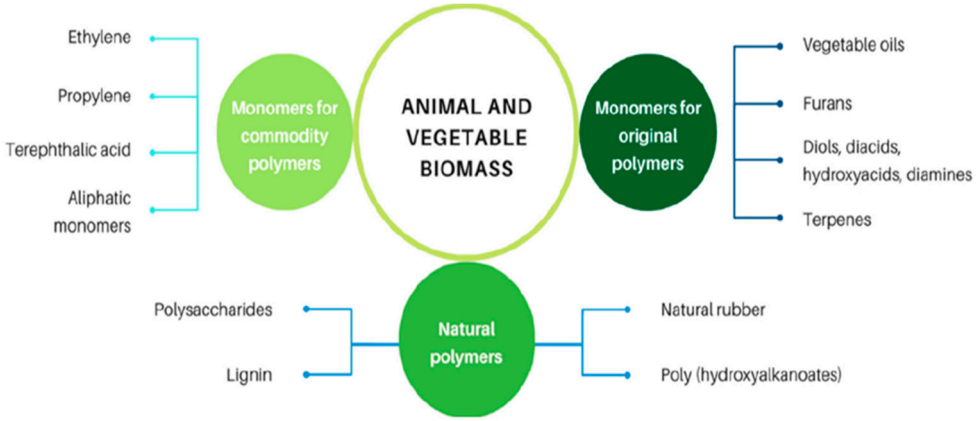


Figure 3. Monomers and intermediates from biomass [30].

Sustainable polymers are then created by using monomers from renewable resources, with low energy costs, minimum use of harmful reagents, and controlled release of harmful by-products. The Furan platform is one of the most relevant renewable resources of polymer chemistry. The 2,5-furandicarboxylic acid is used as a monomer for the preparation of poly (ethylene furanoate) (PEF). PEF is desirable due to the use of renewable monomers and the improved barrier, mechanical, and thermal properties compared to PET. The polarity of the furan ring in PEF imparts an increased equilibrium of water solubility of approx. 1.8 times averaged over the entire concentration range compared to PET. Permeability reduction is approx. 2.8 times for water in PEF compared to PET at 35 °C. PEF then exhibits approximately a five-fold reduced water diffusion coefficient [29,31].

New types of polymers are from bio-intermediaries or polymers created by microorganisms [25–27]. Some biopolymers are directly suitable for the creation of textile fibers [32]. During the textile processing of fibers from biopolymers, problems can generally arise both with the construction of textile structures (many of these fibers are fragile, not very extensible, etc.) and with possible finishing and dyeing. This, "together with the relatively high price of biopolymer fibers", leads to the fact that their industrial use is currently limited to special applications.

In the group of synthetic fibers, some biopolymers [21,33], like poly (lactic acid) (PLA), poly (butylene succinate) (PBS), bio-PET, and poly (ethylene furanoate) (PEF), can also be included in the mass production of fibers. Replacing fossil-based fibers with bio-based fibers is really advantageous because fossil-based fibers at their end of service will generate greenhouse gas emissions. Bio-based materials of natural origin are carbon-neutral because the CO_2 that they can emit at their end of life (because of incineration or degradation due to microorganisms) is balanced by the CO_2 consumed during the growing of the plants.

PLA [34–37], being both renewable and biodegradable in industrial composting plants, can represent an interesting perspective for replacing fossil-based polymers such as PET and PP [37,38]. Bio-based polyamides were developed to replace standard fossil-based polyamides [39]. Polyhydroxyalcanoates (PHA), created by microorganisms, can be used for producing natural bioplastic fibers [40], but their high cost and difficult processability are currently directing them mainly toward biomedical applications.

Most fibers do not meet the requirements for complex sustainable development. They are a source of fiber microplastics that threaten the environment and are a source of difficult-

to-process waste [41,42]. Another problem is the reduced length of the polymer chains due to degradation processes, which limits the reusability of the fibers.

In the production of raw materials and materials for textile applications, environmentally friendly "green" technologies using renewable resources for the creation of biopolymers (biodegradable and safer for handling [43]) will be preferred.

