Sustainable Textiles: Production, Processing,
Manufacturing & Chemistry

Subramanian Senthilkannan Muthu
Miguel Angel Gardetti *Editors*

Sustainability in the Textile and Apparel Industries

Sourcing Synthetic and Novel Alternative Raw Materials

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Preface

As anyone can imagine, sourcing is the vital first step in apparel production, whereas the choice of sustainable raw materials plays a crucial role in deciding the fate of the product in terms of sustainability. There is a generic division of raw materials, namely natural and man-made ones. Apart from natural and man-made raw materials, there are ample amounts of novel and new textile materials arising these days for textile sourcing, and this volume lists all those materials under regenerated and man-made ones along with the novel, alternative, new sustainable alternatives and their production, processing, and properties.

This volume gives a comprehensive outlook on various sustainable synthetic raw materials for raw material sourcing and the key issues around how to change man-made and regenerated fibers from unsustainable origin to sustainable ones and with detailed implications. This book also deals with the novel, alternative sustainable raw materials and their sourcing.

This book presents nine chapters. The first chapter, *Important Step in Sustainability: Polyethylene Terephthalate Recycling and the Recent Developments,* by Sedat Kumartasli and Ozan Avinc, explores recycling methods and the steps of used waste polyethylene terephthalate materials and the rebirth of waste polyester materials in new textile products and also related recent developments was comprehensively reviewed.

Secondly, Angela Liliana Dotor Robayo, in *Thinking Textile Materials from Their Nature: Ethical Materials for Fashion Design with Technological, Social, and Aesthetic Sense* aims to expose two research projects started in 2016 at the University of Bogotá Jorge Tadeo Lozano, which are case studies of living laboratories co-disciplinary spaces that promote sustainability in fashion. This co-disciplinary approach for the softening and improvement of Creole sheep wool with peasant community; an artisan community who work silk; the silk nanostructuring for color change and luxury design; the characterization of antibacteriality in Creole sheep wool for functional fashion; and the generation of a biopolymer from rice are discussed.

The following chapter, *Sustainable Green-Based Composites from Renewable Resources in Textile: Industrial Cotton Wastes* by Emine Dilara Kocak, Munir

Tasdemir, and Cigdem Gul explores cotton wastes in the apparel industry, and the opportunity of recovering them as recycled yarns. It analyzes different opportunities and potentials of reusing short fibers as cost-effective, profitable, renewable, environmentally friendly, and sustainable.

Subsequently, Aravin Prince Periyasamy and Jiri Militky author of the chapter entitled *Sustainability in Regenerated Textile Fibers* analyzes fibers as the basic raw material for textiles and explores the necessity to use sustainable materials and therefore produce sustainable textiles. Therefore, the author describes sustainability in regenerated fibers, including the cellulose and protein and their recent developments, including lyocell, bamboo viscose, modal, seacell®, smartcell®, and sustainable protein fibers.

Moving on to the next chapter, *Use of Roselle (Hibiscus Sabdariffa) in Composite Materials for Sustainability*, Munir Taşdemir, Çiğdem Gül, and Emine Dilara Kocak describe plant-based materials generally used to produce light composites. The authors present Roselle (Hibiscus sabdariffa) fiber that is employed to reduce carbon footprint and increase sustainable production aiming to increase the mechanical properties of the proposed material as well as the cost-effective production.

Then, Sedat Kumartasli and Ozan Avinc present *Recycling of Marine Litter and Ocean Plastics: A Vital Sustainable Solution for Increasing Ecology and Health Problem.* They explore and analyze marine litter and recycling of marine litter and ocean plastics and cover recent commercial developments for marine litter recycling.

In the next chapter, *Sustainability in Polyurethane Synthesis and Bio-based Polyurethanes*, Hilal Olcay, Emine Dilara Kocak, and Zehra Yıldız explore the composition, raw materials, and properties of polyurethane (PU) materials used in textile and other sectors. They also analyze the possibilities for bio-based PU synthesis.

Later, Songyi Yan, Celina Jones, Claudia E. Henninger, and Helen McCormick, in the chapter entitled *Textile Industry Insights Towards Impact of Regenerated Cellulosic and Synthetic Fibres on Microfibre Pollution* investigate microfibre pollution (MFP) from the textile industry perspective and what challenges and/or solutions are associated with it.

Finally, in *Sustainable, Renewable, and Biodegradable Poly(Lactic Acid) Fibers and Their Latest Developments in the Last Decade*, by the authors, Farnaz Sadat Fattahi, Akbar Khoddami, and Ozan Avinc, PLA [Poly(Lactic Acid)] stands as a potential option in many different fields for reducing environmental concerns and for a more sustainable future. The authors comprehensively review sustainable, renewable, and biodegradable PLA fibers and their latest developments.

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Contents

Important Step in Sustainability: Polyethylene Terephthalate Recycling and the Recent Developments

Sedat Kumartasli and Ozan Avinc

Abstract Human history has encountered massive environmental issues due to the outcomes of industrialization in today's societies, development of industry, increasing population, etc. The rise in the level of welfare around the world and its spread throughout many different societies and countries are adding on undesirable environmental problems. This negative trend seems not to stop and unfortunately is on the rise. The persistence on failure to keep up with change and development may trigger further environmental calamity increase leading to an unsustainable world. Therefore, today's society is called as the "Consuming Society" by many different authorities. If one would like to monitor the dimensions reached by this "Consuming Society" concept on the basis of textile sector, the examination of per capita consumption of textile fiber could be the right approach. Textile product consumption amounts are increasing in direct proportion with the increase in the world population. Unfortunately, natural fibers cannot meet the increased fiber demand. The remaining supply share in the increased fiber demand has been fulfilled with the production and consumption of chemical fibers. Therefore, the supply shortage in natural fibers has been substituted, wherever possible, by synthetic staple and filament fiber production. Natural fibers leave their throne to synthetic fibers while cotton fibers lose their throne to polyester fibers. Today we can point out polyester fibers as the most popular fiber type. Approximately 35% of the world fiber production is covered by natural fibers while the remaining 65% share is covered by synthetic fibers, and 70% of the synthetic fibers consumed are polyester fibers. Polyester is a general name for many different types of polyester fibers such as polyethylene terephthalate (PET), polylactic acid (PLA), polytrimethylene terephthalate (PTT), polybutylene terephthalate (PBT), etc. Polyethylene terephthalate (PET) fiber is the most important, the most produced, and the most

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consumed polyester fiber. Normally when one calls a fiber as polyester fiber, this fiber is mostly PET and is commonly referred to and used as polyester in public. The majority of PET production is used for fiber production in the textile sector, with 60% share, and 30% of PET production is used for bottle production. Due to the fact that polyester fibers possess obvious advantages in terms of raw material costs when compared with other fibers in the world, it is expected that the consumption quantities for the aforementioned two sectors will increase further in the coming years. Superior performance properties of PET fibers as well as their raw material cost advantages result in an increase in PET fiber production and consumption. Polyesters and similar petroleum and petroleum-derived plastics, which are not very friendly with the environment during their production and have a long natural decay time, gradually take their place among our indispensables in our lives. Their low cost causes their consumption to increase even more. The necessity of recycling these materials, the requirement for renewal in the technologies used in the production processes, and the necessity of disposing of waste materials in an appropriate way have reached levels that cannot be ignored. At this point, we can understand the actual costs of plastics only when we take into account the environmental pollution, recyclability, and their impact on our health. The most obvious example of this is the Asian countries. China and other Asian countries, which have become the center of synthetic fiber production, have a pie share of 70% in the world fiber market and some people believe that therefore they possibly might have the largest share for environmental pollution. The pressures of the countries and the environment in recycling polyester have led to improvements in the waste management industry. Thanks to this driving force, recycling is gaining importance day by day. In the economic sense, the recycling process is seen as the best way to reduce polyester waste as well as to take the advantage of their reusage for new textile products. Recycling and waste management systems are constantly changing and developing in line with new and innovative technologies. In this review chapter, recycling methods and the steps of used waste polyethylene terephthalate materials and the rebirth of waste polyester materials in new textile products along with related recent developments are comprehensively reviewed. Therefore, in this chapter, first of all, recycling processing steps of PET-based materials (cleaning, crushing, washing, drying, and chopping processes) are introduced. Then, the information regarding recycling methods such as mechanical recycling and chemical recycling is given. Afterwards, the applications of mechanically and chemically recycled PET are mentioned. Finally, the recent commercial developments regarding PET recycling are covered.

Keywords Polyester recycling · Textiles · Chemical products · Chemically recycled PET · Mechanical recycling · Sustainable raw materials

Introduction

In today's societies, human history is facing greater environmental problems than ever before owing to the industrialization, development of industry, increase in population density, etc. In addition, the rise in the welfare level in the world and the spread of this in the grassroots of the people create a recent concept that can be expressed as a "consumer society that may trigger the increase in environmental disasters." Climate change poses a serious threat to the world, and to overcome this threat, some attempts have been made by governments to minimize the waste generation or reuse the waste [1]. However, lack of environmental and economic awareness, regulations are becoming a critical problem to minimize solid waste [2]. Recycled polyester is a more sustainable raw material since the usage of recycled polyester protects natural resources, saves energy in production process, and leads to lower greenhouse gas emissions and use of chemicals [3].

Thereof, recycling has become a well-established and well-accepted system with its own logistics chain including post-consumer PET (POSTC-PET) bottles, bottle collection, flake production, and pellet production [4]. If one wants to see the dimensions reached by this concept on the basis of textile sector, it is enough to examine the amount of fiber used per person per year. When the production of synthetic fibers in the world is reviewed, it is seen that the highest amount of production belongs to polyester fibers. Today, polyester fibers are the most popular fiber due to its important textile characteristics. Polyethylene terephthalate (PET) bottles are produced from petrochemical products and, generally, the waste is left directly for environmental decay after use. However, increasing volume of PET bottle waste results in economic and environmental troubles unless recycled [5]. Indeed, fiber production in the world consists of 65% synthetic fiber and 35% natural fiber, while 70% share of the consumed synthetic fibers is polyester and it is widely known that the most produced and consumed polyester is based on PET (polyethylene terephthalate). The wide majority of PET production, about 60%, is used for fiber production in the textile sector, and 30% is used for bottle production [6]. Textile is a suitable sector for recycled plastics especially for polyesters [7, 8]. Approximately 60% recycled PET (r-PET) polymer is used in the production of PET filaments and fibers that displays how important the textile industry is for waste plastic materials. It is extrapolated that the consumption of PET bottle recovery and recycling to PET flakes will increase 10–20% in 5–10 years. However, recycling PET bottles and using them in the textile industry provide added value to the textile products [9, 10]. Compared to other textile fibers in the world, polyester fibers are quite advantageous in terms of raw material costs. Therefore, the consumption amounts are expected to increase further in the coming years in both of these sectors.

Polyester and similar petroleum and petroleum-derived plastics that are not very friendly with the environment during their production and exhibit extremely long degradation time in nature are increasingly becoming indispensable in our lives. Their low cost also leads to an increase in their consumption. For this reason, the necessity of recycling of these materials, the need for innovative improvements in the technologies used in the production processes, and the necessity of disposing off the waste materials have reached inevitable dimensions. PET bottles can be found nearly everywhere in our daily life. Moreover, PET bottle is the most suitable packaging plastic and probably the most widely used plastic throughout the world. Almost all recycled PET (r-PET) chips were converted to useful textile fibers. r-PET could be utilized in a wide variety of applications [4, 11, 12].

The PET recycling industry began as a consequence of environmental pressures to improve waste management. Another factor that acts as a driving force for the PET recycling industry is the slow rate of natural degradation of PET products [10–13]. PET is a nondegradable plastic under normal ambient conditions. There are no known organisms that could consume relatively large molecules. For biodegradation of PET, complex and quite expensive procedures are required [10]. The use of PET bottles can result in some environmental problems, since it is known that the degradation of these PET bottles in soil at 20 °C and 100% relative humidity conditions can take 35–48 years and the degradation may increase by 45% at varying moisture rates [14]. Nowadays, PET bottles could be utilized for soft drinks, drinking water, energy drinks, iced teas, as well as more delicate beverages such as beer, wine, and fruit juices [15]. It is known that approximately 1.2 kg of crude oil is utilized for the production of one PET bottle and for this at least 65 L of water is consumed. In addition, the amount of electricity consumed in crude oil exploration and extraction is not completely known. A plastic bottle does not disappear for 3000 years in nature and saves 14,000 kW/h when 1 ton of plastic is recycled [4, 16]. It is known that too much energy, in total, is consumed in the production of polyester fiber [17]. In addition, recycling of PET bottles results in the reduction of waste and the decrease in the use of raw petrochemical products, water, and energy. What is more, PET bottle recycling is estimated to provide a benefit in greenhouse gas emissions of 1.5 tons of CO_2 per ton of recycled PET [18].

Today, we can understand the real costs of plastics only when we take into account the environmental pollution, recyclability, and health effects. The most obvious example of this is the Asian countries. China and other Far East Asian countries, which have become the center of the synthetic fiber production, have a share of 70% in the world fiber market and some people believe that therefore they possibly might have the largest share for environmental pollution. More detailed information about recycling of PET-based materials, recycling methods, and the applications of recycled PET are given in the below sections.

Recycling of PET-Based Materials

Used plastic bottles are collected by waste collector or waste merchants. After separation, these bottles are sent to the major manufacturers and recycling facilities. Caps, opening rings, and product labels (non-PET components) are removed and then the plastic bottles are shredded, cleaned, and presented as cleaned flakes. These cleaned flakes are then used as a substance in pillows or in furniture as fiberfill applications and in different clothing products [19, 20]. Recycling processes, which can be mechanical or chemical, are the best way to reduce PET waste into economically reusable forms [2, 4–21]. Therefore, it is generally stated that the best way to economically reduce PET waste is through recycling [10–23]. It is important to point out that the recycling process does not reduce costs, but maintaining an ecological balance is essential for sustainable world. PET bottles can be easily separated from other waste, that is, some additional processing is needed. Shredding, washing, and drying processes should take place in order to obtain PET flakes. The r-PET fibers to be used in the textile industry are manufactured by melt spinning system from PET flakes. This recycled product can be easily adapted to the production of textiles [1]. The world's first recycling of PET bottles took place in 1977 [10–24]. Many researchers have reported that PET flakes must meet certain minimum requirements in order to achieve successful PET recycling process [25–27]. Examples of minimum requirements for recycling of post-consumer PET (POSTC-PET) stamps are summarized in Table 1. The main factor affecting the suitability of the POSTC-PET flake for recycling is the level and nature of the contaminants found in the flakes [10].

PET-based solid wastes make up 8% by weight and 12% by volume of the total solid waste in the world. The distribution of PET recovery rate by country is as follows [28]:

- China: 70–85%
- EU: 35%
- USA: 23%
- Japan: 64%
- Other countries: 20–40%

Secondary waste is the mixed waste outside the PET-based wastes, and this group constitutes the majority of waste. Therefore, one needs to separate the plastics

Table 1 Minimum requirements for POSTC-PET [10]

Property	Value
$[\eta]$	>0.7 dL g^{-1}
T_m	>240 °C
Water content	<0.02 wt%
Flake size	$0.4 \text{ mm} < D < 8 \text{ mm}$
Dye content	<10 ppm
Yellowing index	<20
Metal content	<3 ppm
PVC content	<50 ppm
Polyolefin content	<10 ppm

from other materials before separating them from each other. Recycling of plastic waste is carried out in four ways [7]:

- *Primary Recovery*: In the primary recovery method, waste plastics are treated with mechanical shredders. Plastic dimensions are reduced and mixed with the original plastics and processed again.
- *Secondary Recovery*: This recovery is undertaken for the production of secondary quality products that are not equivalent to the product obtained from the original polymer from waste plastic.
- *Tertiary Recovery*: It is also described as chemical recovery. The main objective is to produce the monomer. The original polymer and various chemicals from waste plastics can be used for other purposes.
- *Quaternary Recovery*: It is a burning process to recover heat from plastic wastes. Here, plastic wastes are burned and their energy is utilized.

There are three approaches to reduce pollution. The first is to take advantage of new innovations that are less polluting. The other is to treat textile waste in a viable manner so that the final output complies with normal standards. The third and most appropriate route is to recycle the waste several times before its release [29].

During recycling, contamination of PET is the main cause of deterioration of physical and chemical properties during reprocessing [10–39]. The main problem was that the ingredients contained in the drink were often absorbed into the polymer, as well as harmful compounds from containers that were possibly used for storage of cleaners or garden chemicals. If such absorbed postconsumption toxins are not removed from the packaging polymer during the recycling process, they may be transferred from the recycling material to the foodstuff [30].

The procedure of converting PET into recycled polyester necessitates much less energy than in the case of normal polyester; it takes around 33–53% less energy. There are two chief benefits of this process:

- Utilizing more recycled polyester decreases our dependence on petroleum as the raw material for our fabric requirements.
- Diverting PET bottles for this process decreases landfill and therefore less soil contamination, and air and water pollution in return.

Other advantage is that the garments made from recycled polyester could be recycled again and again with no degradation of quality, allowing us to diminish wastage. This means that garment production could potentially become a closed-loop system; polyester could forever be reused and recycled again and again [40].

In the recycling facility, the materials are first passed through a vibrating sieve to remove unwanted materials such as loose soil and sludge, and at the end of the conveyor belt, the materials are passed through electromagnetic field and separated from steel and tin materials. The magnetic rods placed at the end of the conveyor belt also separate aluminum materials from plastics [28]. The waste plastics then move to the plant where they are gathered as bales (Fig. 1).

Fig. 1 Waste PET bales

Cleaning Process

The bales of the packaging wastes delivered as presses are unpacked, and passed over the conveyor belt. Then firstly, the foreign materials are separated and afterwards manually separated according to their color if necessary. The main purpose of the separation of the collected plastic waste is the recovery of the recovered plastic with the highest possible purity and unchanged properties [7, 31]. There are two important issues in here. Only the PET bottles, no other plastic bottles, should be processed, since the applied processes may not be suitable to other plastics. Such mixtures of PET bottles and other kinds of plastic bottles will generate major problems in the next operations.

Separation of PET wastes is an important and critical step. Increased contamination with other substances causes degradation of waste PET during further processing steps. Plastics that cannot provide a uniform mixture with each other can impair mechanical performance. For this, each lot must exhibit a good distribution and homogeneity. There is a very important point to consider when weeding process is in progress. This point is the process of separation of PVC (polyvinyl chloride) materials. The PET material can be separated easily by using the density difference between the thermoplastics by the flotation–immersion method (Table 2). However, since the densities of PVC and PET are very close to each other, we need to carefully separate PVC in here [23].

The PVC material is transparent, just like PET; therefore, it is difficult to separate both manually. The melting temperature of PVC (212 °C) is much lower than the melting temperature of PET (265 °C); PVC melts and burns before PET and turns the color of PET into brown, damaging the quality and the value of the product. In this context, different technologies have been developed to separate PVC [32, 33]; for example:

- Optical separation system
- X-ray fluorescence method
- Near infrared spectroscopy
- Hydrocyclones
- Electrostatic charges and surface properties

In addition to these mentioned technologies, the search for better and more useful methods, and research, is still continuing [32].

Crushing Process

The waste bottles are either crushed as in their dry condition or crushed after passing through the prewash basin. The crushing machine makes the PET material smaller to be recycled to 10–12 mm. Since PET is a hard material, blades for PET wastes are not very long lasting. Therefore, prewashing or wet crushing of the PET bottles reduces the dust content in the material and extends the life of the crushing blades. Grinding machines for PET blades are also a must in a PET recycling plant [32].

Table 2 Densities of thermoplastics [31]

Thermoplastics	g/cm^3
PP	0.9
LDPE	0.9
HDPE	0.95
Polystyrene	1.05
Polyamide	1.15
PVC	1.4
PET	1.4

Washing Process

PET washing process removes the floating plastics such as labels and caps from the crushed PET bottles. However, this process should also be designed in such a way that unwanted impurities (such as oil, cola, sugar, and label adhesives that are left in the PET packages) could also be removed [32]. In the first washing unit, crushed PET pieces are thrown into the flotation sink. As the density of PET is greater than water, PET will sink. Other materials such as paper, covers, and labels such as polyethylene (PE) and polypropylene (PP) will float due to their lower density than water. Generally, a 2% caustic solution is used and the washing is finished with a rinse in the second washing unit at 93 °C [31, 32].

Drying Process

Drying process reduces the moisture content of PET caused by the washing process leading to less than 3% and also removes the particulate dust from the PET fractures through the centrifugal holes. Drying process is an essential step in recycling. PET manufacturers apply drying processes at 140–170 °C for 3–7 h. Under typical operating conditions, more than 0.02% water is not allowed in PET particles and the PET is usually subjected to a drying process at 170 °C for 6 h to provide this level of water content [32]. Reducing the moisture content of the particles also reduces the hydrolytic disintegration effect. The dried PET chips are optionally passed through a fine chopper again. Although various studies state different numbers, life cycle analyzes generally show that 1 kg of PET flakes is obtained from a 1.33 kg PET bottle [4, 31].

Chopping Process

The chopping process results in smaller waste PET materials leading to better processability for further stages. The degree of the chopping process is generally adjusted according to certain sizes. The resultant material of the chopping process is called PET flakes (Fig. 2).

Recycling Methods

From this point on, the method of PET recycling plays an important role. There are three major types of recycling methods: thermal, mechanical, and chemical. Thermal recycling is based on the generation of electricity by burning PET bottles and the

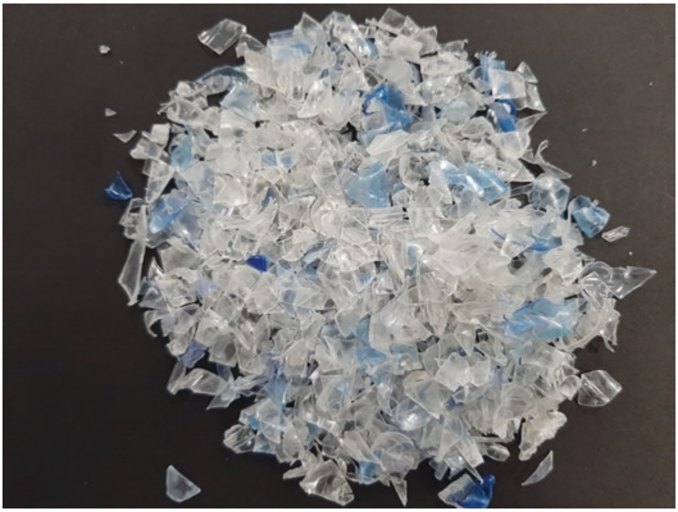

Fig. 2 PET flakes

combustion temperature is generally higher than other domestic wastes [4]. However, this process type should not be considered among recycling options due to the resultant CO_2 emissions [34]. Thermal conversion can be considered as a kind of recovery method rather than recycling and reprocessing. It is important to note that before the mechanical and chemical recycling, some requirements are needed to process the PET chips obtained [10]. These requirements depend on whether we use closed-loop or open-loop management in garbage management system [4]. The production of PET bottles from PET bottle products is a closed-loop process. Open-loop process is to produce different products from PET bottles (PET flakes) such as textile products, or composite or construction materials [4, 35, 36]. PET flakes obtained from waste PET bottles will also be used in PET bottle production. Open loop means that we will use it in different areas of recycling. For instance, one can use PET chips (Fig. 3) from waste PET bottles in fiber production, or automotive or construction industries [35].

Of course, closed loop is more advantageous for us. Since with this method, PET bottle gains the quality of primary raw material and has a longer life time than open cycle. Today, the collection and recycling of waste PET bottles is a controversial issue in terms of health and technological requirements. The polymer iteration at each heating of the material causes the material to degenerate [6, 10]. The most important obstacle in recycling PET bottles is the structural viscosity. As the viscosity value of PET materials increases, so does their commercial value. However, after recycling of PET bottles, the viscosity values decrease in each process step and this value can be reduced to viscosity of 0.9 dL/g and below depending on the condition of the waste. The ideal viscosity for PET bottle production is 1 dL/g [10, 34, 37].

Generally, PET chips have a viscosity of 0.5–0.7 dL/g as a result of polycondensation, which is very low for bottle production. Viscosity of PET chips can be

Fig. 3 PET chips

increased in order to obtain the required final viscosity for further processing [10, 34, 37]. Apart from technological limitations, there are serious concerns about health in the production of PET bottles from waste PET bottles. Failure to meet the minimum requirements for the recycling of PET chips can result in serious health problems as thermoplastic polymers are not mixed with a homogeneous dispersion [10, 37]. There are some limitations to the use of recycled plastics in contact with food. It is expected that values such as dye content, yellowing index, metal content, polyvinyl chloride content, or polyolefin content in these PET materials will be below specific ppm limits [10]. Still, these materials are generally used in composite form, with nylon coating applied on them. However, in some studies, it is thought that the use of waste PET bottles in PET bottle production again is not healthy today [33]. Therefore, it makes more sense to use waste PET bottles in different areas as open-cycle production rather than producing new PET bottles with a closed loop. Textile and fiber sectors are the leading sector in these different fields. Approximately 60% of the PET polymer produced in the world is used in the production of polyester filament and staple fibers. Moreover, structural viscosity, which is the biggest obstacle in PET bottle production, does not prevent the use of PET polymer in textile sector (Table 3). It is known that viscosity decreases in each melting process. However, even in the textile sector, the reduction in viscosity can be overcome during fiber drawing depending on the area in which the fiber is to be used.

Two types of PET flakes obtained from PET bottles (via mechanical and chemical recycling processes) are generally preferred to be used in textile sector. In addition, 5–10% of the waste (including unused quality fibers and yarns) during the production of raw polyester fibers can also be utilized in the production line [36].

Table 3 Structural viscosity required in polyethylene terephthalate (PET) polymer [37]

PET	Viscosity (dL/g)
Low-tenacity fibers	0.40–0.50
Wool-like fibers	0.58–0.63
Cotton-like fibers	0.60–0.64
Multifilament	0.65–0.72
Technical yarns	0.72–0.90
Tire cord yarns	0.85–0.98
Film, foil	0.60–0.70
Injection blowing molds	0.90–1.00

Mechanical Recycling

Complete recycling lines for the recovery of waste plastics include: washing, cleaning, chopping, drying, melting, and converting granulated plastic into plastic raw materials [7]. Recycling is valuable if the recovered product can exhibit the original properties of the polymer at the first use, and this is also economically necessary. The technologies of the products that have been obtained through recovery have some limitations which are known as downcycling [6, 36]. The properties of the product obtained here are often slightly worse than the original material. The mechanical recycling is divided into two types: mechanical (flake to fiber) and semi-mechanical (flake to pellet).

The material conversion is the conversion of PET chips from the melt to the fiber using the fiber spinning method. In the mechanical method, the fiber is obtained directly from the PET flakes. On the other hand, in the semi-mechanical method, the PET flakes are subjected to a fine chopping process again and then extruded into chips. Although there is a material efficiency of 99% (1.01 kg flake gives 1 kg fiber) in the mechanical method, it works with 94% (1.07 kg flake gives 1 kg chips) efficiency in the semi-mechanical method. In addition, energy savings of up to 60% are achieved in the fiber conversion with material conversion [4, 32, 37]. The polyester fiber recovered by material transformation is shown as r-PET in Table 4.

With the reduction of both energy costs and raw material costs, recycling fiber has an important economic advantage. Furthermore, r-PET fibers are less harmful to the environment with less formation energy expenditure and less carbon emissions (Table 5). In addition, the use of chemicals such as bisphenol-A and antimony that damage the hormonal system of our body will be reduced [6]. The quality of the polymer after mechanical and semi-mechanical conversion is directly related to the purity of the waste and the efficiency of the previous cleaning processes. But, unfortunately, we have little knowledge of the history of recycling material. For example, there is difficulty in answering many different questions such as how many times it has been processed, or questions regarding thermal decomposition, domestic waste, outdoor waste, and heat and weather exposure. The characteristics of the PET bottle will vary depending on the thermal, mechanical, oxidative, and photochemical

Table 4 Embodied energy used in production of some textile fibers [37]

Fiber type	Energy use (MJ/kg)
Hemp (organic)	2
Linen	10
Hemp (conventional)	12
Organic cotton (India)	12
Organic cotton (USA)	14
Cotton (conventional)	55
Wool	63
r-PET	66
Viscose	100
Polypropylene	115
Polyester	125
Acrylic	175
Polyamide	250

Table 5 Weight (in kg) of carbon dioxide emissions per ton of spun fiber [37]

Fiber type	Product growth	Fiber production	Total (kg/ton)
Polyester	0	9.52	9.52
Cotton	4.2	1.7	5.89
r-PET	---	5.19	5.19
Hemp	1.9	2.15	4.1
Organic cotton (India)	2	1.8	3.75
Organic cotton (USA)	0.9	1.45	2.35

conditions to which it is exposed. If a clean bottle is used and separated and treated carefully, it is clear that it will achieve normal fiber quality [31]. But, in its basic form, the molecular weight changes with thermal loads during melting, and therefore the tensile strength, stretch, and dyeing properties of the fibers can change. Recycling can also provide new and versatile possibilities for us to reuse products by repolymerization of waste directly as an alternative to melting and extruding if the material is not to lose its value [36].

Chemical Recycling

Chemical recycling (chemolysis) of PET is achieved by total depolymerization to monomers or partial depolymerization to oligomers. The chemicals utilized for depolymerization of PET contain water (hydrolysis), methanol (methanolysis), and ethyleneglycol (EG: glycolysis). The main drawback of PET chemolysis is its high cost [10]. Although there are a wide variety of methods, there are mainly two methods accepted in the market: glycolysis (back to oligomer) and methanolysis (back to monomer).

In the glycolysis process, the PET product is depolymerized by glycolysis decomposition and separated to its oligomers, bi-hydroxyl ethylene terephthalate (BHET) [33]. Methanolysis depolymerizes the PET product to its monomers dimethyl terephthalate (DMT) and ethyleneglycol (EG) [33]. The properties of the PET polymer separated into their monomers are similar to those of raw (untreated) PET. When separated into oligomers, it can be characterized as similar except for dyeability [4].

Applications of Recycled PET

Applications of Mechanically Recycled PET

There are many chief application fields for the PET textile sector such as staple and filament fibers, nonwoven fabric, and fiberfill. Commonly, recycled PET has been used for fibers of more than six deniers, whereas the prime market for the PET fiber industry (clothing and apparel applications) is in the 1.5–3 denier range. These fibers necessitate high-quality feedstock, and post-consumer PET flakes utilized for these fibers should have consistent intrinsic viscosity around 0.7 dL/g [41]. Conventionally, recycled PET has not been extensively utilized for filament manufacture due to the possible contaminants leading to filament breakage. Melt filtration of the PET is implemented in order to achieve high quality of the resin. Nonwoven fabrics, utilized as filters and absorbents, are created by spun bounding technology. The melt spun filament fibers are spread and distributed on a screen belt under strong vacuum condition, and the fibrous materials are compressed into a mat for web-forming. Fiberfill is used for numerous applications such as filling materials and insulant in sleeping bags, pillows, and bedding. These end-use applications allow the utilization of colored PET flakes and necessitate PET with intrinsic viscosity in the range 0.58–0.65 dL/g.

Applications of Chemically Recycled PET

Chemically recycled PET could be utilized for applications in the production of continuous filament and unsaturated polyester resin. The oligoesters obtained from PET glycolysis can be used as the starting material for PET chips production [42]. Unsaturated polyester resins have been utilized comprehensively as a matrix for high-performance fiber-reinforced polymer composites, and they could be synthesized from virgin material or from recycled PET [41, 43].

Recent Commercial Developments

Virgin polyester is being produced in much higher volumes day by day due to the increasing world population and their clothing needs. This increasing international demand for textile fibers also makes the price of the recycled polyester to be more competitive. Multinational sporting goods companies were in their early stage for the utilization of recycled polyester in their products. In the recent years, even the giants in the fashion industry have begun to use recycled polyester more and more. In the long term, it is expected that the prices of recycled polyester will decline, especially if the companies and industries work together and provide clear signals to the suppliers so that they dare to invest [44]. Many companies are now using recycled polyester in the production lines. This trend is expected to increase in the upcoming years for many more different companies.

Currently, most of the world's recycled polyester fiber production is being used for home textiles according to Indorama Ventures Public Company Limited (IVL), which is the largest PET producer with a 20% market share globally. Almost 100% of the company's recycled polyester is used for products such as bedspreads, blankets, and chair stuffing [45]. Around 35 companies in India recycle PET bottles leading to production of 50,000 tons of recycled fiber in a month. This equals almost 50% of the virgin polyester produced in the country. For instance, Tamil Nadu has 2 PET recycling plants, 1 each in Tirupur and Karur, and most of their 450 open-end spinning mills have begun using recycled fiber. It is reported that, now, their use of recycled fiber is on the rise [46].

Unifi launched REPREVE in 2007, and it is now one of the world's leading branded recycled fiber. Many of the most recognizable, global brands in the world use REPREVE. It was reported that, to date, they have recycled more than 14 billion plastic bottles. Recently, Unifi aims to recycle 20 billion bottles by 2020 and 30 billion bottles by 2022 [47]. For instance in Turkey, Polyteks fiber production company launched POLY-eco® as their recycled PET fiber and yarn brand in 2011, and now it is one of the Turkey's leading branded recycled PET fiber (Fig. 4). This yarn has come to life in many different textile end-use products since 2011.

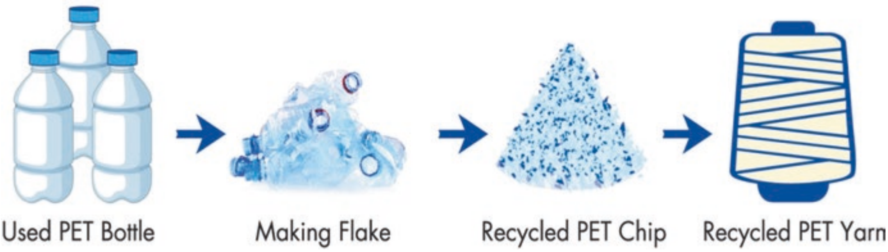

Fig. 4 The journey of used plastic bottles to become recycled PET yarn (POLY-eco® recycled PET yarn brand, POLYTEKS)

One of the core ways that brands are introducing sustainability into their collections is through the use of recycled materials—primarily recycled polyester. Major international brands including Zara, H&M, Marks and Spencer, Levi's, G star, and many others have adopted this approach [45]. More than 40 textile, apparel, and retail companies comprising famous brands such as H&M, Lindex, Target, Adidas, Dibella, Eileen Fisher, and Timberland have signed either commitments or supporter agreements in order to enhance their usage of recycled polyester by at least 25% by 2020. This new pledge has been organized by the Textile Exchange Recycled Polyester Working Group and is in line with the UN Sustainable Development Goal Target 12, which targets to accomplish the sustainable management and efficient utilization of natural resources, including reducing material footprints [48]. For example, global clothing company H&M used 325 million PET bottles in its recycled polyester in 2018. According to 2018 sustainability report of H&M, H&M is the sixth largest consumer of recycled polyester in the world. Additionally, in year 2017, H&M's Weekday swimwear brand was created completely from recycled nylon and polyester [49].

Nike has been active in using recycled PET in jerseys for a long time. Recycled polyester was used in the uniforms for the US basketball team during the Summer Olympics and the US Women's soccer team for the FIFA World Cup. Nike has diverted more than three billion plastic bottles from landfills into recycled polyester since 2010. Nike is also decreasing the energy consumption in the production process by up to 30% compared to virgin polyester via the usage of recycled polyester [50]. Moreover, it is stated that Adidas intends to use recycled plastic in all of its products by 2020 [51].

Conclusions

Throwing away plastic bottles, rather than recycling them, means that the most used waste plastic unfortunately would end up in landfills or in the oceans. Many landfills have become already overcrowded and occupy the valuable space that can be utilized for other purposes. Moreover, landfill waste lets out pollutants into the soil and water. Furthermore, animals that live in oceans are constantly ingesting small bits and pieces of this residual plastic, leading to ending up in our plates. Plastic recycling is very significant and must be taken staidly. Used and unneeded plastics create a huge amount of solid waste and need centuries to break down in landfill or in the ocean. Consequently, all recyclable plastics should be recycled to decrease landfill, and conserve energy and environment. Hence, recycling is important and the market share of the recycled yarns used is expected to increase.

When the production of synthetic fibers in the world is reviewed, it is seen that the highest amount of the production belongs to polyester fibers. Today, polyester fibers are the most popular fiber due to its important textile characteristics. Polyethylene terephthalate (PET) bottles are manufactured from petrochemical products and, generally, the waste is left directly for environmental degradation after use. However, increasing volume of PET bottle waste results in economic and environmental problems unless recycled. Recycled polyester is a more sustainable raw material since the usage of recycled polyester protects natural resources, saves energy in production process, and leads to lower greenhouse gas emissions and use of chemicals.

Therefore, in the recent years, multinational sporting goods companies and even the giants in the fashion industry have begun to use recycled polyester more and more. Many companies are now using recycled polyester in the production lines. This trend is expected to increase in the upcoming years for many more different companies. Hence, recycling is an inevitable remedy for more sustainable and greener planet, and for carrying our world to the future for next generations in a best possible shape.

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Thinking Textile Materials from Their Nature: Ethical Materials for Fashion Design with Technological, Social, and Aesthetic Sense

Angela Liliana Dotor Robayo

Abstract This chapter aims at exposing the development of two research projects that started in 2016 at the University of Bogotá Jorge Tadeo Lozano, which are case studies of living laboratories. From them arise pieces of textile design and sustainable fashion following a systemic approach, by means of a methodology that includes recognition of the fibers, their material and its DNA, cultural analysis and re-signification, in order to establish a productive and ethical system within a mixed work methodology environment, a real articulation and transfer of information between community and academy. In so doing, product design cohabitates in the crossroad of social, scientific, and technological recognition and is thus integrated into a creative act of clothing design which in turn becomes a platform for dialogue that re-signifies culture and proposes product design with a socio-functional approach based on the work with the associated communities involved in the production of natural fibers such as silk, wool, mulberry, and rice starch.

Following a co-disciplinary approach for the softening and improvement of Creole sheep wool with peasant community, through the improvement in textile and fashion design with artisan community of silk in the department of Cauca, the silk nanostructuring for color change and luxury design, the characterization of antibacteriality in Creole sheep wool for functional fashion, and the generation of a biopolymer from rice, we were able to design living laboratories as co-disciplinary spaces that promote sustainability in fashion. In this way, in a country like Colombia, fashion can be thought of as a system with sustainability, local identity, and development that helps ameliorate the precariousness of the production conditions of rural communities, especially of women.