6. Production of Textiles

Textile production technology for a sustainable future will focus on the following main areas [7]:

- Realization of ecological production (not adversely impacting the environment and not endangering life on the planet);
- Reducing the production of waste (waste-free technologies utilizing concepts of regeneration, recuperation, and reuse);
- Reduction in energy consumption (use of alternate reaction media), process optimization, and alternate energy sources;
- Use of renewable resources (biotechnology, green chemistry);
- Elimination or replacement of potentially toxic compounds usually due to degradation processes (new kinds of solvents, replacement of heavy metals, and some dyestuffs);
- Disposal of waste and used products (biodegradation, reuse of raw materials, transformation, and upscaling into high-value products).

In general, it is more economical to use fewer machines with higher production speed while maintaining product quality. This is the reason why technologies with higher production speeds are still being developed. In textile engineering, in addition to increasing production speed, efforts will continue to reduce the weight of machines, apply mechatronic principles, control machine functions by computer, and ensure flexible production. However, all of these concern the textile industry in the long term, as they involve investment-intensive modifications of machinery, and the payback is relatively slow. The search for new technologies with lower energy consumption (bioprocesses, catalytic processes, use of alternative energy sources), reduction in reaction volumes, efficient insulation of machines, and optimal use of thermal energy is often less demanding. The quickest development today is the field of finishing and functionalization (adding new properties [44]) of textiles oriented to the use of less or non-toxic substances (dyestuffs, finishing agents, auxiliary substances) and nanomaterials (see Figure 4) [45].

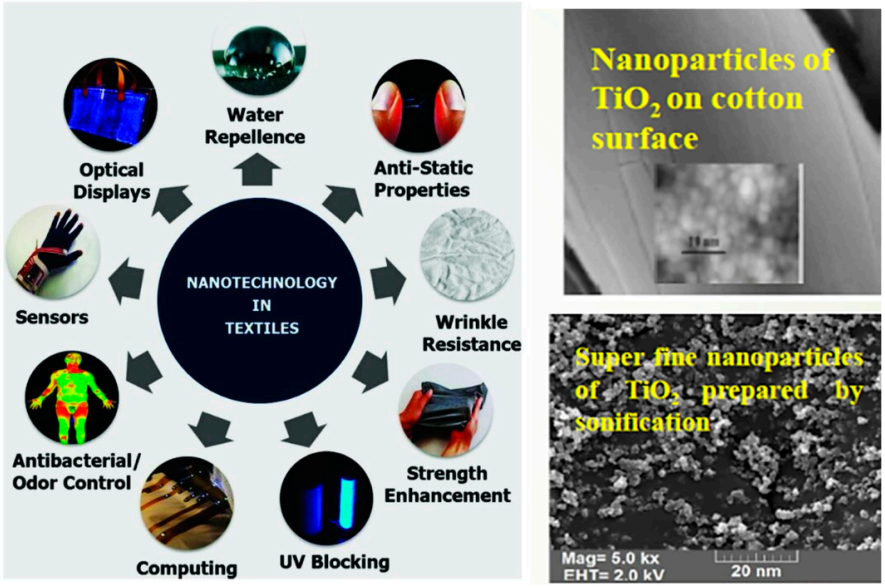


Figure 4. Selected use of nanostructures in textiles [46].

However, nanotechnology often does not follow the requirements of sustainability because its long-term negative effects on humans and the environment are still not fully understood [47].

The ongoing basic and simple method of heat transfer by convection in air and water is already supplemented by IR heating (many polymer fibers have absorption bands in the near IR region) and microwave heating (based on rapid polarity-rotation changes of polar molecules) requiring 10 to 100 times less energy than classic heating. Another option for intensive (local) heating of surfaces and thin subsurface layers is the use of plasma [48]. Electromagnetic radiation of a suitable wavelength can also be used to ensure a wide range of reactions (polymerization) on the surface of textiles. UV curing is commonly used. In special cases, excimer lasers (emitting pulsed radiation of high intensity) are suitable for grafting reactions and surface etching [49,50]. Unconventional methods of heating or activation of reactions will also require the selection of suitable treatment agents and other supporting substances, enabling their functionality.

Suitable liquids for ecological and less energy-intensive manufacture of textiles will probably continue to be used. The question that needs to be answered is the form and type of liquid [2]. Water remains the most commonly used liquid. Water is cheap and readily available, and can be used in many applications. However, there are certain physical limitations. Water is necessary for the functioning of society and nature and requires rigorous cleaning when polluted. The options for replacing water and volatile organic solvents (VOCs) are currently focused on solvent-free technologies (the difficulty of exothermic reactions, inhomogeneous environment, mixing problem), fluids in a supercritical state (CO_2), ionic liquids, or lactates [2]. For effective use of these possibilities, their real limits must be understood. There is no universal solvent yet [2]. A near-term perspective auxiliary solution could be more use of rainwater.