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Keywords Wool · Silk · Textiles · Felted · Fashion system · Sustainability · Nanotechnology

Introduction

This chapter presents wool and silk fibers within their cultural and social sphere in Colombia. It aims at thinking and creating an ethical, cultural, and sustainable textile production system with people and natural resources.

In a first instance, it starts from an explanation of the problem of artisanal textile culture and of the unsustainability of fashion with the aim of identifying the need to work in the creation of cultural and ethical sustainable systems as work axes for textile design. In a second instance, it focuses specifically on the characterization of fibers to promote and re-signify productive dynamics, giving continuity to the textile process. The methodology and experimentation undertaken to produce nonwovens as an alternative to handmade textile product design of wool and silk are outlined. The process of co-participative creation and living laboratories as a methodology for product design with local fibers and identity with various actors is also described. Co-creation seeks the spread of knowledge, the promotion of transparent and clean dynamics, and the generation of value in the development of sustainable textile products (some handmade, others with chemical characterizations) in order to generate innovation products that open up local fibers for other functionalities and sustainable luxury markets.

Finally, it is shown how system design work under the laboratory method accounts not only for the production of textiles that can be handmade and technologically improved at the same time, but also for the construction of social dynamics that result in the production of environmentally friendly and creative textiles as fruit of the co-disciplinary work in a social and aesthetic system.

The Unsustainability of Culture and Fashion

There are many concerns when facing the unsustainability of the fashion system, from how to combat bad industrial practices, how to propose a viable identity and design product in a framework of intensive fashion globalization tendency, how to generate differential design and be ethical with resources and people, and, perhaps the one that commits us the most, how to build a sustainable product.

In this sense, understanding sustainability stems from the idea of thinking about the work ecosystem. Thinking about local identity requires understanding of the territory as a system under the framework of systems theory [1] and culture theory [2]; that is, to put in dialogue local realities of different actors, and dynamics of rural and artisanal thinking with design thinking; and make scientists work together in the construction of products with local identity [3], and intelligent products from local fibers—thus understanding textiles, yarn, fibers, and clothing as elements of the Colombian material culture.

Thinking About the Cultural Sphere

Creole sheep wool is a fiber that is rooted in the pastoral and rural practices of different areas in Colombia such as the Cundiboyacense highlands, part of the Santander departments, and the southern part of the country bordering Ecuador and Perú.

The first forms of clothing and ornament for practical purposes of usability and human protection were focused on the use of sheep fleece to protect against cold and for feet covering. Given the characteristics of high resistance of the fiber, the social system where the wool had its roots gave rise with time more productive forms and more elaborate products.

In the Colombian Andean territory, a social system has been generated around the fabric, spinning and wool shearing. In nowadays tourist centers such as Ráquira, Villa de Leyva, Paipa, Nobsa, and Cucunubá, wool is seen as a fiber that represents peasant and indigenous culture of the rural areas and its resilient local identity. In those places, wool is sold raw and in pieces of clothing of rustic morphology, under basic and natural lines such as the ruana, tapestries, blankets, shawls, sweaters, and scarves.

Wool is thus a symbol and a representation of Colombian Andean peasant culture, which expands its cultural memory linked to its territories; and the fabric is referred as a social practice that promotes social integrity, concentration, and a way of thinking that leads to spaces of dialogue, and of construction of meaning and identity, which, as an artisanal practice, should be considered as an intangible heritage of Colombian culture—a heritage that transforms itself into important social values for weavers and into a culture resilient to disappearance.

In the case of silk, mulberry is produced and worms are raised only in Cauca and Caldas departments, in towns such as Tambo, Timbío, and Anserma. Mulberry is a protein fiber developed by “sericultors.” The technique and the larvae were brought from China, but sooner joined the local artisan community. Ancestrality and local identity are maintained and promoted around the fabric by small groups of artisans and weavers, mostly rural, and peasant and indigenous women who practice weaving on vertical, waist, and horizontal looms as part of their family and cultural weaving tradition.

In this context, it is possible to talk about the identity of territory of weavers, women and men, of spinners and agriculturists, and about a rural cultural development that maintains current ancestral practices rooted in cultural, social, and mystical values around the fabric.

However, a main problem with products made of silk and Creole sheep wool arises from its low competitiveness given that producers experience its low market opening: there is little demand, few buyer alternatives, and obvious aesthetic and experiential product flaws.

This situation means that the fiber must be considered within the complexity of the system in which the material is placed. Thus, when silk and wool are framed in economically unsustainable scenarios, the system is at risk of disappearance.

In the case of Creole sheep wool, the problem is even greater since it involves management and design failures; also, the physical and chemical characteristics of Colombian Creole wool are to be considered. The wool has features that define its own morphology and structure that depend on the Creole sheep breed and the way the sheep is cared for. So, the first problem in the design product from wool is the roughness of the fiber, which causes allergies and itching when garments and textiles are made and woven with this fiber. Moreover, these handmade products haven't had any renovation in their design, a factor that has affected and stagnated sales possibilities.

On the other side, national costume design faces two main problems: first, the construction of local identity; second, the generation of sustainable design methods. In this context, two big problems of two twin systems are interwoven: on one hand, the design system; on the other, the cultural system of handicraft products with fibers and identity fabric. Their appropriate joining is here postulated as an exercise that could no doubt generate an ethical and socio-aesthetic design system respectful of people, culture, and the environment.

Thinking About Fibers and Environmental Sustainability

Fibers and filaments are the basic units used for the manufacture of threads and fabrics. They give textiles texture, appearance, and performance [4]. Silk is the only natural filament with unique characteristics such as high gloss and softness.

According to Elices *et al.* [5], natural silk is generated by the worm belonging to the domesticated species *Bombyx mori*, which produces it during a certain stage of its biological cycle. This is the reason for its high price and shortage. Because of this, in the search of materials that would make up this inadequate supply and high price of silk, Neri Guerrero [6] states that by the end of the nineteenth century a rayon was discovered and was called "artificial silk" because it replaced natural silk in the manufacture of stockings, fabrics for lingerie, and outerwear.

The discovery of the viscose rayon gave way to the production of many artificial fibers, and then to synthetic ones. The nylon, developed by Dupont in 1935, was the first synthetic fiber, that is, 100% man-made; it was a fiber with which washable and easy-care fabrics were produced [7]. According to Hollen *et al.* [4], nylon allowed perfection in terms of toughness, elongation, ironing temperature resistance, and, most of all, resistance to sunlight.

This event triggered the consumption of synthetic fibers, with more and more uses and low-cost markets [7]. What nobody realized was that all these "benefits" would create a problem of sustainable development for the entire planet because, according to Sánchez [8], the large-scale production of artificial and synthetic textiles that predominates nowadays has a reduced biodegradability rate and is driven by indiscriminate consumption of clothes produced by people who work for a livelihood.

This situation is against sustainable development. Buarque [9], cited in IICA [10] states that sustainable development is a process of social change that harmonizes economic growth, environmental conservation, and social equity in time and space; and

IUCN, UNEP, and WWF, cited by UNESCO ([11], p. 4) state that sustainable development implies "improving the quality of human life without exceeding the carrying capacity of the ecosystems that support it."

In the search for patterns of accelerated economic growth, which usually do not project the irreparable consequences to the environment associated with polluting waste [12], a sustainable artifact is one that does not imply an intensive, extensive, and irrational use of natural resources. A sustainable article is one whose production did not contribute to the depletion of natural resources, environmental degradation, increased poverty, and the absence of intergenerational solidarity [13].

There is no doubt then that the production of natural fibers such as silk in a local and family production environment, when compared to large-scale systems, as described by Pokorny *et al.* [14], exhibits great advantages at an environmental and socioeconomic level because small producers usually take care of the land and biodiversity, and they live by generating an income that is distributed equitably for the benefit of many families.

Polyester derived from petroleum, whose reserves are estimated between 10 and 25 years, is not degradable or takes at least thousands of years to degrade [15]. Natural silk, instead, has low resistance to sunlight and abrasion; and that is why it decomposes easily [16].

Natural silk also has characteristics that make it unique, such as the fact that it is not irritating to the skin and does not get dirty easily due to its smooth and soft structure [4].

Communities in developing countries that struggle today to maintain alive sustainable lifestyles are at their last generations: their economies are not of governmental interest. In the case of Colombia, natural silk that is produced and transformed manually into threads, textiles, garments, and accessories in the department of Cauca, needs a boost that ensures its continuity. This impulse can be at the level of incorporation of new knowledge and new working techniques that inspire artisans to generate designs that enable the expansion of their product portfolio. In this way, it would contribute to the sustainable development of a local family economy that seeks to work in harmony with nature, and not against it, by means of the organic maintenance of mulberry crops (staple food of the silkworm) and of silk artisanal transformation techniques.

Understanding Physical and Chemical Characterization of Fibers: Silk Produced in the Department of Cauca and Wool from the Cundiboyacense Plateau

It is important to understand fibers in depth. For this reason, chemical and physical laboratory studies for their characterization are also essential. Among the characterization tests carried out for fibers, there are Fourier transform infrared spectroscopy (FTIR), colorimetric analysis, scanning electron microscopy (SEM), and coefficient of friction and mechanical resistance tests.

Silk Fiber

Silk has physical and chemical properties that allow it to be considered as a fabric of great attraction for the textile industry; it is a biomaterial produced during the development of the larva and occurs inside the silk glands (sericigens) in aqueous conditions. The worm secretes a silk filament from the glands through a spinning nipple that is located at the center of the lip in order to build a cocoon of continuous thread, which can have lengths up to 1500 m.

Silk fibers are mainly composed of fibroin and sericin. It has an amphoteric behavior, so it is compatible with most dyes used in textile dyeing. Some of its chemical properties are as follows.

Resistance to mold: it is not affected by mold, except when in long periods under extreme humid conditions.

Reaction to alkalis: It is not especially sensitive to alkalis except at high temperatures and concentrations thereof. Cold alkali solutions have a slight solvent effect, while at high temperatures they dissolve it.

Reaction to acids: It is resistant to most mineral acids. Organic acids do not harm it, but highly concentrated hydrochloric acid does.

Affinity for dyes: It is very compatible with dyes, but has little resistance to light.

Sweating resistance: It is damaged by perspiration and may even deteriorate.

Bleaching reaction: Strong bleaches containing sodium hypochlorite deteriorate silk, while mild bleach (sodium perborate and hydrogen peroxide) can be used with caution without affecting silk fibers.

As for its physical properties, it is a fine fiber characterized by its shine and softness; it is also strong, elastic, and resistant by nature; it is considered a good insulator for heat and electricity.

Silk fibers have a triangular cross section with rounded corners. This reflects light at different angles, giving the silk its special shine.

Colombian Creole Sheep Wool Fiber

With regard to chemical characterization, different organic components, structure, and material that make up this fiber were studied. The Creole sheep wool fiber is of protein origin and is mostly keratin: its composition and structure are similar to those of human hair.

Wool is constructed by a *medullary canal*, usually filled with a soft substance, a *main body*, and *scales*, located at the outside. Wool is composed of fats, mainly lanolin and suintine.

The fineness of the fleece is of the utmost importance since it determines its final use. Fleece is the total covering of the animal. The ideal diameter fleece is less than 22 μm; and the color of the white and clean hair, free of contaminating agents such as residues of plant or animal origin and feces, must be soft to touch. It has a physiology built for a rapid ventilation of the fiber, which allows a quick drying when moistened.

In the central regions of Colombia, the diameter of the wool fiber is in a range of 34–40 μm, thus making it thick and rough.

Building the System for Fibers and Textiles: Suppliers of Sustainable Fashion, Silk, and Wool

When considering the field of fashion as a system, several approaches have been proposed. The first approach claims for a non-view of the sector as a linear productive chain, and thus claims to understand the productive space as a social and technical space in which all the actors with different implications, interests, conflicts, networks, and evolutions interact. Following this approach, fashion gives rise not only productive systems but also "socio-technical systems" [17], whose almost complete organic functioning maps production dynamics and its involvement in social relations.

Systems theory proposed by Maturana and Varela [18] in the seventies, with its autopoiesis principle whose meaning is anchored to "the ability of systems to produce themselves," postulates a theory of living beings as nonindividual social beings: emerging principles of living systems such as autonomy, operational closure, self-structuring, and self-poietic reproduction are thus established. This form of systemic thinking, when translated to fashion, lays the basis for a reflection on the creation and related social, political, and environmental processes from the point of view of an organic and complex thinking perspective.

Specifically, the complex look on fashion for sustainable design raises different methodologies, which are coined to different parts and spaces of the system in which forecasting and development of materials, the production process, the distribution, the sale, and the final product life-cycle system are integrated; in this way the pillars of social, environmental, and financial responsibilities must be seen as the ethical and social basis of the system, thereby promoting not only a technological system but also a social system with conscious awareness.

The wool, silk, and mulberry systems, according to Luhmann's contributions [1], can be categorized as a social systems that produce memory and consciousness. There are several analysis categories within this system. It can be defined as a productive, economic, and cultural system. Under this expanded view, the systemic approach can be used, considering it as a social sphere that contains a series of know-hows regarding the production of current handmade fibers and fabrics.

Social System, Design System as a Living Laboratory

> *Todo sistema productivo genera intangibles culturales (representados en dignidad de vida, capacidad de transformación desde la fuerza laboral, alimento del espíritu humano*

> *desde la creatividad y la innovación) que transforman el entorno social*[1]
> *Sandra Marcela Velez* (Patiño Mazo, E; [19])

The concept of living laboratory, as defined by Molina Garrido, Mendoza Simmonds, and Ortega Hoyos [20], refers to groups created to generate social appropriation of knowledge and innovation in communities, for consumption and collaborative work, and for entrepreneurship support.

In this sense, the configuration of a co-disciplinary system between the different actors seeks the grouping of spinners, weavers, farmers, animal keepers, and designers with the purpose of thinking about the system itself and its dynamics, and thus facing an exercise of understanding, re-signification, rescue, and creation from the inclusive and responsible collaborative work of each of the actors.

The laboratory began with visits to the two systems at different times. The first visits were aimed at the establishment and understanding of know-hows, and studying the amount of variables and problems involved in order to establish a map that will make possible a dialogue with reality. In a second stage, an effort was made aimed at an exercise of conceptualization of the know-hows of the system, its agents or actors and their narratives, in order to explain why the fabric and its associated social systems are forms of resilience in a world of globalized textiles and clothing; at understanding how these rough, rustic, and even precarious morphologies are an important part of the intangible heritage of Colombia; and, most important, at understanding how the productive dynamics involved are clean and potentially relevant for the development of artisanal and design products.

The conceptualization of the collaborative social context with students, artisans, designers, and chemists allowed to understand not only the cultural importance of silk and wool materials, but also their practices and the productive dynamics of fibers, giving rise to a map dynamics where each agent, weaver, farmer, and spinner, works hand in hand with the other. The development of the fibers has been also the result of rural development and peasant culture, culture that must be updated and developed so as not to be endangered of disappearance and precariousness, factors that in some circumstances have lead people to activities like mining.

In a second stage, a physical and chemical characterization of the materials was done in order to allow its use from their DNA, and thus transform them into potential biomaterials and sustainability engines. Such characterization included the examination of the fibers under a microscope for determining resistance, friction, and subsequent characterization with nanoscale particles.

Finally, clothing was worked in collaboration with artisans under the principles of social design of Maria Ledesma [21]: principles of inclusion, collaboration, and social technology.

Under this co-disciplinary approach, designers and chemists worked with artisans in their rural territory; the main problems were evidenced and worked upon together as a starting point in the search of added value. In the case of wool, it involved the softening of the rough Creole sheep wool with the aid of added silver

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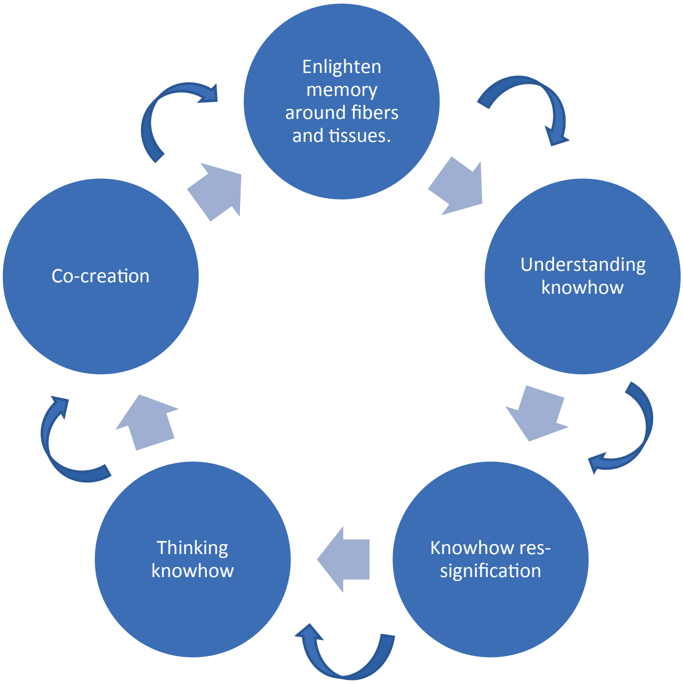
[1] Every productive system generates cultural intangibles (represented in dignity of life, transformation capacity from labor force, nourishment of the human spirit from creativity and innovation) that transform the social environment.

nanoparticles to make it antibacterial; it was woven together with artisans to have different possibilities, among them a soft antibacterial blanket for babies; woven tennis shoes for diabetic foot were also developed. In the same way and in the case of silk, the working group realized that silk is itself antibacterial, and can even become biocompatible. Therefore, its potential is much higher except that in the scenario of clothing and handicrafts one of the major problems with silk is to take it to a stage of luxury, innovation, and technology. It was then decided to confer it thermo-chromatic characteristics, that is to say the possibility of color change without dyes in reaction to cold or heat. So, the added value of the garment would lie in the organic, the natural, and, at the same time, in the technological.

In this way the products developed in collaboration allowed not only the improvement of the characteristics of the materials, but also the promotion of a supply system provision for sustainable design, and the promotion of a system of artisanal and cultural design respectful of handicraft practices and that fosters local social technologies.

The Dynamics of a Living Laboratory



Source: own elaboration

Understanding the Know-How of the Socio-technical Systems of Wool and Silk Through Immersion

Laboratory Understanding of Know-Hows: Silk

The best way to get to know the silk system is to be there in the territory with people to understand their know-how, and then to think about the know-how in the design laboratory.

Located in the department of Cauca, with a mild climate of 20°C on average, specifically in rural territories such as Tímbío and Tambo, 30 min away from Popayán, mulberry producers and cultivators are mostly women. They cultivate the mulberry plant and likewise are responsible for raising the silk worm, which is fed by the same mulberry they plant. Mulberry has a permanence and plant replacement crop cycle of 2 or 3 years. The life cycle of the worm is approximately 28 days until its "despupe" or extraction of the cocoon. During those days, caretakers feed the worms twice a day so that the caterpillar begins its growth and soon its metamorphosis; and when it becomes a butterfly the silk extraction begins.