7. Utilization of Textiles

When textiles are used, wear occurs primarily through abrasion and partial depolymerization through degradation mechanisms. Both processes are combined during the maintenance of textiles (cleaning, especially washing, drying, and forming the shape) and during exposure to the thermal and moisture effects of the local climate and UV radiation from the sun. They can often be simply limited, for example, by choosing the method and frequency of maintenance and using suitable auxiliary agents. The prediction of the durability of textiles in extreme conditions of use is also important. This implies a need for new metrological methods of characterizing the condition of textiles and their changes over time.

During the use and processing of fibrous textile products, the fragments and particles (called microplastics if their dimensions are under 5 mm) are created. Some of the largest sources of microplastics are from virgin sources, recycled sources, and wastes. These fibrous microplastics commonly also contain chemicals used in dyeing and chemical treatment of textiles. They are usually composed of higher-density polymers, making these parts not easy to spread. Due to the more varied chemical composition, higher toxicity, and size variation, much more complicated elimination from the environment can be expected. Thus, fibrous microplastics have some degree of danger; they occur in the air and water, including drinking water, and immediately threaten practically the entire biota and humans.

Particles, broken fibers, fragments released from synthetic fibers, and microparticles from fibers based on natural polymers are often referred to as "fibrous microplastics." The reason for this extension of the term "microplastics" is the exact mechanism of origin, similar toxicity, and environmental behavior. When textile microplastics are carried by air, they usually accumulate mainly in household and office dust and support the development of allergies, asthma, and many respiratory problems. When released during washing, textile microplastics accumulate in rivers, seas, wastewater treatment plants, and drinking water. Almost a third of microplastics are released mainly during the washing of garments [51,52].

Fiber microplastics are potentially more dangerous than other types of microplastics for the following reasons:

- They are mainly fiber fragments and are usually needle-shaped. The reason is the internal fibrillar structure of the fibers and the geometric shape of the textile fibers, which are long and thin. The consequence of the needle shape can be easier mechanical damage to tissues and cells, mechanical disruption of cell walls, etc. [53,54].
- Compared to other polymers, textile fibers are usually contaminated with potentially non-polymeric toxic compounds, which can be textile dyes, finishing agents, TiO_2-based matting particles, and, more recently, metal and metal oxide particles.
- Fiber microplastics are a consequence of the everyday use, maintenance, and reprocessing or mechanical recycling of textiles, so their adverse cumulative effects are serious.

The total volume of microplastic generation is related to the consumption of fibrous structures, including recycling strategies. In industrialized countries, textile consumption is around 25–30 kg per person per year, and in developing countries, it is about 10–15 kg per person per year. From the prediction of human population development, it is therefore possible to estimate the amount of generated microplastics in the case that there will be no modifications in the composition, construction, and production technologies of fibrous structures. During the construction, use, and recycling of textiles, it will be necessary to simultaneously solve problems related to optimizing technological processes, the construction and functionalization of fibrous structures, and ecological requirements to suppress microplastic formation.

The formation of fibrous microplastics can be controlled by the appropriate selection of fiber-forming polymers, control of supramolecular structure and surface structure of fibers, suitable construction of fibrous structures (linear and planar), and suitable methods of their maintenance and recycling. These are complicated tasks, for the solution of which both modelling and simulation, such as the abrasion, washing process, mechanical damage during recycling, experimental results, and morphological analysis of microplastics, will be used.

8. Waste Processing

Growing consumer awareness of the importance of environmental care leads to increased demand for products with minimal impact on polluting our planet. Proper waste treatment is, therefore, not about protecting the health of an individual but about promoting a good state of the environment, which is important for all of society.

The idealized circle of processes that would lead the textile industry to become more sustainable and socially responsible is shown in Figure 5.

Now, there is a paradigm shift toward a circular economy, where waste is considered to be a valuable resource, and elimination of it is considered in the design stage, disassembly, and recycling. The end-of-life stage must be thoroughly understood. The use of recycled raw materials from waste usually leads to a reduction in the consumption of natural resources, whether renewable or fossil. It can also reduce energy consumption, reduce the production of carbon dioxide (CO_2) and other emissions, and reduce the volume in landfills.

Generally, waste treatment is focused on product-specific (product reuse or life extension) or material-specific (using wastes as new resources). There are so-called spiral loops of waste processing:

(i) Reuse loop: extending the life of the product by multiple uses;
(ii) Repair loop: After completion of a preceding product cycle, damage control or repair is required to make the product ready for successive cycles;
(iii) Reconditioning: use of the used product as a raw material for the manufacturing of a new product;
(iv) Recycling loop: Waste generated is collected and reprocessed to prepare starting material for the new products. Recycling textiles into lower-quality products (downcycling) is especially not very challenging, as the products require less stringent compositional

and mechanical properties. In order to recycle textiles into higher-quality products (upcycling), new kinds of fibers from waste are obviously needed.

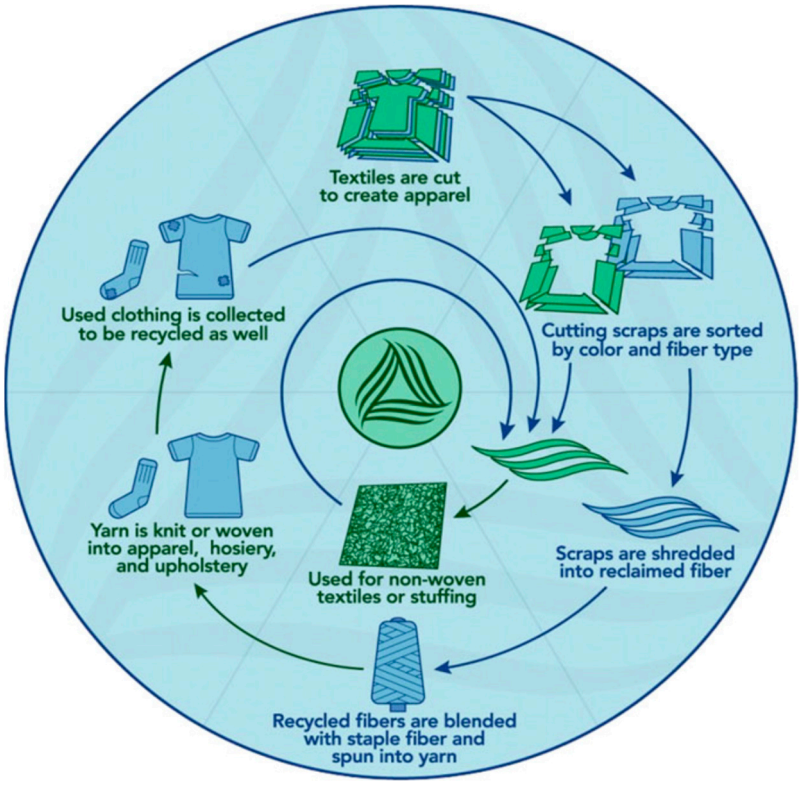


Figure 5. Textile product life cycle and recycling approaches [2].

Textiles are a special category of materials that are classified as waste for various reasons, which impacts their lack of reuse and the possibility of further processing (Figure 6) [2].



(**a**) (**b**)

Figure 6. Fibrous wastes: (**a**) wastes from textile production and (**b**) wastes from used textiles.

The demand for textiles has increased significantly in the last decade due to the increase in people's living standards. However, increased demands for textiles have also brought challenges to disposing of significant amounts of waste generated during the processing and end-of-life of textile materials [55,56].

When analyzing textile waste, it is important to divide it into returnable and non-returnable waste with regard to the possibility of their use as secondary textile raw materials [57,58]. Returnable waste is used again in the same products during the production of which it was created. Non-returnable waste can be used in products other than

the products from which it was produced. In general, textile waste is classified as pre-consumer (more precisely, textile industrial waste) or post-consumer (more precisely, collection textile waste). Pre-consumer textile wastes are fibrous residues from the production of textiles and textile products. These are textile composite waste, textile scraps, fiber waste, and thread waste [59].

Fibrous textile waste is essentially all textile fibers that are discarded during their production process (these are unfinished chemical fibers with insufficient length or with varying degrees of damage or contamination) or fibers discarded during processing.

Thread waste is yarn scraps of different lengths, skeins, etc. Thread waste is produced during yarn processing, e.g., by spinning, drafting, and carding. It is also created during processing into flat textiles.