The silk and mulberry farming population is a group of 15 artisans in Tambo, and 20 more in Timbío. There are two ways to produce the silk thread: a thin one of 1 mm in diameter, and a thicker one called "chape" of 0.7 mm in diameter. The latter can be manufactured at home but for a finer one that may be even more commercial the cocoons with their pupa are taken to Corseda in Popayán where when joined together in a system of cooperative solidarity they start the treatment under an artisanal technology, which includes the following steps:

1. Putting the cocoon in solar ovens to dry the worm or pupa
2. Hot water cocoon hydration for handmade spinning process
3. Spinning by breathing and "despupe": each cocoon can form up a continuous filament up to 1500 m
4. Wire winding

Then the transformation process begins for textile and clothing purposes that focus on dyeing and weaving processes that are done individually: in so doing, each craftswoman begins her craft production.

It is worth noting that the silk weaving trade in Colombia is carried out by women. It is learned as an artisanal rural practice and has become an informal form of work that has sustained and brought forward the silk families.

The dyeing process of the silk is developed according to color needs, narratives, and available resources. With natural and chemical dyes the color of the fibers, motons, veneer, and threads is transformed. The first natural dyes are applied based on current ancestral practices orally transmitted among weavers of the region and in interlocution with southern wool weavers in territories such as Pasto and Ipiales. But transculturation and urban and industrial information has also led them to use chemical dyes to achieve more exotic or bright colors not achieved with natural dyes.

Oxidizing mordants and color fixers are mineral and volcanic stones; they use vinegars and sodium as chemical compounds; and there is not, unfortunately, an adequate control on dye residues.

The process of weaving was ultimately a key to identity for many reasons: learning of the tissue, weaving, and the loom as center and pillar of a house turn the fabric into a form of culture, life style, and social development.

Women weave many hours a day. The forms created are mostly geometric. They make shawls, scarves, and ruanas. They weave with a unique fiber that shines and resists, and is antibacterial. But they ignore many properties of the fiber and of their work as artisans that generate local and national identity.

The silk fabric is worked on a horizontal loom with taffeta, twill, and satin stitches that allow composition in the textile. As for the vertical loom, it draws on the warp and it allows playing with the weft, thus mixing different stitches or schemes.

Laboratory Understanding of Know-Hows: Wool

In places where the sun seems to heat less, Creole sheep wool in Colombia is produced in the central Cundiboyacense highlands. A peasant culture lifts sheep in free grazing, without special care, and their "caretakers", rural people of peasant culture, act in the first part of the fiber development process, which is subsequently done by farmers, shearers, artisans, and weavers in this way:

Shearing: It is done once a year or more, and it consists in removing the wool hair from the sheep. It is equivalent to a haircut. In the process of cutting the fleece, one seeks to remove it with scissors or shaving machines but without hurting the sheep. It is generally done at a time of good weather so that the animal adapts well to the change.

Degreasing or fleece washing: Fleece is washed with cold water so that it does not shrink. Solid impurities, fecal residues, and knot specks are removed and then it is dried in the sun so that it becomes as soft and clean as possible. Drying can be on a diagonal surface that allows draining, on a horizontal mesh, or by hanging outdoors.

Untangling: In this stage, sheared wool is classified and stretched, carefully separating by hand the fibers without cutting them in order to facilitate spinning and generate a uniform circuit in quantities useful for texture and thickness.

Spinning: It is made with a spindle or with a spinning wheel. An appropriate torsion is given to the wool fiber to obtain a thread of the desired thickness, and thus preparing it for textile or clothing purposes. Famous spinning festivals take place in the region like the Cucu Festival.

Dyeing: It is the process of dyeing with basic or natural dyes. It is based on dye products from plants and minerals provided by nature such as branches, roots, weeds, stones, and all sorts of minerals. In almost all of them, water is boiled with the coloring product and salt and vinegar from mordants are added so that the color adheres better to the fiber.

Once the fibers are ready, that is, dyed and dried, artisans proceed with the weaving process. Traditionally, among the Cundiboyacense communities, it was a masculine job; nowadays, however, it has become a mixed exercise by older men and women, and with almost no young people participation. Fabric in horizontal and vertical looms is still a common practice in places like in Cucunubá (Cundinamarca) and Villa de Leyva (Boyacá).

The fabric focuses mainly on flat and knitting techniques, so that three schemes are mainly used: satin, twill, and taffeta. As for knitting, crochet and two needles are used.

Laboratory: Re-signifying Knowledge

Once know-hows are established, they are socialized to everybody without hierarchies or distinctions in order to comply with a systemic attitude, and with responsibility and group intelligence to think about pathways to be taken. From the knowledge about properties of fibers, and silk and wool textile artisan techniques, meanings of social practices are derived, and a developmental action is established with the revaluation of the fabric as a working social practice and, most important, what they means as part of the identity of people and territory.

In this view, people are the fibers of the system and become the center of re-signification in order to maintain and generate memories about the knowledge of the two systems: that of wool from the Muisca and Chibcha ancestors, and that of silk around the fabric. The two become a social value that is maintained as long as it is economically viable. When it does, revaluing the fibers and taking them into a scenario of exclusivity and design is a way for the sustainability of culture.

Thinking About Doing Laboratory: Building Tissues and Non-tissues

The work with looms in vertical and horizontal flat weave is an identity key to be maintained in the two systems, silk and wool: it is a practice that unites families and their neighborhood; so, knitting and felted or nonwovens are also designed in collaboration.

The technique for obtaining nonwoven silk fabrics involves non-polluting and simple processes that allow obtaining textile surfaces with interesting and novel appearance. To obtain a silk nonwoven fabric, the following material and steps were considered.

Materials:
- 1 wooden frame
- 500 cc beaker
- 7 g of sodium bicarbonate
- 500 cc of water
- 6 silk cocoons

Procedure:

- Dissolve sodium bicarbonate in water
- Incorporate silk cocoons
- Heat the bath and boil for 15 min
- Cooling
- Spread each cocoon on the wooden frame, using its angles to form a veil
- Remove the veil and hang to dry outdoors

As a result of the above, a silk nonwoven fabric is obtained (Image 1).

One of the purposes of a natural silk nonwoven fabric is to give a softer touch to the felt of national wool, taking advantage of the following common characteristics that make them compatible:

- Protein fibers
- Natural fibers
- Similar color (ivory)
- Similar abrasion resistance
- Similar legal moisture rate
- Similar elastic recovery
- Similar percentage of elongation at breaking point
- Similar resistance to sunlight
- Equal ironing temperature (148 °C)
- National wool is rough in touch, while natural silk is soft in touch

The method for adherence of the nonwoven fabric of natural silk to the felt of national wool was that of punching by means of felting needles. In so doing, it is possible to obtain a double-sided textile with a silk face with softness characteristics, a new feature of national wool (Images 2 and 3).

Laboratory: Thinking About Thermo-chromatic Dyeing and Softness as Added Value

Thermo-chromatic pigments have advantages over traditional synthesized pigments since they can be used for processes where a certain temperature is known. This fact can be potentially exploited with different industrial applications such as textiles, natural and synthetic fibers, cosmetics, and polymers. In addition, they lack toxicity since they do not contain radioactive substances or heavy metals that could cause unwanted effects on health and the environment.

With the aim of generating added value to woven pieces, they are dyed with thermo-chromatic pigments, making them sustainable—this is the reason for using substances other than water such as fatty acids for the dilution—and also a recovery of the pigment is done at the end of the process, so that all the dye is used.

As for the softening of the wool, physical traction was employed and keratin was applied directly by artisans. In so doing, they were provided with technological

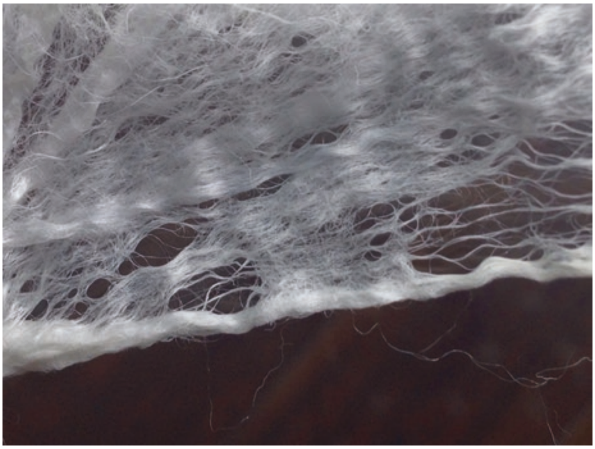


Image 1 Natural silk nonwoven fabric. (Source: Photo by the author. Fabric developed at the Textile Lab of the Universidad de Bogotá Jorge Tadeo Lozano)

Image 2 Nonwoven fabric adhered to wool felt by a punching method. (Source: Photo by the author. Fabric developed at the Textile Lab of the Universidad de Bogotá Jorge Tadeo Lozano)

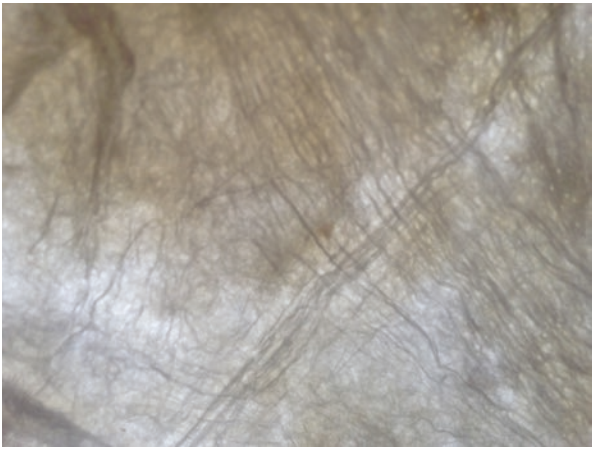
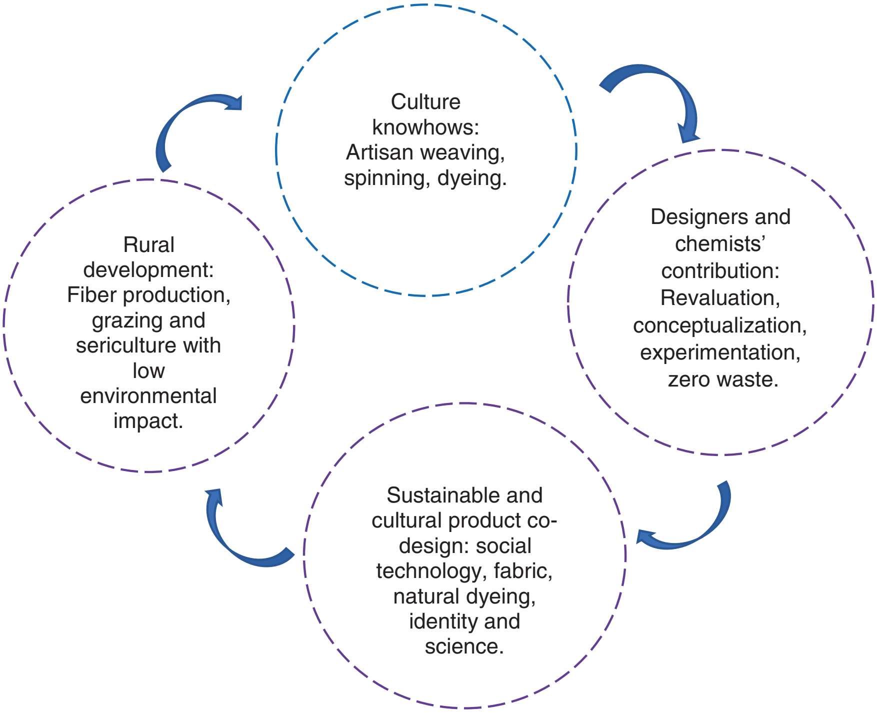


Image 3 Nonwoven fabric adhered to wool felt by punching method (detail). (Source: Photo by the author. Fabric developed at the Textile Lab of the Universidad de Bogotá Jorge Tadeo Lozano)

options for materials and their improvement and competitiveness. In addition, a chemical coating with silver nanoparticles was done to give antibacterial properties to the sheep wool.

Making Design



Dynamics of co-creation in a socio-aesthetic system. (Source: own elaboration)

Designing textiles and clothing under the collaboration and co-creation method is a proposal to work the conceptual design process in the midst of an inclusive and collaborative dynamics, following the principles already mentioned of the social design theory of Maria Ledesma [21], principles that are inserted in living laboratories as a methodology.

Following this inclusion perspective, a conceptualization based on the construction of textiles and clothing was proposed. Starting from a metaphorical thinking that could give rise to the creation of ethnic clothing with local sense and identity, it is intended to give artisans and designers a chance to reinvent themselves through the fibers produced within the system, to design lives with weavers, to reactivate and improve processes of their own, to generate added value with technological dyes, and to give softness to ethnic fashion collections.

Once the supplier and his/her context are known, and how a product impacts their life, a balanced textile system guarantor of good practices in production and respectful of people, the environment, and the culture can be devised. In this sense, each actor is an important part of the product; and design is no longer an exercise of an individual for his/her own taste, but becomes instead a collaboration and a teamwork so that the consumer who buys the product, whoever he/she may be, can be a part of the culture and of the manual work of weaving and good practices.

Sustainable Decisions of the Design System

To work in co-creation is a decision that allows understanding the socio-aesthetic sense of the system, thus considering different perspectives of ethical, environmental, creative, and aesthetic coexistence for the purpose of productive, creative, and social development. And it allows making a conceptualization from the social context to the aesthetic weave, a process that Aurelio Horta defines as a transition from a cognitive weave to an aesthetic weave [22] in which the field and the design operation are expanded.

Under this view, the design project ventures into social practice and identity construction, and that is why it is important to reconstruct the whole concept. Paraphrasing H. Arendt, the concept of identity is defined by discourse *and* its actions; it coherently tries to provide the discourse of the weaving identity of the territory and the subjects with the resilience values and needs of the rural.

In this laboratory and design space, the discourse of wild morphology preserved in the work of weaving local fibers without industrialization coexists with creative and scientific actors who seek to return to natural materials and agricultural developers as a way for the sustainability of clothing and of the fashion system. In doing so, it is intended to provide a social discourse far from the colonizing markets of large retails, increasingly moving away from capitalist and inhumane lifestyles; on the contrary, it responds with a resilience force from the united actors. All together, they devise a way in which everyone assembles ideas in order to weave a new approach to clothing by weaving bodies with the wild and rough forms of the landscape and of the fibers, with different thicknesses and knots that shape the nature of the territory, of the hands, and of the fibers that make up the textile and weaving society. The making of those garments is clearly a subject of technology, but above all of identity.

Within a socio-aesthetic system, production is transparent and in plain sight for everyone. It allows the reinvention with local fibers: weavers, artisans, and designers, addressing local textile techniques, exploring culture, and producing reinterpretations based on their own work experience.

The laboratory space is intended not only for the rescue of textile techniques with looms and products characteristic of rural economy, but also as a dialogue between different individuals: narratives are woven and assembled together around the Andean peasant life. An important feature of this dialogue is the resilience of culture against the global trends of the market and fast fashion. This resilience opens up spaces of re-significance, well-being, and cooperation between weaving communities and academic work.

At the same time, the commitment of textile and clothing design with Colombian peasant and artisan culture is seen as an alliance aimed at closing the gap between the urban and the rural, and between culture and science: the design exercise operates not for the benefit of an individual or frivolous media, but is instead committed to social development.

In a first stage of the design process, a series of workshops were celebrated for the reflection, recognition of identity, and re-signification of people, fibers, fabric, and trade. It was an appropriate space to feel the experience of being a weaver and how to represent a positive look about the history, the territory, the fabric, the techniques, and the associated landscape. Creative panels for ideation emerged, with color change possibilities, as well as transition, structure, silhouettes, and tissue patterns that made possible building a representation of the narrative to be told in the textile.

A second stage moved from conceptualization to creation. It consisted in the design of textiles with felts and double-sided wool–silk pieces, others in knitted and flat fabric, as well as the design of fabrics and patterns for the creation of a clothing collection with the designers Maria Alejandra Rodríguez, Laura Mejía, and Angela Dotor. Formal values of the collection relied on rural resilience materialized as shape, color, and texture; and on the application of thermo-chromatic dyes by Alis Pataquiva, Juan Pablo González, and Ivonne Moreno: they devised alternatives to give silk color change properties with temperature and also to take it to a stage of a new experience and “luxury”. Thus developing applications or ornament colors for the evening, for example pink, and others for the night such as black. Color change occurs when the temperature has a variation of four degrees. Color change of the entire garment is under current research.

Regarding the design of footwear with sheep wool fiber, a research of the design area involved was carried out to make a proposal compatible with the ergonomics and physical needs of the potential users of this footwear. It was established that it was necessary to perform a nanostructuring with silver particles that would give the fiber antibacterial qualities, softness, and hypoallergenic resistance in order to reduce the possibility of contracting infections. Everyone contributed to the production of functional, sustainable, and cultural design, with the inclusive and responsible ethos of sustainability as background.

For the design of clothing, retaking simplicity was the guideline, the unisex silhouette linked to inclusion discourses, and the rough/wild organic forms of the fabrics as well as the basic forms of the peasant clothing are fundamental for the reconstruction of identity around these fibers (Images 4–6).

Results

The design project achieved different results: first, the multidisciplinary creation of a productive dynamics for a socio-aesthetic system following social design principles; second, local identity reconstruction by a process of conceptualization of the culture of weaving, its actors, and its territory.

Regarding textile development, a re-signification and rescue of basic traditional techniques was made; and an experimental methodology for nonwoven textiles with different design purposes was devised. Felted textile pieces with 100% silk cocoon, 70% silk, 30% wool blend, and 100% wool were created, as well as fabrics in horizontal and vertical handlooms (Images 7 and 8).

Application of silk thermo-chromatic synthesis and silver nanostructuring in wool with antibacterial properties were devised (Images 9 and 10). A collection of unisex clothing pieces, design and development of handmade footwear, application of silk in handmade yarn braids, and investigation of waste treatment in a garment collection were carried out along with the development of experimental textile pieces that resulted in objects, clothing, and accessories whose degradation times lie between one and three years according to their composition (Image 11).

Conclusions

The unsustainability of the prevailing fashion system is based on rapid fashion production. The stress of satisfying the insatiable trend-following market has generated a production of disposable textiles and clothing with bad social practices that do not respect humans and the environment: there are plenty of practices already known such as slave labor in inhumane conditions, and solid waste materials derived from polymers and dyes that pollute water and make people sick. That is the reason for the creation of systems and laboratories aimed at the sustainability of clothing and textiles: a return to degradable natural materials with easy access and to rural production embedded in practices that develop and activate farming, pastoral, sericulture, and artisanal communities, as in the present case of fiber and textile productive systems with local identity in Colombia.

Establishing methodologies and constructing rural collaborative systems for co-creation is a way to counteract the environmental damage linked to massive industrial production with non-easily degradable materials, and to stop the mass use of clothing that erases any local identities. In this sense, sustainability is a stance that becomes also a resistance to the homogenization of fashion.