Textile scraps are pieces of textile of various shapes and sizes. This is textile waste produced during the production of flat textiles. Textile scraps are divided according to the type of fibers, the kind of fabric, the size of the scraps, and the color of the scraps.

Textile composite waste is actually waste from the production of industrial textiles, which consists of at least two parts (phases). They can be textiles with sewn-in yarns that are fixed on the reverse side with a coating (latex, hot melt, etc.), such as bathroom mats. These wastes can often be easily used for the creation of other structures (non-woven fabrics, filling materials, insulation, etc.

Pre-consumer textile wastes are used in the production of yarns, non-woven fabrics, and industrial cotton wool [59]:

- During yarn production, textile secondary raw materials are processed on shredding machines into fibers that are used as an admixture to primary fibers. When processing fiber waste, the length of the fibers must be checked, in particular with regard to spinnability [60].
- The production of non-woven textiles currently uses the largest share of textile secondary raw materials. Non-woven textiles for the technical industry do not place such an emphasis on color or surface appearance, as is the case for home textiles. Non-woven textiles made from secondary raw materials are mainly used as heat and sound insulation material in the construction industry, as sound insulation and filling material in the construction of vehicles and aircraft. These materials are suitable as insulating materials in the electrical industry. They are also used in the clothing, footwear, and housing industries [59].
- Industrial cotton wool (waffle) is formed by densifying the fibers into a fleece, in which the fibers are held together by natural cohesion. In order to preserve the characteristic features, industrial cotton wool is sometimes strengthened by applying a binder to the surface of the fleece. Bandage cotton wool is made from raw cotton material; a fiber mixture is used for the production of industrial cotton wool. Textile waste is also used as a secondary raw material for non-textile processing, e.g., for the production of paper, special boards, flat textile boards, fillers, and reinforcing materials [59].

Various textile waste is used as the basic material for the production of flat textile boards, especially the waste of hard felt; textile floor coverings; non-woven, laminated, and layered textiles; or cord fabric from tires. Textile waste is crushed or chopped. The waste is combined with other substances (foils, plastics) where the fusion of them is used. Surface boards are produced from these secondary raw materials, the properties of which are determined by the basic material, the chemical binder, as well as the production method or surface treatment [61].

Post-consumer textile waste (usually the remains of used clothing) is usually disposed of by landfilling or incineration. Incineration of textile waste is energy-friendly. Textile waste has a calorific value of 14,500 kJ/kg, which is comparable to, for example, brown coal of 15,000–20,000 kJ/kg. Both landfilling and incineration have a negative impact on the environment. During the biological decomposition of textiles in landfills, methane is released into the air, CO_2 is produced during combustion, and toxic gases can also be released [55,56].

Post-consumer textile waste can also be divided into three categories according to their original use:

A. Used clothing that can be pre-sorted or part of municipal waste. For pre-sorted waste, the main problem is both the mixture of different fibers and the presence of non-fibrous materials (buttons, zippers, membranes, plastic and metal parts, etc.). Municipal clothing waste is normally heavily polluted and can be attacked by various microorganisms. These wastes are normally created only after the physical or moral wear of clothing textiles or the termination of their real applicability.

B. Used home textiles, such as carpets, covers, curtains, etc., which are usually multi-layered and contain a predominant proportion of non-fibrous materials in some layers. In some cases (e.g., replacement of floor coverings in US department stores), there will be a local need to process a large volume of practically the same waste, which will facilitate the search for an economically advantageous solution. These wastes are created over a longer time horizon.

C. Waste from industrial textiles (e.g., construction textiles) and composites containing a fiber component again contain a significant proportion of other polymeric or non-polymeric components that are normally combined in one layer. In a number of cases (e.g., the automotive industry), it is a requirement that the problem of waste processing already be solved at the product design stage, which leads to the selection of materials in order to facilitate the process of recycling or further processing. These wastes are created in the medium to long term.

Partially worn textiles that can still be used. The textile still maintains its functional properties, and its labeling as waste is motivated by aesthetic factors (change in shade, non-compliance with the requirements of fashion, inappropriate size, etc.). These textiles can either be directly used by other consumers, suitably modified (revival of shade, bleaching, dyeing, printing), or modified in terms of design (see Figure 7). They can still be recovered and reused. Their use as waste for recycling is possible but economically less advantageous.