As social beings, all humans are linked to technologies of communication, production, and materials. Those technologies and their socio-productive dynamics give rise to consumption and societal behaviors that in turn give rise to forms of interaction between the people and the objects of their culture. In this way, humans, as socio-technical beings, end up thinking and acting according to the social and symbolic technologies of the systems they build. That is why the construction and

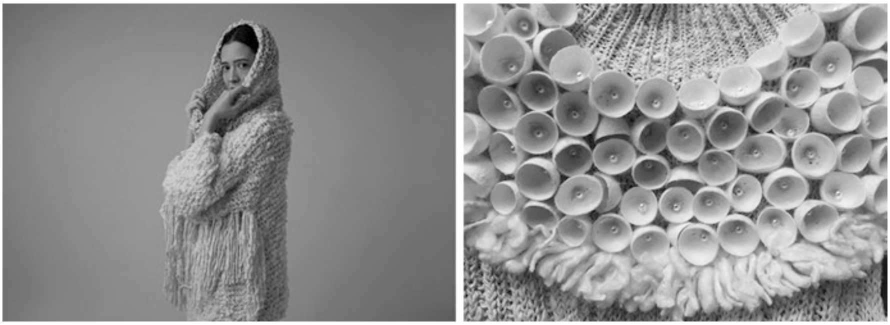
Images 4–6 Photographs: textile experiments by the author. (Fabrics developed at the Textile Lab of the Universidad de Bogotá Jorge Tadeo Lozano. First photograph courtesy of Laura Mejia)

Images 7 and 8 Photographs by the author: felted textile pieces

identification of the social system is fundamental in order to create good practices in the industry that produces handicraft textiles respectful and closely joined with the local culture. This respect guarantees the formation of subjects within an ethical social dynamics that consume in clean and responsable ways.

Promoting the design of woven and nonwoven clothing and textiles with natural fibers contributes to artisanal production of low energy consumption, to zero waste of fibers and fabrics, to a wider use of fibers, and to a reassessment of people that results in common and not just individual, benefits.

The fashion and textile designer's exercise has been transformed into a social practice that is capable of producing artifacts but above all productive dynamics that develop community and new social practices. In the present co-disciplinary and systemic proposal, the design operation became more committed and impressive.



Images 9 and 10 Wardrobe with thermo-chromatic application. (First photograph by María Camila Rincón; model: Laura Melissa Forero; cloth design by Alejandra Rodríguez and the author)

Image 11 Photograph by the author: handmade sheep wool shoes

Results in terms of objects and aesthetics are as important as the social exercise that promotes culture.

In the global context of the non-sustainability of clothing, it is proposed to return to weaving practices with low-energy consumption natural fibers rooted in traditional handicraft and ancestral cultural practices as alternatives for the development of sustainable textile and clothing material. Their low environmental impact is complemented with the preservation of local practices of social fabrics.

To believe in the continuity of the production and artisanal transformation of wool and natural silk in a family and local production environment is to believe on a sustainable development project. As indigenous people take care of plants and forests, local producers take care of the land and biodiversity in a responsible way, because they value and appreciate it: those are their working sources for family support. In the case of natural silk, its high sensitivity to acids, alkalis, high temperatures, and abrasion makes it a highly biodegradable fiber: time for degradation fluctuates between one and three years.

The production and transformation of artisanal wool, on the other hand, does not require a large investment capital. The promotion of these family and local industry would greatly contribute to the sustainable production of a textile fiber that, according to Hollen et al. [4], is considered by the Wool Bureau as the most wonderful fiber of nature, since it has properties that no artificial fiber can equal. Those same authors highlight the ability of wool to adjust to forms by application of heat and humidity, its initial repellency to water, its ability to get felted, and its fire retardant property. Moreover, wool fiber takes 3–5 years to degrade: This latter feature makes wool a fiber of easy and useful disposition when waste is at stake given that its high nitrogen content makes it a good soil nutrient.

Artisanal industries of wool and natural silk must be considered as agents of development of local economies with great potential to join the national and world economy. Their adequate encouragement in terms of the generation of innovative identity products with a defined short life cycle would create employment and family collective income, and an impact on the life quality of communities.

The articulation and inclusion of technology contributed to the improvement of the fibers, and to the addition of features of functionality and luxury. But most important, technology with very low impact on natural resources was considered: characterizing antibacterial materials to be cleaned without water, color dyeing without water, zero solid-waste production, resistant but degradable materials, and light foam-like materials for fillers and exteriors that are not polymeric but natural and developed with nonwoven techniques such as felted. All of them were developed as prototypes for the construction of an industry committed to people and culture, incorporating at the same time ethical principles such as sustainability. In doing so, it generates conscious social systems that result in designed objects with a defined life cycle subject to the natural and nonpolluting degradation of materials, as is the case of wool and silk.

Thinking about the life cycle of the sustainable product means to analyze the textile and clothing from the point of view of production, consumption, degradation, and upcycling. Natural materials can be produced in a friendly and responsible way; their degradation does not impact negatively on the planet and guarantee a sustainable production.

Finally, the paradigm of consumption materialized in gloss, plastic, and fast fashion must be replaced by the consumption of handmade fashion from systems of ethical and transparent production with local identity. We have named them “socio-aesthetic fashion systems” throughout these lines.

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Sustainable Green-Based Composites from Renewable Resources in Textile: Industrial Cotton Wastes

Emine Dilara Kocak, Munir Tasdemir, and Cigdem Gul

Abstract Cotton is the most generally used fiber in the textile industry and it is utilized in all areas of textiles. The amount of cotton production is approximately four to five million tons annually on a global scale.

Waste cotton fibers can be reused even after being disposed of. In the apparel industry, a large majority of cotton wastes are recovered as recycled yarns. However, waste cotton fibers with the dimensions of 0.10 and 0.50 mm is not processed for the manufacturing of recycled yarns.

Nowadays, the field of development of composite from cotton waste paved a way for increased research studies because of the properties of cotton waste such as cost-effective, profitable, reusable, renewable, environmentally friendly, and sustainable.

In this study, between ~0.10 and ~0.50 mm in length of cotton waste fiber is obtained from the recycling yarn factory. Five percent, 10%, and 15% different ratios of cotton waste in recycled polypropylene (r-PP) were blended. The blends were produced by the twin-screw extruder. The composites were tested in terms of mechanical properties (tensile strength, elongation, yield strength, Izod impact strength, and elasticity modules), Melt Flow Index (MFI), Vicat softening point temperature, and hardness.

Results of cotton waste/recycled polypropylene composites which is shown an increasing cotton waste percentages are evolved mechanical properties, especially elasticity modules.

Keywords Sustainably · Cotton waste · Recycled polypropylene · Composites · Ecological · Renewable resources

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Introduction

The world’s population continues to increase rapidly. According to estimates, the world population will arrive 8.2 billion in 2025, with a present annual growth rate of 1%. About half of the world's population currently lives in cities or is moving toward urban areas. In developing countries, with growing industrialization, which may increase energy consumption and waste generation [1]. In 2016, the worlds’ urban produced 2.01 billion tons of solid waste and annual waste produce is foreseen to increase by 70% from 2016 levels to 3.40 billion tons in 2050 [2]. The textile industry contains many production phases, that is harvesting, cleaning, spinning, weaving, dyeing, finishing, etc. The wastes generated at the end of these production phases are increasing day by day. The textile industry generates great volumes of fibrous waste. Approximately 15% of the fibers used in the textile industry are composed of fibrous waste [3]. Recent studies are directed toward the development of fiber-reinforced composites of these fibrous wastes. The use of waste materials or recycled materials for the creation of raw materials in the composites is an actual issue, with a promising future and firstly aimed at environmental protection. The future of the composites market looks more attractive with trends and opportunities in transportation, marine, wind energy, aerospace, pipe and tank, construction, electrical and electronics, consumer goods, and other fields. The volume of the global composites market arrived 10.8 million tons in 2016 and expected to reach 12.9 million tons by 2021 [4]. According to Lucintel, the composite material market is expected to reach approximately $ 40.2 billion by 2024 [5]. Glass fiber has a large share in the production of reinforced composite materials. It provides good mechanical properties (great strength and stiffness, resistance to corrosion, etc.) but recyclability and biodegradability are a big problem for fibers. Natural fibers are cheaper than glass fibers, it is a renewable resource and less harmful to human health. Besides, natural fibers have many advantages compared to synthetic fibers such as glass and carbon fibers. They are abundant in nature and lightweight and have low density. Natural fiber-reinforced composites can be easily disposed of (combusted or composted, etc.) [6]. Traditionally, different kinds of natural fibers such as cotton, silk, wool, polyester, polypropylene, and polyamide are used to manufacture the composite. In the literature, it is possible to find many examples of natural fiber-reinforced composite materials. Araújo et al. produced cotton waste reinforced/polypropylene composite material with high mechanical and advanced thermal properties for the automotive industry [7]. Mwaikambo et al. studied a composite material produced using kapok/cotton fabric, isotactic polypropylene, and maleic anhydride grafted polypropylene [8]. Petrucci et al. studied waste cotton fiber/PP composites [9]. Song et al. studied to obtain polypropylene/microcrystalline cellulose composites [10]. Kimura et al. studied waste cotton fiber and nonwoven waste/PP composite [11]. Kim et al. studied cotton fiber/PP composites [12]. Yang et al. studied rice-husk flour and wood flour/PP composites [13]. Panaitescu et al. studied waste jute fibers/PP composites [14]. Bourmaud et al. studied hemp and sisal/PP composites [15]. Vidal et al. studied PP/cotton linters and PP/rice husks composites [16].

The production of materials currently used is extremely difficult in terms of consumption of energy, raw materials, and costs. Therefore, efforts to find alternative material sources are in the foreground. These alternative materials should be capable of local, renewable resources, and low energy requirements [17]. Renewable material resources are also very important for the sustainability of material resources. Using fiber sources obtained from agriculture is one of the solution methods. Another approach is using industrial waste or industrial recycled materials in composites.

In this chapter, the studies are carried out to produce composite material from cotton waste and polypropylene. The studies are based on the investigation of the mechanical properties of composites.

Polymers

During the past few decades, the idea of producing low-cost and lightweight materials intensified interest in the field of a polymer. Polymers have emerged as an alternative to some conventional materials such as metal due to their easy manufacturing, structural control, efficiency, easily accessible, and low costs [18]. According to their origin, polymers are generally divided into two types: natural and synthetic (Table 1).

Natural Fibers

Various kinds of natural fibers are used all over the world. Natural fibers are generally classified as derived from plant, animal, or mineral sources. Plant fibers are extracted from fruits, seeds, leaves, and stems of plants.

Table 1 Classification of natural fibers

Type	Fıbers	References
Bast (stem)	Flax, hemp, jute, kenaf, banana, roselle, and ramie	[19, 20]
Leaf	Abaca, sisal, pineapple, henequen, banana, and agave	[21, 22]
Seed (fruıt)	Cotton, kapok, rice husk, coconut, sugar, loofah, and milk weed	[23, 24]
Stalk fiber	Sugarcane, maize, sunflower, wheat, and rice	[25]
Grass (reed)	Bamboo, bagasse, and canary	[26]
Wood	Eucalyptus, yellow poplar, maple, spruce, pine, and acacia	[19, 27–29]

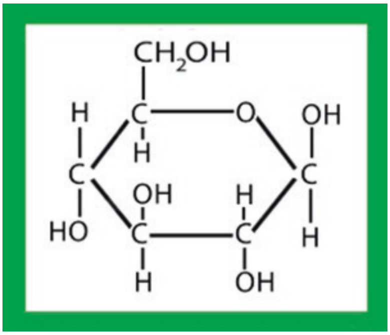
Generally, natural fibers contain cellulose, hemicellulose, lignin, and pectin. The most extensively used natural fibers are cotton, flax, and hemp, even though sisal, jute, kenaf (hibiscus cannabinus), and coir are identically popular. The use of natural fibers as reinforcing fibers in different polymer matrices provides several advantages, such as environment and cost. The cotton fiber for automotive use is a cost of about 1.5–2.2 USD per kg, but the cost of glass fiber is about 3.25 (1.7/3.8) USD per kg [30].

Recently natural fiber-reinforced composites are using in commercial applications such as decks, windows, door panels, sports equipment, packaging, furniture, and automotive industries [31]. Most of the famous car manufacturing companies such as Mercedes Benz and Daimler-Chrysler/Germany, Toyota/Japan, Suzuki-Maruti/India, Hyundai/Korea, and Proton/Malaysia are using jute-composites in their automobiles [30].

Cotton Fiber

The cotton plant belongs to the Malvaceae family and the genus Gossypium [32]. Cotton fiber is lignocellulosic that is a source of renewable and recyclable raw materials. It consists of mostly α-cellulose (88.0–96.5%) and cellulose in the cotton fibers have the highest molecular weight among plant fibers [33]. It has a long and rigid molecular structure and highly crystalline and very well oriented. Cellulose consists of a thousand times repeated glucopyranose rings bound by β-1,4-D glycoside bond [34]. There are hydroxyl groups (OH) attached to each glucopyranose units, and these hydroxyl groups are attached to carbons C_2, C_3, and C_6. Hydroxyl groups interact with both the oxygen atom in the same ring and the oxygen atoms in the other chain. Hydrogen bonds are formed inside and outside the molecule. Thanks to hydrogen bonds, very tightly packed linear chains form crystalline regions. Furthermore, irregular and loose amorphous areas are formed [35]. The degree of polymerization of cellulose can be changed depending on the source and it is approximately 15,000 units for cotton-derived cellulose [36]. Figure 1 shows the chemical structure of the cellulose polymer.

Fig. 1 The chemical structure of β glucose



Cotton fiber is the most widely used plant fiber in the world for clothing, household goods, and industrial products. According to International Cotton Advisory Committee (ICAC) sources, world cotton production increased by 17% to 26.8 million tons in the 2017/18 season. The countries that make more than 75% of cotton production in the world are China, India, the USA, Pakistan, and Brazil, respectively [37]. Cotton fiber production in Turkey was reported to be 988 thousand tons (2018–2019 season) in ICAC Plenary Meeting [38]. There are many physical properties (e.g., length, strength, color, micronaire, fineness, and maturity) that affect the quality of cotton. Fiber length is one of the most important indicators of the fiber quality and defining yarn and it plays a crucial role in defining yarn quality. Table 2 shows the main properties of cotton fiber.

Textile Recycling Processes

Any substance that is not needed and removed from the environment can be defined as waste. In the textile industry, large amounts of waste are produced as a result of various processes. Various fossil fuels used in production processes cause the release of harmful gases such as CO_2. Today, the world is aware of the efforts to reduce the CO_2 gas that affects our environment and causes global warming. The increase in CO_2 gas in nature causes an increase in carbon footprint. Therefore, the importance of textile waste recycling is increasing rapidly. The recycling of wastes consisting of natural and synthetic based materials used as raw materials is extremely important for sustainability. Recycling is seen as the best solution for both natural and synthetic-based textile wastes due to reducing environmental impacts in production processes and preventing problems when they are thrown into nature.

Natural fibers are renewable materials. Cotton is one of the most used raw materials in textile products such as woven, knitted, and yarn form. The products can be recycled for reuse at the end of their life. Textile recycling, many times means the reprocessing of pre- or postconsumer textile wastes for use in new textile or nontextile products [44]. Recycled cotton described as converting cotton fabric into cotton fiber that can be reused in textile products [45]. For instance, recycled fibers are made from the wastes of fabrics obtained from clothing industries. First of all, fabric scraps that cannot be used in textile and garment enterprises are collected. The

Table 2 Mechanical properties of cotton fibers

Parameter	Value	References
Fineness	1–4 dtex/2.3–6.9 μm air	[39]
Density	1.5–1.6 g/cm^3	[40]
Tensile strength (MPa)	287–597	[41]
Young’s modulus (GPa)	5.25–8	[42]
Elongation (%)	3–10	[43]
Moisture content (wt%)	7.9–8.5	[42]

collected scraps are separated and stored separately according to their contents, colors, and types. Waste fabric shredding machines enable the opening of valuable fibers in the fabric. The fibers are cleaned and mixed by the carding process and made ready for spinning. Sometimes the fibers are not spun but simply pressed.

The biggest problem encountered in cotton-working enterprises is dust and fly. Powerful air conditioning systems are used to solve this problem. Generally used air conditioning systems obtain moisturizing, heating, cooling, dust, and fly collection. Cotton fly, which is composed of machines, is collected with the help of suction systems.

There are different waste sources during cotton yarn production, yarn preparation, and spinning process. These wastes can be described as licker waste, hat waste, draw frame pneumophile waste, draw frame waste, and suppository waste such as pneumophilic waste, roving waste, and ring pneumophil waste. All of the waste produced in the yarn transfer process is waste. Another type of waste produced in the yarn production process is air-conditioning dust. The dust accumulated in the filters of the suction units in the plant is collected as air conditioning dust waste [46] (Fig. 2).

According to the published report of the World Commission on Environment and Development, the sustainability concept is described as meeting the needs of today's generation without compromising the needs of future generations [47]. In the literature research, it is seen that textile wastes are used in various industrial applications (such as building structures, and automotive industry) in terms of sustainability. One of the applications where textile waste is used mostly is composite materials. Recently, with the increasing environmental sensitivity, studies on composite materials have focused on natural fiber-reinforced composites and composite production from waste materials [48].

When the composite material is examined, three main structures are observed. These structures are a matrix, reinforcing element, and interface (bond structure).

Fig. 2 Recycle cotton fiber waste

The matrix material can be thermoplastics (such as polypropylene (PP), polyethylene (PE)), and thermosets (polyester (PES), epoxy (E)).

Polypropylene

Polypropylene (PP) is a thermoplastic material formed by polymerization of propylene molecules. It is rigid and has low density (about 0.9 g/cm^3), low cost, good impact resistance, and high melting point. The low density is one of the biggest advantages of composites. Nowadays, lightweight is one of the desired properties of the produced materials. Polypropylene is lighter than other thermoplastics. Therefore, it is widely used in automobiles and other vehicles [49].

Despite the advantages of natural fiber-reinforced composites such as lightness, recyclability, and low cost, they have low strength values due to poor fiber-matrix interface. There are several methods to improve the fiber/matrix interface adhesion. One of the most effective methods to increase fiber/matrix compatibility is the addition of maleic anhydride binding agents.

Covalent bonds are formed at the interface of cellulose fibers with a hot maleic anhydride polypropylene (MAPP) copolymer. MAPP improves the mechanical properties of fiber-reinforced composites [50].

Figure 3 shows the bond structure formed between the surface of the lignocellulose fiber and the maleated polypropylene (MAPP).

SEM method is used for the examination of composite surface structure. SEM is used for three-dimensional imaging of the sample surfaces. Figure 4 shows the SEM images of cotton waste/PP composites. When SEM imagines taken from broken surfaces are examined, it can seem that there are hollows between matrix surfaces and fibers.

It is observed from the literature survey that natural fibers were used as reinforcement materials in composite structures and the following studies can be shown as examples for this purpose.