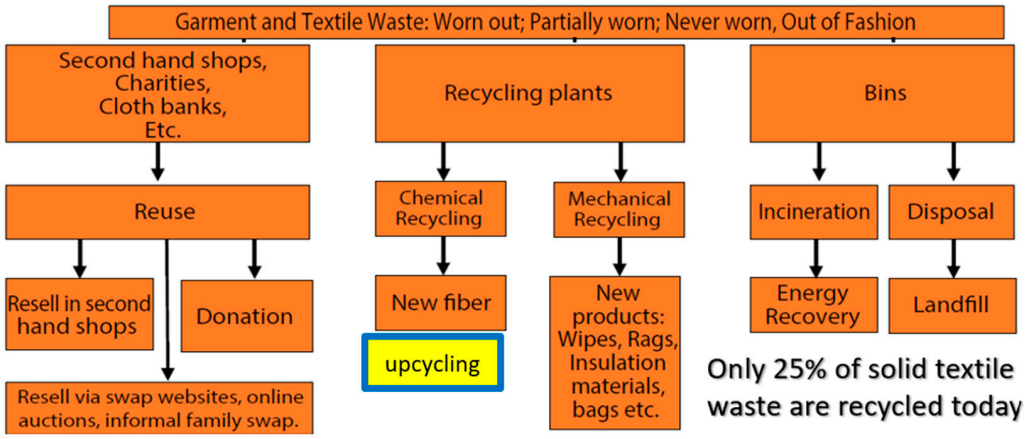


Figure 7. Basic ways of post-consumer fibrous waste treatment.

Locally mechanically broken textiles are a frequent case where inclusion in the waste occurred due to local mechanical damage caused by energy fields acting only locally. Depending on the extent and size of the violation, the defect can be repaired or the waste can be classified as suitable for recycling. The special design, which is a combination of not-damaged parts to create clothing, is the challenge.

Physically worn and damaged textiles are classic cases where, due to degradation processes, significant depolymerization occurs, accompanied by a reduction in mechanical properties. This is manifested in partial disintegration of the entire textile structure and fiber fracture due to shorter chain lengths and reduced molecular weight. This type of textile waste (see Figure 6b) is suitable for recycling only to a limited extent.

Conventional practice is to discard the post-consumer textile waste (garments) after use without any sorting, which causes waste and pollutes the environment. In the future, it will be necessary to improve the percentage of upcycled waste (see Figure 7).

Professional collectors, charity organizations, and municipalities sort and collect used garments and either resell them or donate them to needy ones. Non-reusable garments are recycled. Discarded garments are usually either incinerated or sent to landfill as solid waste.

Part of recycling (mechanical recycling) is usually the separation of fibers or fragments of textiles by mechanical processes. The subsequent part is the creation of new products from these textile fragments or the preparation of new raw materials (chemical recycling).

For all types of textile waste, it is possible to use controlled depolymerization to monomers and repeated preparation of polymers [7]. The basic problem is the frequent use of intimate fiber blends, which require the separation of components and residues of chemical treatment agents or dyes, affecting the purity and applicability of monomers.

Sorting and categorizing textile wastes are, therefore, necessary conditions for efficient recycling. The solution is not to process wastes arbitrarily but also to consider their subsequent impact on the environment and their durability in new structures.

There exists a serious barrier limiting the recycling of textile waste:

Economic disadvantages: Many recycled textile wastes are unsuitable for use due to the widespread production of lower-grade products from textile recycling. Prices of recycled textile fibers are influenced by the high cost of the recycling processes.
Composition of textile products: The base components of many textile products make them unsuitable for recycling. There are difficulties in separating the mixture of various polymers with different properties. Increased textile fiber strength complicates their shredding.
Non-availability of recyclable wastes: The quantity of textile waste that is suitable and accessible for recycling is insufficient. A limited quantity of textile waste only is usually collected and sorted for recycling.
Technological limitations: There is a lack of technologies for sorting textile waste in preparation for recycling. Most methods cannot separate dyes and other contaminants from the rest of the waste fibers.
Limited public participation: Knowledge (ignorance of what to recycle) and attitude (non-commitment to the ideals of recycling) barriers.

Poly (ethylene terephthalate) (PET) is one of the most frequent polymers appearing in waste (packing material, plastic bottles, foils, textiles, etc.), and it is sensitive to different chemical degradation [62]. PET chemical recycling leading to the creation of monomers and intermediates is realized by glycolysis, methanolysis, hydrolysis (alkali, acid, neutral), ammonolysis, and aminolysis mainly (see Figure 8) by the mechanism of ester bond cleavage (nucleophilic attack) [63,64].

Hydrolysis needs special conditions such as pressure, temperature, and a long-term process. The cost of product purification is high.

Methanolysis needs low pressure, but the purity of products is not high.

Catalytic glycolysis needs high temperature and pressure. Organometallic catalysts have a lower reaction rate and are destructive to the environment due to metal toxicity.

Aminolysis needs a temperature lower than 70 °C, and it is faster than ammonolysis.

Catalytic-assisted depolymerization mechanisms using organo-catalysts, ionic liquids (e.g., choline-based), or metal oxide/acetate/chlorides/sulfates can improve aminolysis, glycolysis, methanolysis, and other chemical recycling processes. Zinc acetate is the best organometallic catalyst; zeolites as large surface-area catalysts and nontoxic metal salts as ionic liquid catalysts are beneficial.

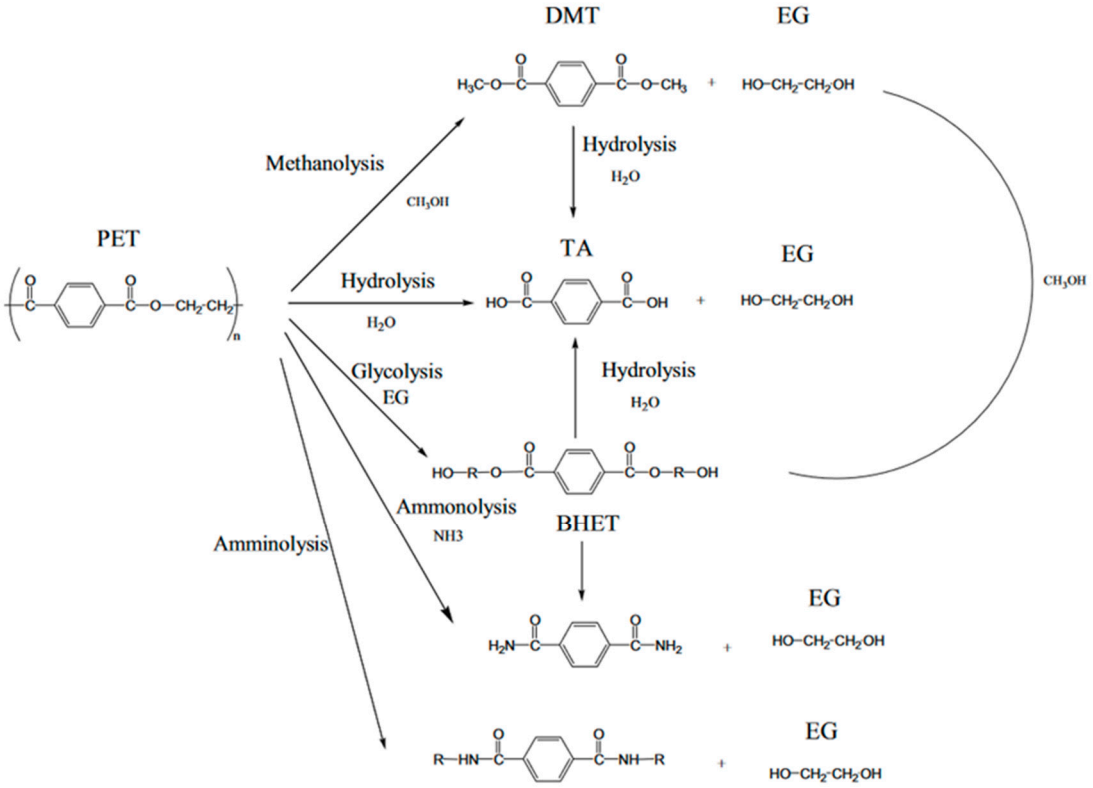


Figure 8. The main ways of PET depolymerization (adopted from [64]).

The technology of depolymerization, which is a combination of physical and chemical treatments with enzymatic ones (chemoenzymatic), could be applied to textile waste in the future [65].