Tasdemir et al. [51] examined the composites produced by using waste silk and cotton fibers as reinforcement material [51]. Petrucci et. al. [9] studied waste cotton fiber/pp composites [9]. As explained in the introduction, Araújo et al. studied

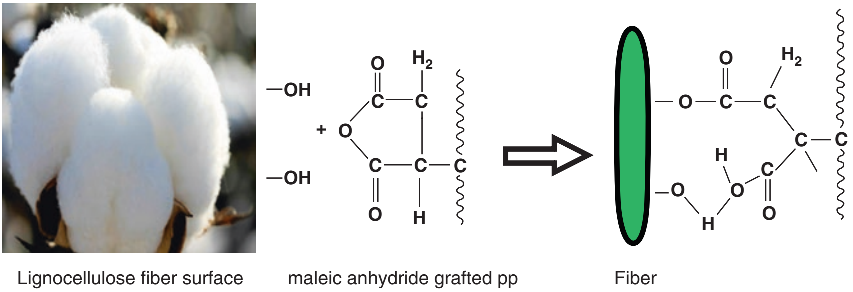


Fig. 3 Schematic description of the maleic anhydride with the lignocellulose fiber surface

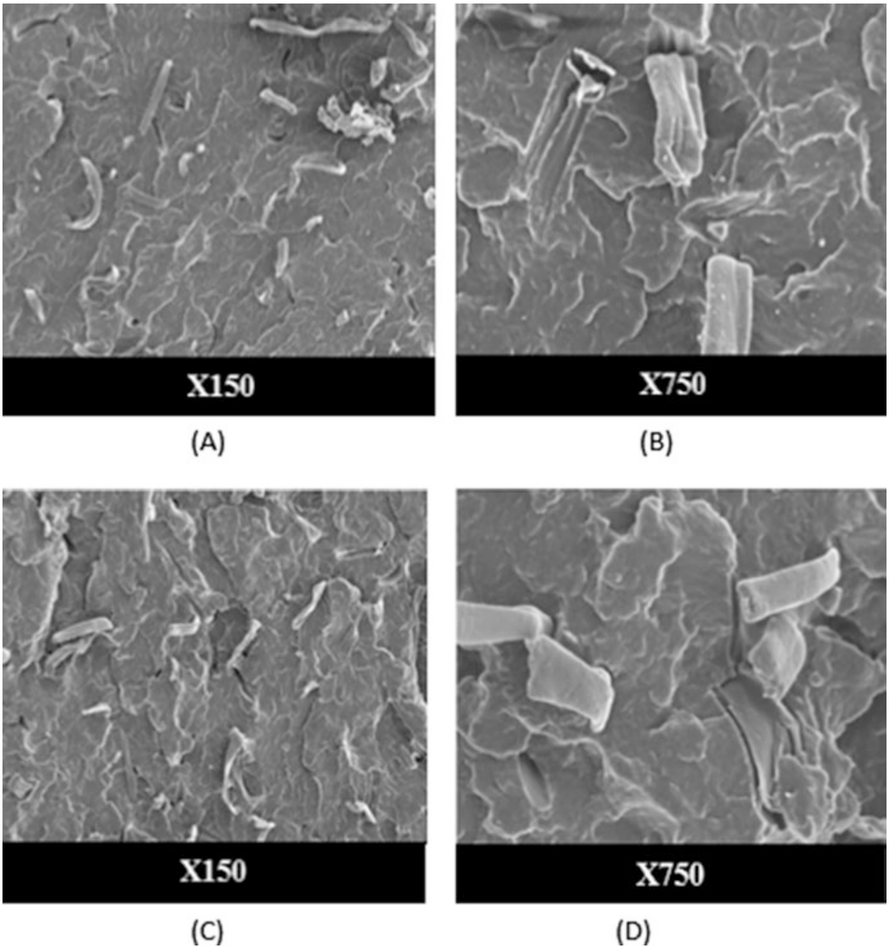


Fig. 4 SEM images of PP/waste cotton composites in various magnifications: (**a**) PP/cotton (97 = 3) (×150), (**b**) PP/cotton (97 = 3) (×750), (**c**) PP/cotton (94 = 6) (×150), and (**d**) PP/cotton (94 = 6) (×750) [51]

cotton waste/polypropylene composite, Mwaikambo et al. studied kapok/cotton fabric/isotactic polypropylene/maleic anhydride grafted polypropylene [7–8]. Song et.al. studied polypropylene/microcrystalline cellulose composites, Kımura et.al studied waste cotton fiber/nonwoven wastes/PP composite, Kim et.al. studied cotton fiber/PP composites, Yang et.al. studied rice-husk flour/wood flour/PP composites, Panaitescu et.al. studied Jute Fiber waste/PP composites, Bourmaud et.al. studied hemp/sisal/PP composites, Vidal et. al. studied cotton linters/PP and rice husks/PP composites [10–16].

In this study, it was aimed to obtain lightweight, environmentally friendly composite materials by using recycled waste cotton as reinforcing elements. Recycled cotton waste/PP/MAPP composites with different loading of 5, 10, and 15 wt% were prepared via the injection molding method. Mechanical properties of the recycled cotton waste/PP/MAPP were evaluated. The purposes of this study to increase recycled cotton waste loading in the PP matrix to enhance the mechanical properties of recycled cotton waste/PP composites. Up to now, most of the works have done on the recycled cotton waste/PP composites with different technique but the studies related to injection molding technique are limited. Finally, tests were performed to determine composite mechanical properties and results were evaluated.

Materials and Methods

Blends Preparation

Waste cotton fibers are spilled down from grids during the opening, carding and combing process. Waste cotton fibers are spilled down from grids during the opening, carding and combing process. Waste cotton fibers are short cotton that is thrown into the environment during the opening and carding processes. Air conditioning dust is supplied from different spinning factories in İstanbul. Polypropylene was supplied from Slovnaft Tatren IM 1579 impact copolymer (Bratislava, Slovakia) and maleic anhydride polypropylene (MAPP) was produced by grafting MA to PP (Bondyram 1001 CN, Polygram Group, Ramon, Israel). Fiber lengths are between 1 and 5 mm. Table 3 shows the mixing ratios and fiber size of composites.

Production Techniques

In our study, polypropylene polymer and MAPP were mixed with air conditioning dust waste that is obtained from spinning mills and composite materials were produced by using various methods. The samples are produced with double screw extruder (Maris TM40MW–Maris America Corporation Baltimore, USA) and Arburg injection machine.

The injection molding method was used to produce PP and air conditioning dust composites. Two types of samples (100% PP and air conditioning dust/PP

Table 3 Mixing ratios and fiber sizes of waste cotton composites

Groups	PP/waste cotton (fiber lengths 1–2.5 mm, 5 mm mixed)
1	%100 polypropylene
2	95% PP–5% waste cotton
3	90% PP–10% waste cotton
4	85% PP–15% waste cotton

Table 4 Extrusion and injection molding conditions in composite production

Parameter	Extrusion	Injection
Temperature (°C)	85–190	210–230
Pressure (bar)	24	40
Waiting time (s)	–	10
Screw rotation ratio (rpm)	355	–
Cooling water temperature (°C)	85	40

composites) were shaped via Arbung injection molding. Different weight percentages, 5, 10, and 15 wt% combinations of air conditioning dust/PP/MAPP composites were used. MAPP weight percentage is fixed 10 wt% for all combinations. Table 4 shows extrusion and injection molding conditions in composite production.

Mechanical Characterizations

The mechanical characterizations of 100% PP and air conditioning dust /PP composites were defined using a Zwick universal tensile tester. Tensile strength tests were performed with Zwick impact tester in accordance with ISO 527, 2. Impact tests were performed with Zwick impact tester in accordance with ISO 180, TS 1005, and ASTM 2782 Standards. Melt flow index (MFI) tests were performed according to ASTM D 1238 standard on Zwick 4100 test device.

Results and Discussion

Mechanical Properties

In this study, mechanical properties (e.g., tensile strength, elongations, elasticity modulus, Izod impact, hardness, and MFI) are measured. Generally, mechanical properties increased with increasing fiber content in the composites. However, the presence of MAPP may cause a decrease in some mechanical properties. Detailed information on changing mechanical properties is explained below.

Tensile Strength

In this study, the effect of the mixture ratio on tensile strength was investigated. Figure 5 shows the tensile strength of PP/air conditioning dust composites. The highest tensile strength value is observed in the composite containing 15% by weight of air conditioning dust. Karnani et al. reported that increasing the amount of lignocellulosic fiber in composite increased in tensile strength [52]. The tensile strength test results in our study coincide with the information given in the literature.

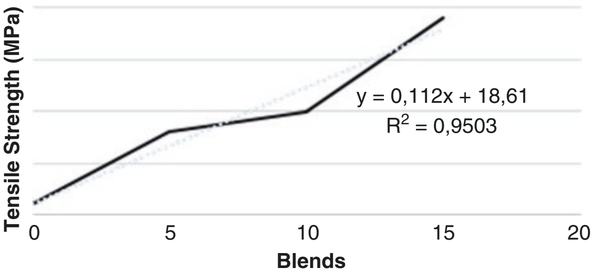


Fig. 5 Tensile strength (MPa) value of air conditioning dust/PP composite

Elongations (%)

In this study, the effect of the mixture ratio on elongation was investigated. Figure 6 shows the percent elongation value of PP/air conditioning dust composites. The highest elongation value was observed in the composite containing 5 wt% air conditioning dust, while the increase in fiber content appears to reduce elongation. In principle, the elongation decreases when the hardness of a material is increased with reinforcing fibers. Mirza et al. reported that increasing the amount of lignocellulosic fiber in composite resulted in a decrease in elongation [53]. The elongation test results in our study coincide with the information given in the literature.

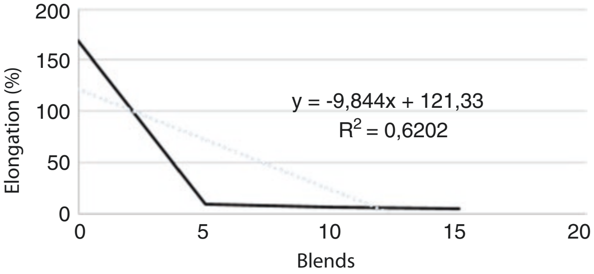
Elasticity Modulus (MPa)

In this study, the effect of the mixture ratio on elasticity modulus was investigated. Figure 7 shows the elasticity modulus value of PP/air conditioning dust composites. The highest elasticity modulus was observed in the composite containing 15% by weight of air conditioning dust while the elasticity modulus increases as fiber content increases. Srinivas et al. reported that increasing the amount of natural fiber in composite increased elasticity modulus [54]. The elasticity modulus test results in our study coincide with the information given in the literature.

Izod Impact (kJ/m^2)

In this study, the effect of the mixture ratio on the Izod impact was investigated. Figure 8 shows the Izod impact value of PP/air conditioning dust composites. The highest Izod impact value was observed in the composite containing 5 wt% air conditioning dust, while the increase in fiber content appears to decrease Izod impact. Bodur examined the effect of fiber content on natural fibers/PP composites containing MAPP. Izod impact was decreased in composites that are containing MAPP binding agent. The reduction in impact strength is the crosslinking or intertwining of chains due to MAPP [50]. The Izod impact test results in our study coincide with the information given in the literature.

Fig. 6 Elongation (%) value of air conditioning dust/PP composite



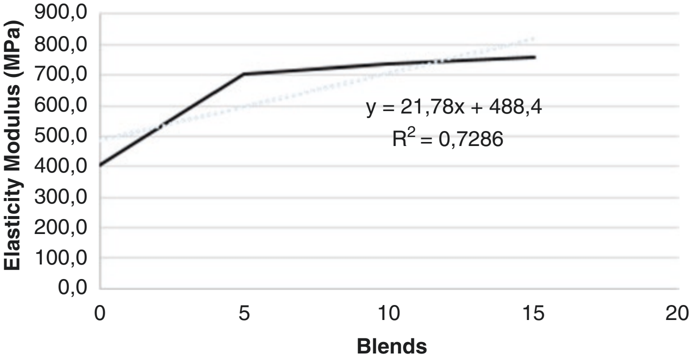


Fig. 7 Elasticity modulus (MPa) value of air conditioning dust /PP composite

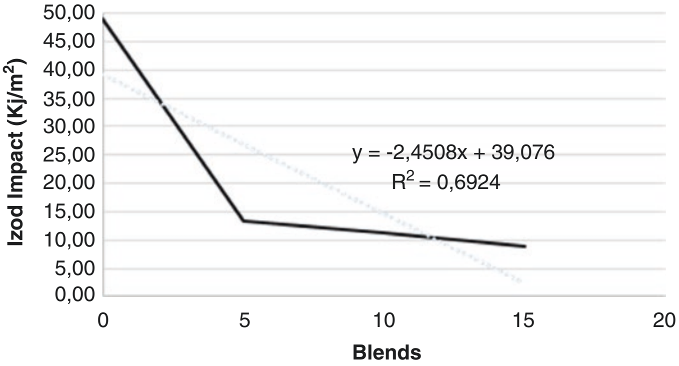


Fig. 8 Izod impact (kJ/m^2) value of air conditioning dust composites/PP composite

Fig. 9 Hardness (Shore D) value of air conditioning dust/PP composite

Hardness (Shore D)

In this study, the effect of the mixture ratio on hardness was investigated. Figure 9 shows the hardness value of PP/air conditioning dust composites. The highest hardness was observed in the composite containing 15% by weight of air conditioning dust while the increased hardness as fiber content increases. Kasim et al. reported that average hardness values increased with an increase in fiber loading [55]. The hardness test results in our study coincide with the information given in the literature.

Melt Flow Index

In this study, the effect of the mixture ratio on the Melt Flow Index was investigated. Figure 10 shows the melt flow index value of PP/air conditioning dust composites. The highest melt flow index was observed in the composite containing 5% by weight of air conditioning dust while the decrease in melt flow index occurs as fiber content increases. Soleimani et al. reported that the increase in the natural fiber content of the composite and addition of MAPP resulted in a decrease of MFI [56]. The melt flow index test results in our study coincide with the information given in the literature.

Conclusion

Mechanical properties such as tensile strength, elasticity modulus, hardness, and melt flow index of cotton waste reinforced composites have been investigated. Cotton waste/PP composites *with different fiber loadings of 10, 20, and 30 wt% were prepared in an injection molding machine*. The effects of MAPP on cotton waste/PP composites were investigated in terms of mechanical properties. Tensile

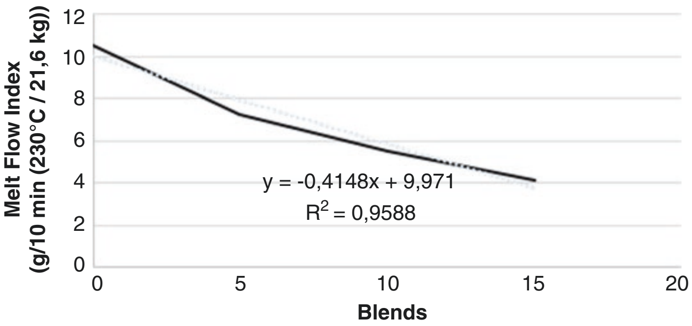


Fig. 10 Melt flow index value of air conditioning dust /PP composite

strength, elasticity module, and hardness of composites increased with increasing cotton waste contents loads, while elongations, Izod impact, and MFI values decreased. The study is summarized as follows:

1. In recent years, there has been an increase in the use of natural plants to produce sustainable environmentally friendly, biodegradable, and recycled materials. In this study, we produced environmentally friendly biodegradable and lightweight materials.
2. It has been examined that composite with fiber loading increased mechanical properties. These results propose that the cotton waste fiber reinforcement composite can be pointed out in different fields such as automotive and aerospace.

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Sustainability in Regenerated Textile Fibers

Aravin Prince Periyasamy and Jiri Militky

Abstract One of the biggest threats to living species is environmental damage and consequent global warming. Industrialization in every field is responsible for these issues. We know that the textile industry is a gigantic industry and a huge polluter. Fiber is the basic raw material for textiles, it is necessary to initiate utilization of sustainable materials to produce sustainable textiles which reduce the environmental burdens. Most of the natural fibers having better properties toward the comfort characteristics, resulting in the huge demand which directly increasing the environmental threats. For example, cotton is the world's most popular natural fiber, accounting for 80% of all-natural fibers used, but the cultivation of cotton is a thorough environmental and health disaster which is almost unbelievable. But all of these environmental and health hazards can be taken care of by the cultivation of organic cotton and perhaps organic cotton alone couldn't replace the cotton. Therefore, it is necessary to find some alternatives; however, it should be in a sustainable manner. Based on these facts, we briefly describe in this chapter about sustainability in the regenerated fibers which include the cellulose and protein and their recent developments. This chapter deals with various sustainable regenerated fibers used in textiles namely lyocell, bamboo viscose, modal, seacell®, smartcell®, and sustainable protein fibers.

Keywords Bamboo viscose · Cellulose · High wet modulus rayon · Lyocell · Rayon · Regenerated cellulosic fibers · Regenerated protein fibers

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Introduction

The world's population rises exponentially, in turn, it increases the demand for food, energy, water, resources, and chemicals. Due to this fact, pollution to the environment is increased with decrease in finite resources like water, land, and fossil. World's population has been increasing enormously with scarcity in producing natural fiber, henceforth in order to give significant development in the quality of life and availability of products for consumption, since 1930, studies and researches have been conducted on synthetic chemical products. The first synthetic textile fibers, nylon was first developed by DuPont in 1935 and then in 1941, the first polyester fiber, Terylene was introduced by the Imperial Chemical Industries, and Dacron was developed by DuPont in 1946. Obviously, waterbodies are drained out clearly and the pollution from synthetic textile exhibits deliberately introducing plastic or microplacti accumulation on our Earth is only the protruding for a longer period that outspread further away not only in the land also in oceans. However, we are mostly initiating pollution to the oceans from where we stand: the land. The global production and consumption of synthetic fibers have rapidly risen since more than 70 years. Twenty-four percent of insecticides and 11% of pesticides are used in cotton farming in spite of 3% of the world's arable land [1]. To produce one kilogram of cotton corresponding to a single t-shirt and pair of jeans 20,000 L of water is required [2]. The fourth largest lake in the world, Aral Sea has disappeared because of cultivation of cotton crops. UN specified this to be one of the worst environmental disaster of the Earth. The renewable biomass is utilized to reduce the footprint of carbon in textiles. Massive quantity of CO_2 is released to the atmosphere due to the fossil fuels burning and deforestation, in turn, implicating the imbalance of carbon cycle. This cannot be further compensated by photosynthesis process or dissolution in the oceans. The contamination released by the textile units can be minimized by using natural raw material. Cotton grown organically requires most extreme measures of pesticides and manures. Yet, small-scale farmers find difficulty in organic farming due to its lower yield which is directly proportional to profit margins. The greenhouse gas (GHG) emissions and environmental concerns have made consumers to be more cautious; henceforth, for sustainable development, the renewable resources can be considered [3–6]. Consequently, it is significant to examine the sustainability of any products in which one among them is textiles [7]. Recently, almost every industry manifests the sustainability movement which is worthy for the environment. Sustainability can be a systemic concept, which relates to the continuity of social, economic, and environmental aspects of human society. Living organisms can be able to encounter their needs and keeping the biodiversity intact and also the ecosystem [8–10]. In case of spoiling the biodiversity, all the level of ecosystem gets affected including the next generations. As mentioned already cotton requires an enormous amount of pesticides and water. Likewise, synthetic fibers such as polyester, nylon, polypropylene, and polyacrylonitrile depend on fossil fuel which is available which in turn increases the GHG. Therefore, a substitute for this fiber is regenerated fibers. Thus, there is a demand for renewable polymers recently. There is a pattern shift from petrochemistry to green chemistry. The impact of manufacturing processes through careful management of feedstocks, energy, waste, and products to the environment can be minimized by focusing on the green concept [11, 12]. This chapter aims to deliver the comprehensive details of regenerated fibers comprising cellulosic and protein-based fibers and also deliberates their production, properties, and prospects as sustainable fibers in the market.