For the production of recycled fibers, it is necessary to synthesize PET. This synthesis requires monomers of high purity and no presence of other diols or diacids able to act as comonomers. Theoretically, virgin and regenerated PET fibers have very similar behavior and properties because they are chemically identical, but there are many practical reasons for obtaining differences. The main important factors are:

A. Quality of wastes containing PET

The quality of waste depends on the type of waste. Post-consumer textile wastes are usually not 100% PET but are composed of other materials, such as different fiber types (often cotton), sewing threads, finishing agents, dyestuffs, and non-fibrous materials (zippers, buttons, strips, frills, etc.). These materials can be removed only partially, and special techniques should be used [66]. It is the main reason for not using textile wastes for recycling on an industrial scale as yet. As a source of waste for PET depolymerization, beverage containers (bottles) are mainly used [67]. Here, recycled PET should be analyzed for benzene and limonene content. Benzene is a byproduct of PVC contamination and degradation. Limonene is a flavoring agent primarily carried over from residual citrus juices and may potentially impact the organoleptic properties of the packaged beverage. A byproduct of processing PET is acetaldehyde [67]. Other plastic packaging waste products are useful as well [68].

B. Pretreatment of wastes

For the pretreatment of wastes, mechanical recycling is applied. This technology requires relatively little energy and few resources. However, mechanical recycling causes various problems, such as thermal–mechanical degradation and immiscibility of different polymers. Recyclates of sufficient quality for subsequent chemical recycling are very challenging [69]. Another problem is the presence of certain components, such as odorous

constituents, non-polymeric components, and inks, often containing metals and halogens [68].

C. Depolymerization system

Depolymerization product (monomers and intermediates) quantity and quality are critically dependent on the used method (see Figure 8). Terephthalic acid (TA) and ethylene glycol (EG) after purification are used directly as raw materials for polycondensation. Other types of monomers (as diamines) will act as comonomers in polymeric chains, changing their melting behavior, melting viscosity, and arrangements in a solid state (opening supermolecular structure).

D. New synthesis of PET

PET synthesis is described comprehensively in the book by [9]. The main problem is to select a suitable method, i.e., direct esterification or trans-re-esterification, and an optimal catalytic system [70]. Especially for fiber preparation, sufficiently high molecular mass and narrow mass distribution are required. These parameters can be influenced by the presence of various intermediates.

E. Preparation of fibers

Hydrolytic and thermo-oxidative degradation are also important in PET extrusion. To eliminate hydrolytic degradation, drying must be carried out before each processing operation in the melt. The properties of fibers are easily changed by drawing and thermal treatment, and the variability of mechanical properties is obviously not due to the use of recycled fibers [70]. The presence of other organic materials in polymeric chains and different particles between chains can be the reason for variations in thermal properties, sorption properties, and pilling. The microplastic generation can also be different. Textile processing of recycled fibers will be influenced by the proper spin finish.

With regard to EU legislation, the pressure on recycling or reusing textile waste from both production and at the end of the cycle of textile use will continue to increase. In this context, it is necessary to ensure that this issue is addressed comprehensively from the design of the textiles. Finally, any synthetic homopolymer uses many ingredients, such as catalysts of heavy metals or additives to alter functionality, dyes, colorants, etc., which make it very difficult to recycle them.

9. Conclusions

Recently, the textile industry has been at a crossroads in its impact on society. While there have been many inventions and innovations that have driven the industry forward, it is facing headwinds due to the need for a sustainable solution.

Waste recycling and environmental sustainability are not questions of achieving a goal but rather a direction and process of improvement. There is no final state that one is completely satisfied with reaching. We can always adjust to make our planet a better and safer place for all life forms. This can only be achieved through a comprehensive approach involving environmental, social, and economic aspects of problem-solving.

Instead of focusing on the local growth of the economy, it is necessary to make an effort in a broader time horizon that also includes nature and its possibilities or limitations. This does not mean promoting either ecology at the expense of economics or economics at the expense of ecology at all costs, but rather comprehensively balancing the entire system of human needs integrated with nature. Industrial processes must move from linear systems where wastes are in the final stage to closed-loop systems where wastes are inputs for new processes. The use of new, more efficient types of more sustainable fibers can be a small but important step to a sustainable future.

The main aim of this article is to demonstrate that sustainable development in the field of textiles is a complex and complicated task. There are a lot of known partial solutions, but without a comprehensive approach utilizing all aspects of the value-chain design–production–use–disposal value chain, they will only be isolated. The governing factors

must be addressed from the very beginning, and a sustainable strategy should be adopted. New research and scientific achievements should be used to modify technologies and add new functionalities focused on environmental and sustainable solutions.

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