Production of Regenerated Sustainable Fibers

In nineteenth century, *viscose rayon is the first manmade fiber which developed for the alternatives for silk.* Since 1938, first-generation cellulose fiber, viscose rayon was manufactured and the second generation, Modal referred for softness. The third generation is Lyocell which is eco-friendly due to its combined properties of softness, drape, and antibacterial quality while processing. As that of natural cellulosic fibers, all of them are referred to as 'regenerated cellulosic fibers due to their manufacturing process. With desired characteristics, a range of regenerated cellulose fibers are created by using raw materials and manufacturing methods due to the evolving research. Viscose rayon, high wet modulus (HWM) rayon, and lyocell are the types of rayon fibers based on property variations. Bamboo was used as raw material for cellulose, in which regenerated bamboo fibers were evolved with properties of inherent antimicrobial and UV protection. Polylactic acid (PLA) is the best alternatives for polyethylene terephthalate and it is referred as bioplastic due to the environmentally friendliness as well as produced from renewable resources [13]. Chitin is the second most available natural polymer after cellulose; it is the best alternatives for chemically synthesis polymer toward the medical applications [14]. For the sustainable product development, it is important to consider three important pillars which are social, environment, and economy as described in Fig. 1. This principle must be applied to any textile product development.

Fiber Produced with N-*Methylmorpholine*-N-*Oxide (NMMO) Route*

Commercial regeneration of cotton or wood cellulose in the form of fibers and films has been based on solvent systems such as those used in the xanthate and cuprammonia processes. There has been an intensive search for the commercial regeneration of cellulose because of the environmental problems associated with the xanthate process. Recently, tertiary amine oxides have drawn attention as powerful cellulose solvents, with *N*-methylmorpholine-*N*-oxide (NMMO) being the most common. The NMMO process is considered to be the most environmentally friendly method of producing regenerated cellulose fibers on a commercial scale [16, 17]. Regenerated

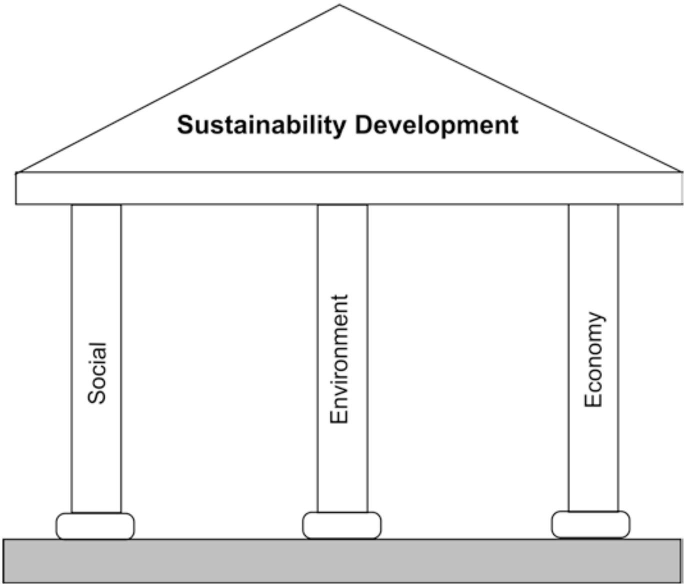


Fig. 1 Sustainability development pillars. (Inspired from [15])

Table 1 Properties of regenerated cellulosic fibers and their production methods

Property	NMMO process (lyocell)	Modal	Xanthate process (viscose rayon)	Ref
% Crystallinity	55	47	35	[19, 21, 22]
Decomposition temperature (°C)	305	296	282	[23, 24]
Total crystalline index (TCI)	0.74	0.72	0.68	[21]
Lateral order index (LOI)	0.341	0.52	0.54	[19, 21]

cellulose fibers produced from NMMO process are claimed to have considerable advantages over the traditional regenerated cellulose fibers produced through the viscose or cuprammonium process [18]. Fibers obtained from NMMO process (lyocell fibers) show considerable variations in tensile, mechanical, and performance properties. Lyocell fibers had higher % crystallinity than viscose fibers (Table 1). Lyocell fibers were also more thermally stable which was related to the higher crystallinity and better crystal orientation in the fibers [19]. In a theoretical study using viscoelastic models, it was determined that regenerated cellulose obtained using the lyocell process had higher tensile properties in the dry and wet conditions attributable to the higher molecular weights and crystallinity [20].

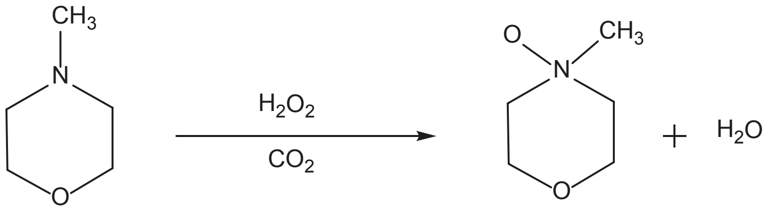


Fig. 2 Chemical reaction involved during the production of NMMO

Microwave heating has been used to decrease the dissolution time and energy consumption during NMMO process of fiber production (Fig. 2).

Alternatives to NMMO Process

Still now, there are many processes tried for the sustainable alternative process for the NMMO process; however, only few processes could be reached to pilot stage, that is carbamate process [25–27]. Ammonia and urea were used for swelling the cellulose, later it can be heated to 130 °C to form a carbamate, which is easily dissolved in the alkali to from soda cellulose. However, handling ammonia is not so easy and controlling the parameters too. There are few alternative processes, as follows:

- Phosphoric acid [28]
- $ZnCl_2$ [29]
- Dimethyl formamide/LiCl [30]
- NaOH/water/urea [31–33]

Eco-Responsible Viscose Rayon

EcoVero is the newest and purified viscose rayon made from a sustainability way. This fiber is similar in softness as like traditional viscose rayon. Due to softness, it provides silky feeling and looks like luxury. The wood for EcoVero is harvested from the managed forest with European certified (i.e., either any of one organization FSC (Forest Stewardship Council) or PEFC (program for Endorsement of Forest Certification Schemes)), which provides the information on the managed forests and their sustainability. Closed-loop system could be followed to make yarn from fibers which ensure the drastic reduction of emission due to unwanted transportations. Every chemical which is used for the production of this fiber could be recycled, also the wood pulp can be bleached by nonchlorine based bleaching agents [34].

Lyocell

The needy of the society are satisfied by the plants in a numerous way as people knew about it. The science and technological development lead the people to create things which are ecologically and communally responsible [35–40]. Lyocell wood pulp in an amine oxide solvent system is one of the examples with spinning technology of economically friendly. Lyocell is considered as a substitute to viscose. Research program of first Tencel which came to reality was in mid-1970s. In 1976, the American Enca Corp. USA conducted research to produce "newcell". A license was granted to Lenzing (Austria) and to Courtaulds (U.K.) in 1990 by Akzo in 1987. Lenzing lyocell was named after Lenzing Austria) and took of $500 million U.S. dollar and 16 years to develop this fiber and its exclusive manufacturing process in which almost all the solvent used was recycled. Solvent spinning process made a first new generation of cellulosic fibers, Lyocell [41, 42]. Development of this is mainly due to demand and environmentally accountable by utilizing renewable resources as their raw resources [38, 40, 43–46]. Lyocell consumes only organic-based chemicals in less amount starting from manufacturing. Once the manufacture is completed, the solvent and water can be recyclable (Fig. 3). Severe environmental and health hazards are the results of processing viscose rayon rather than lyocell. Henceforth due to the facts like ecologically friendly process, raw materials which are renewable, biodegradability in nature brands lyocell as an eco-friendly fiber (Fig. 4). Comparatively the manufacturing process of lyocell requires 3 h with less

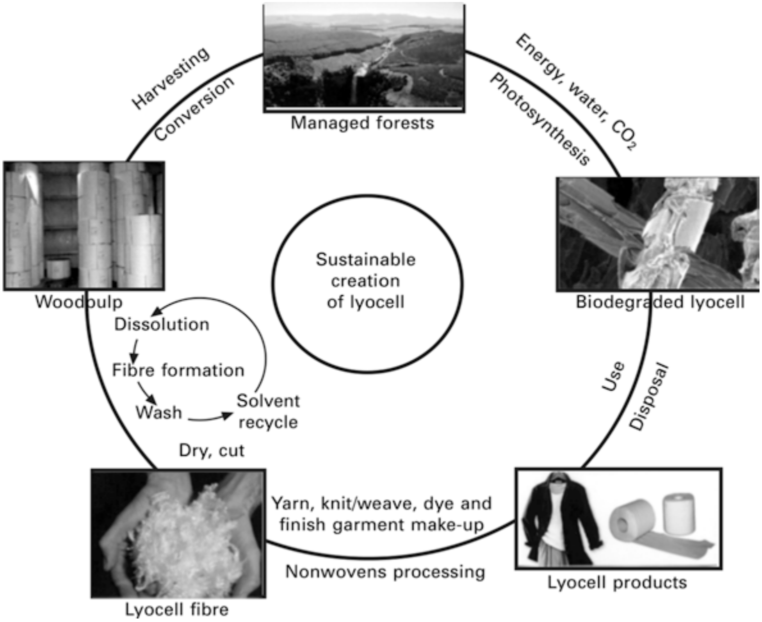


Fig. 3 Lyocell fibers and their sustainability. (Reproduced from White et al. [49] with the kind permission of Elsevier Publications)

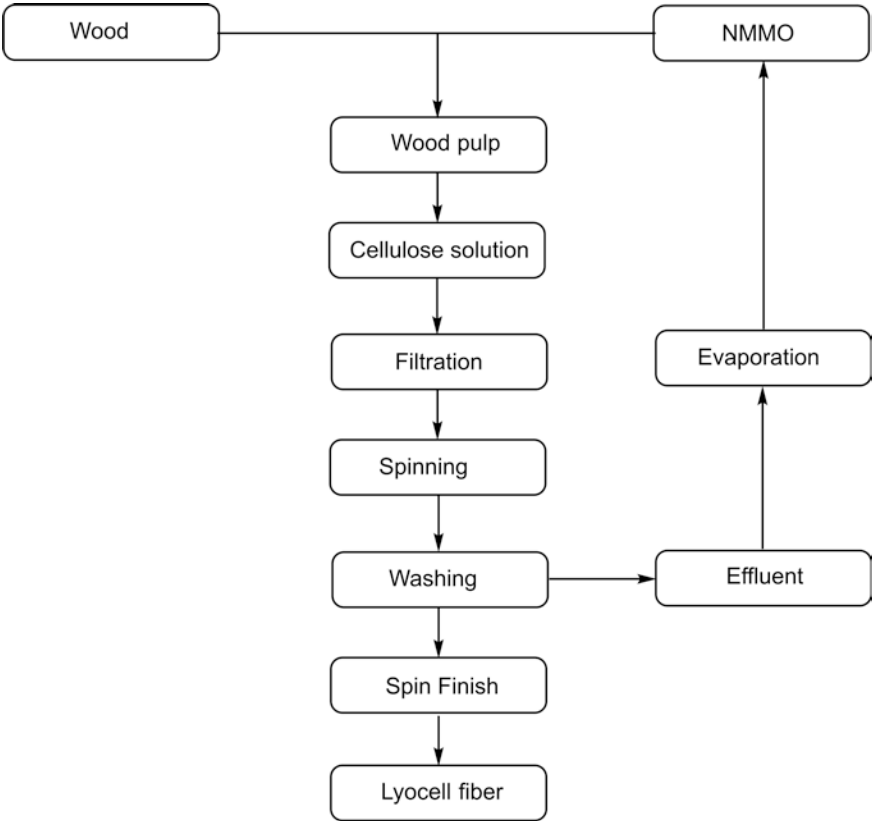


Fig. 4 Production sequence of lyocell fibers

energy and water but for viscose rayon stable fiber it takes of 40 h. Therefore, lyocell is an absorbent and exceptional in handling and drape which considers it to be a cellulosic fiber. Due to the high wet strength property of lyocell to yield the finer yarns and fabrics than that of viscose rayon. Breathable, good moisture absorbent and high dimensional stability are additional property of Lyocell to be exceptional [47, 48].

Production of Lyocell Fibers

Wood pulp at first dissolved at the temperature of 90–120 °C under normal pressure with the solvent of NMMO converting into viscose solution later to manufacture Lyocell. The impurities are removed by the filter and extruded into a water bath jet in which solidification takes place to make the polymer to regenerate. Then washing is done thoroughly to fiber formation and dried. The solvent which is used can be utilized later since 99.5% of the solvent can be recovered and reused in forthcoming batches. Compared to cotton raw materials, lyocells are free from the environmental problems with very less land pollution since no utilization of synthetic fertilizers, pesticides, herbicides, and insecticides [32, 33].

Environment Friendliness of Lyocell

In order to prepare lyocell, *N*-methyl morpholine-*N*-oxide (NMMO) is used as a solvent which is an amine oxide group (Fig. 5).

Gerhard Meister et al. [50] studied the biodegradability of lyocell fibers, the results of biodegradability are shown in Fig. 6. Almost in 7 days, there is a huge degradation on the surface of the fibers and it fully degraded within 28 days.

Toxicological Aspect

Since the NMMO can be recycled almost 99.5%, however, there is a possibility of discharging of small quantity which is hard for the environment. Other chemicals which are used to produce the lyocell fiber or in this process cannot make any environmental problems.

Fibrillation of Lyocell Fibers

When compared to other regenerated cellulosic fibers, lyocell process is more technically challenging in fabric and garment form due to its fibrillation. Generally, the overall success in the textile industry is possible only by understanding the dyeing

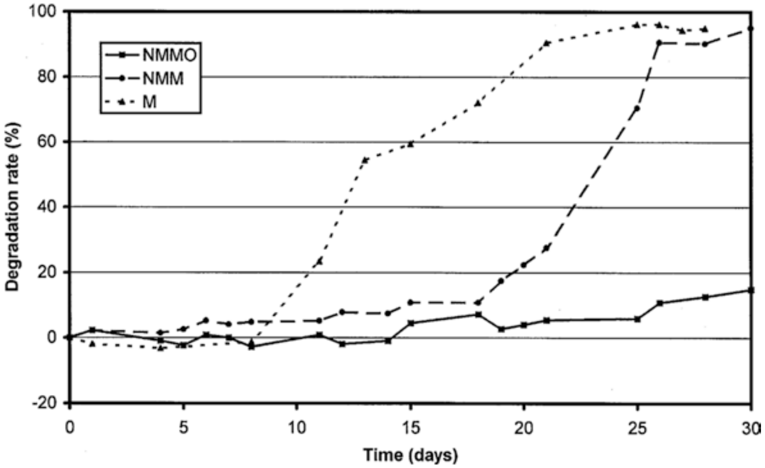


Fig. 5 Biodegradability result of [50] (*N*-methylmorpholine-*N*-oxide (NMMO), *N*-methylmorpholine (NMM), and morpholine (M))

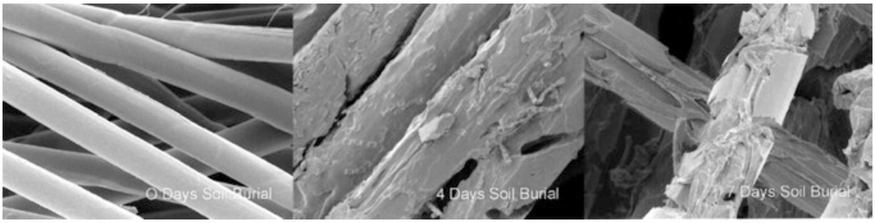


Fig. 6 Biodegradability result of lyocell fiber. (Reproduced from White et al. [49] with the kind permission of Elsevier Publications)

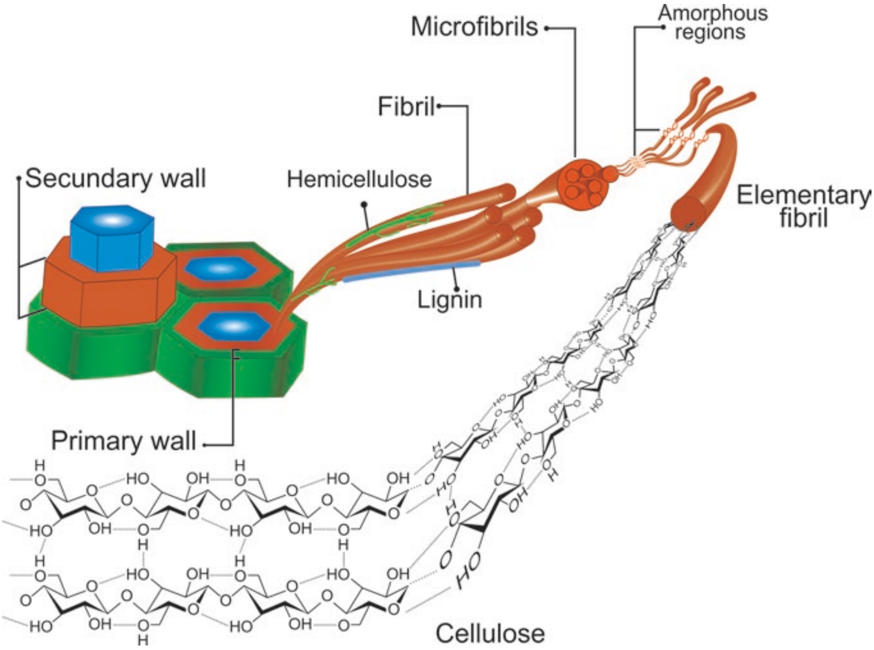


Fig. 7 Structure of cellulosic and it fibrillation generation (i.e., micro and nanofibrils). (Reproduced from [51], under Creative 3.0)

performance of fibrillated lyocell meticulously to overcome this problem. The splitting of fibrils along the fiber surface of individual fibers known to be fibrillation in which lyocell tends to fibrillate by the swelling in water and further by the action of mechanical stress (Fig. 7). Weak interfibrillar bonding of uncross-linked lyocell substrate emphases, particularly staple fiber yarns with a high swelling capacity exposes the tendency to fibrillation throughout its life time. The special effects such as peach-skin, soft touch, sand wash, and microveluttino effect are possible only through fibrillation. Due to this property, it is utilized to upsurge firmness and absorbency and improves the stability of the hydro-entangled fabrics. Due to the remarkably high degree of crystallinity and swelling ability of cellulose spun-from NMMO together with weak inter-fibrillar bonding forces creates the actual tendency lyocell fibers to fibrillate. Through the entire process, the fiber does not have a core structure and is homogeneous. Compared to other standard lyocell fibers, for example, lyocell LF and A 100 fibers, the tendency of fibrillation is very higher in standard lyocell or Tencel fibers.

Primary Fibrillation

Fiber is treated in water and by mechanical action, the primary fibrillation can be achieved. Fibrillation occurs to give entanglement providing a characteristic piled appearance and weak spots are created in fiber. Due the hair on the fabric surface, it is easily abraded during mechanical action. Henceforth fibrillation takes place predominantly. By the presence of long hairs, long fibrils are formed to get entangled to form a pilled fiber appearance.

Secondary Fibrillation

- Fibrillation takes place under wet atmosphere where there are no pilling occurs giving a tiny and even fibrillation. Crossover points of the weave are developed on the upper surface of the fiber where the fibrillation starts. They do not entangle and also the fibers are short. Two effects take place by the secondary fibrillation. They are as follows.
- On the surface of the fabric, a tiny pile is created giving a special surface feel to the fabric known as peach-skin effect.
- Even though they contain the same amount of dye, the fibrils look to be far lighter in color since they form only a small fraction of the size of the fiber giving an effect of mill wash or dusted look on the exterior of fabrics.

Defibrillation of Lyocell

Fibrillation can be controlled through various processing steps:

- During the production
- After production

During the production, it is possible to vary the various spinning parameter to optimize the reduction of fibrillation. The changing parameters are spinnerate size, temperature during the production, drawing ration, air gap, or adding the cross-linking agent; except cross-linking agent, remaining are still in research and not yet commercialized. On other hand, the various chemical processing of lyocell can reduce the fibrillation, they are as follows:

- Alkali treatment of lyocell
- Dyeing of lyocell with multi or polyfunctional dyes

- Treating with cross-linking agent (e.g., resin)
- Biopolishing

Alkali treatment is the most important stage of all cellulosic fabrics. Since, these cellulosic fabrics undergo various alkali treatment such as scouring, mercerizing, and dyeing with reactive dyes. Alkali treatment makes cellulosic fibers to swelling, which causes to change the orientation and crystallinity. Goswami et al. [52] found that alkali treatment reduces the crystallinity when the alkali concentration is increased. Among the alkalis, tetramethyl-ammonium hydroxide provides better results [35–38, 40, 53]. From Fig. 8, it can be observed through SEM images of lyocell after alkali treatments; tetra methylammonium hydroxide shows a smooth surface without any bundle and layer of macro fibrils. Fibrillation can be reduced when it dyed with polyfunctional reactive dyes [54, 55] (Fig. 9).

Advantages of Lyocell

Lyocell has several advantages as compared to existing cellulosic fibers as well as synthetic fibers. They are given below;

- Production of lyocell is entirely environmentally friendly.
- The chemical and solvent which associated with the production of lyocell have been recycled. Therefore, it reduces the raising of hazardous waste (CS_2 in viscose rayon).

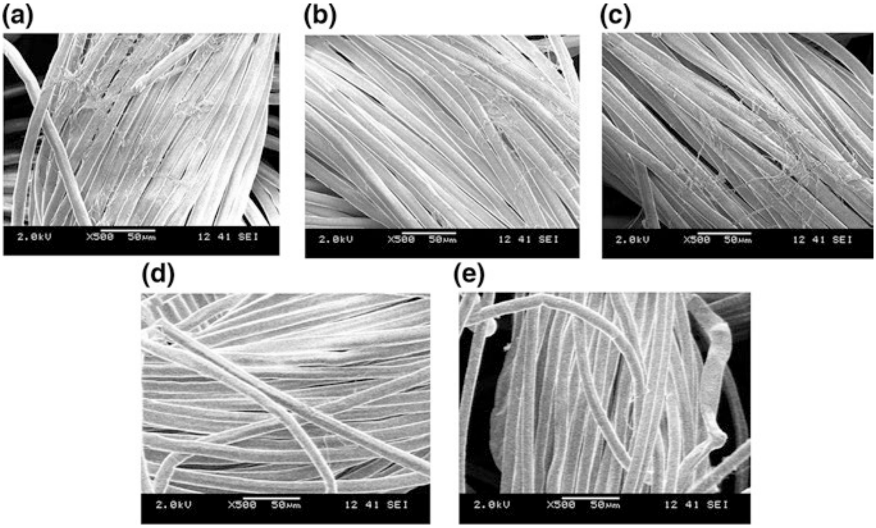


Fig. 8 SEM micrographs of (**a**) original lyocell fabric, (**b**) lyocell treated with 3 mol/L NaOH, (**c**) lyocell treated with 3 mol/L KOH, (**d**) lyocell treated with 3 mol/L Li OH, and (**e**) lyocell treated with 3 mol/L Tm AH

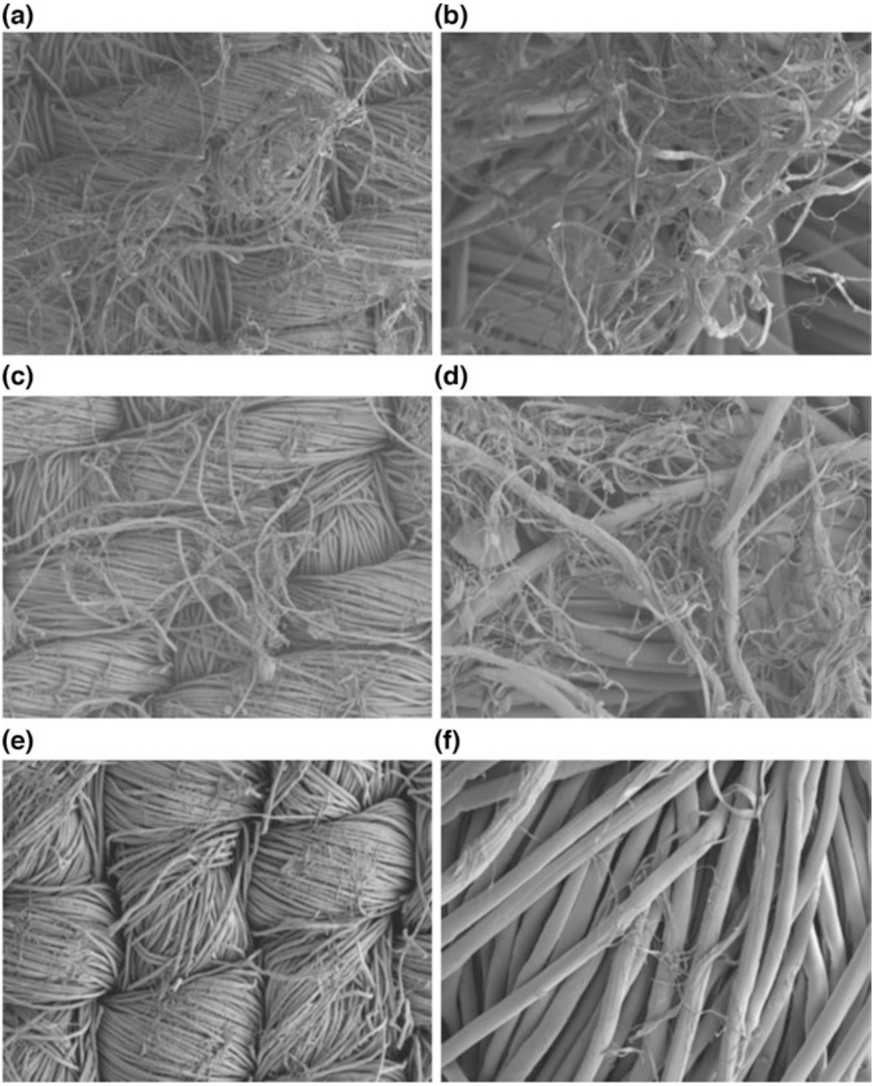


Fig. 9 SEM micrographs of lyocell fabric dyeing with monochorotriziine reactive dyes (**a**) 100× and (**b**) 500× magnification, 5.0% Y dyes, (**c**) 100× and (**d**) 500× magnification, and 5.0% X dyes at (**e**) 100× and (**f**) 500× magnification. (Reproduced from [54] with kind permission of Wiley Publications)

- Lyocell has the properties of natural and synthetic fibers (e.g., cotton and polyester).
- Lyocell can possibly be blended with majority of the natural and synthetic fibers.
- Lyocell ensures the comfort and luster properties of denim. Generally, lyocell is used to produce the soft denim.

- Lyocell provides the better thermal properties as compared to cotton and other fibers.
- Lyocell absorbs more dyes as compared to cotton and linen even in the same concentration of dyestuff. It results in the reduction of pollution load.

Developments in Lyocell

Wet Cleaning of Tencel/Lyocell

The technology that is trending is wet cleaning where it substitutes perc and as an alternative uses water and detergent to clean many garments, which is generally mentioned in dry cleaning care methods. Stains are removed easily by wet cleaning methods like laundering that are water-soluble. During the process, the fabrics are treated mildly by the detergent yet effective in eliminating fats and pigments soil with minimum washing action. This results in protecting fabrics against felting and shrinkage thereby refining stability of dyes.

Tencel A-100 New Development

Similar to Tencel in maintaining the fall and superior feel, Tencel A 100 swells as same. After the process of spinning and washing, Tencel A-100 fiber is treated in a cross-linker bath (triazine compound). The penetrability is higher than the normal Tencel since it is cross-linked in wet conditions. High dry and wet strength is possessed by the Tencel A-100 with high cross-sectional swelling yet without the tendency of fibrillation. In addition, the retention of water is higher to 75% as compared to 65% for normal Tencel resulting in better dye ability of around 50% than the normal viscose fibers. Due to high exhaustion and fixation degree, the open fiber structure has a positive effect on dye ability. Compared to cotton and modal fibers, Tencel A-100 is superior in washing ability. Some pretreatment and optical brightening are essential for white goods even though Tencel A-100 possesses a greater degree of whiteness than normal Tencel. It is necessary to take special care due to its sensitivity to fiber.

Lyocell Fibers with REFIBRA™ Technology

In 2017, Lenzing [56] introduced lyocell fibers from Refibra technology. This technology ensures the circular economy, since it used cotton waste from waste cloths, pulping industry, and textile spinning industry. After the collection of these waste, these are utilized to produce lyocell fibers with conventional NMMO process; a simple process sequence is described in Fig. 10. The advantages REFIBRA™ technology-based lyocell fibers are described below:

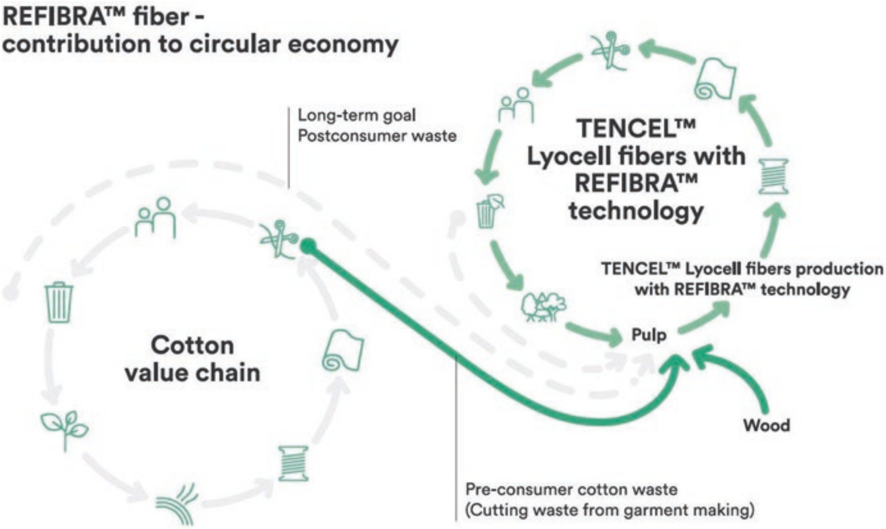


Fig. 10 Circular economy of REFIBRA™ technology. (Image source Lenzing [56])

- Utilize waste into valuable product
- Reduce the utilization of resources
- Replace the virgin cotton fibers
- Recycle the solvent up to 99%

Uses and Applications of Lyocell

- It is used to produce the fine quality fabrics.
- It has the combination of synthetic and natural properties; therefore, it is suitable for technical fabrics.
- Lyocell has better absorption, it can be used to produce as nonwoven for wipes and absorption textiles.
- Due to good tensile strength, it can be used in filtration cloth.
- Used in medical textiles.

Bamboo Rayon

Bamboo trees are the resources of the bamboo fibers with cellulosic fibers. In general, the tropic regions grow it in abundance whereas the highest number of species and largest producing country in the world is China. Bamboo is a plant of growing rapidly; where some species may grow 1 m per day without any pesticides. Since it is grown organically rendering the safety of environment, it takes about 4–5 years to harvest with various advantages to the environment enthralling 5 times more CO_2 than the same stand of trees and generating 35% extra oxygen. Generally, the bamboo fibers can be produced through mechanical and chemical processing. In both the way, the bamboo trees can be splitting with the small strip's formations. But later both the processes are different; in mechanical processing, the enzymes can be added and it helps to crush the stripes of bamboo into fiber forms. However, the enzyme reacts on the bamboo strips slowly and split the fibers gradually. Later, it can be blended with or alone to produce the yarn. On the other hand, alkali was added with bamboo which makes soda-cellulose. This process is similar to conventional viscose rayon manufacturing, where carbon disulfide added in both cases, resulting emission of harmful pollutants; therefore, it is not an environmentally friendly process (Table 2).

Properties of Bamboo Fiber

Antibacteria, bacteriostasis, and deodorization are the characteristics possessed by the bamboo fiber in particular. Bamboo gun is a unique antibacteria agent possessed by bamboo conveying the natural functions of antibacteria and deodorization. The final product with the antibacterial behavior is stimulated by the content of bamboo fiber in blended yarns. When the bamboo content is higher the properties of antibacteria are better. In order to reach the desired effect of antibacteria, it is suggested to maintain 70% bamboo fiber in blended yarn. After washing more than 50 times, bamboo fabric shows the functions of antibacteria. A unique ability of breathability and coolness is acquired by the bamboo fiber. Microgaps and microholes fill the cross-section of bamboo fiber is the reason for better moisture absorption. The temperature of human body is reduced approximately 1–2° than normal apparel

Table 2 Physical parameters various textile fibers (Reproduced from [57], with kind permission of Springer Publications)

Properties	Bamboo	Lyocell	Viscose rayon	Cotton	Polyester	PLA
Dry tensile strength (cN. tex^{-1})	20–29	38–42	22–26	20–24	55–60	40–48
Wet tensile strength (cN. tex^{-1})	15–22	34–38	10–15	26–30	54–58	–
Dry elongation at break (%)	14–18	14–16	16–24	7–9	24–30	30–40
Wet elongation at break (%)	–	16–18	21–29	12–14	24–30	–
Linear density (gm cc^{-1})	1.32	–	1.5	1.4	1.38	1.25
Crystallinity	–	70–80	30–40	70–80	50–70	70–80
Moisture regain (%)	12–13	12–13	11–14	8–9	0.4	0.4–0.6
Cross sections	Serrated with micro gaps and holes	–	Serrated	Bean	Circular	–

in hot summer by the apparel made out of bamboo fiber. Consequently, it is topped as air conditioning dress which absorbs and evaporates human sweat in little moments. Due to modern industrial development and in the impaired environment, the bamboo fibers with unique character of anti-UV is seem to be healthy and appreciated in leading to increased surface ultraviolet radiation. Bamboo fiber has witnessed the degree close to normal finely bleached and has a strong durability; stability is proved by the technological analysis possessing the perfect quality for spinning by withstanding the abrasion. Bamboo is branded as possessing good hygroscopic, excellent permeability promoting hygienic, and delicate touch to skin. As associated with other cellulose fibers, it reveals more dye up with an appearance of lustrous and shiny.

Environmentally Friendly of Bamboo

The growth of bamboo takes place without farming and pesticides compared to other fibers like cotton, it is more sustainable. The environment is polluted widely by cotton by utilizing a large quantity of water and pesticides. Whereas the greenhouse gases are taken in by bamboo and releasing oxygen therefore it is not necessary of replanting or using fertilizers. The roots of it are very good in order to maintain the erosion prone zone without chemical additives as rendering into an eco-friendly fiber. As an essential point, the bamboo fiber is a unique bridgeable textile material. Microorganisms and sunlight biodegrade bamboo fabric by 100% since it is a natural cellulose fiber without causing any pollution to the environment and atmosphere. "Bamboo fiber comes from nature and completely returns to nature in the end". The bamboo fiber is admired as "The natural, green, eco-friendly new-type textile material of the 21st century" .

Applications of Bamboo Textiles

Since bamboo has three key properties such as antibacterial, breathability, and wet permeability, it makes soft hand comfort textiles. It is used as several applications listed below:

- Towels
- Inner wears
- Bathrobes
- Bed clothes
- Bed mats
- Outer wears
- Socks
- Absorption wipes (bamboo nonwoven)
- Surgical textiles
- Sanitary napkins

- Mask
- Mattress

Modal Cellulose

Wood pulp of beech tree can be used to make wooden chips to regenerate a cellulosic fiber, modal. Lenzing Austria is uppermost manufacturers of modal fibers whereas many companies manufacture currently. With enhanced physical properties such as high tenacity and high wet modulus, defines the modified viscose rayon is called Modal. The only variance between viscose rayon and modal is that viscose rayon can be acquired from diverse trees where modal is not. However, the manufacturing method is almost similar. The modal fibers are produced through wet spinning techniques.

Seacell®

SeaCell® is a third-generation regenerated cellulosic fiber is developed by smartfiber AG-Germany [58]. This fiber is produced from the seaweed and follows the lyocell process (Fig. 11). Since it used NMMO as solvent which recycles completely, therefore the manufacturers claim that this fiber is environmentally friendly

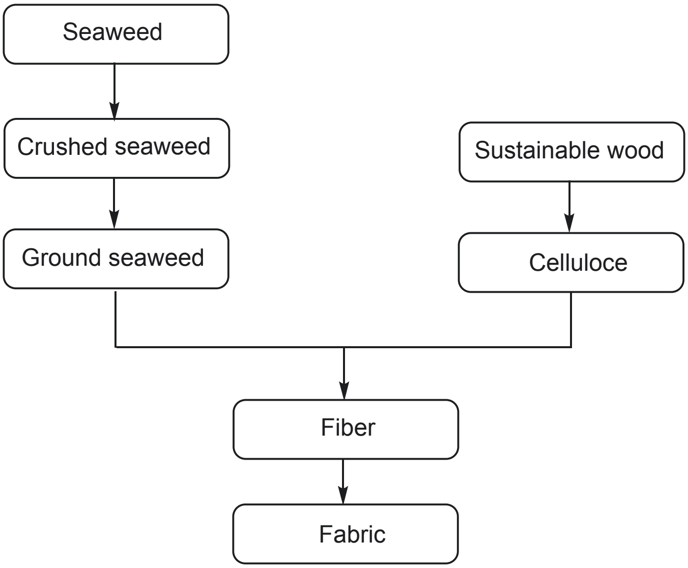


Fig. 11 Production sequence of SeaCell® [61, 62]

fiber. It prefers to use in the field of medical textiles as well as in the skin care applications since this fiber contains various minerals and vitamins, carbohydrate, and amino acids [59]. Commercially, there are two varieties of SeaCell® are available: fiber produced by using of seaweed and cellulose called as SeaCell® pure and addition of silver in this combination is called as SeaCell® active. There is no damage on sea-life due to the extraction of seaweed; it also grows naturally without the addition of fertilizers and pesticides in addition it is biodegradable [57, 60]. SeaCell® is suitable for the sports and outdoor cloths since it has better moisture absorption properties. It can be blend with other fibers to produce combine properties for the better clothings.

Smart Cell®

Recently living atmosphere is becoming worse due to harmful pollutants which lead to ozone depletion, resulting in skin cancer, and other health issues damaging the quality of life. Therefore, the development of sensing textiles is given more attention and research takes place in order to help to create awareness of the consumer [63–67]. Innovation in the textile industry has been increased day by day and there is no limit in the field of functional textiles: smart textiles are one among them [64, 68]. Smart Cell® is a special cellulosic fiber contains Zinc (recycled Zinc) and it is introduced by smartfiberAG, Germany. This fiber is produced with modified lyocell process where the possibilities to add the required additives into the fibers to produce the functional fibers (Fig. 12), resulting the ex-ordinary performance with expected efficiency levels. Eucalyptus cellulose is used to produce the Smart Cell® fiber since Eucalyptus contains lots of minerals which make the inbuilt medicinal

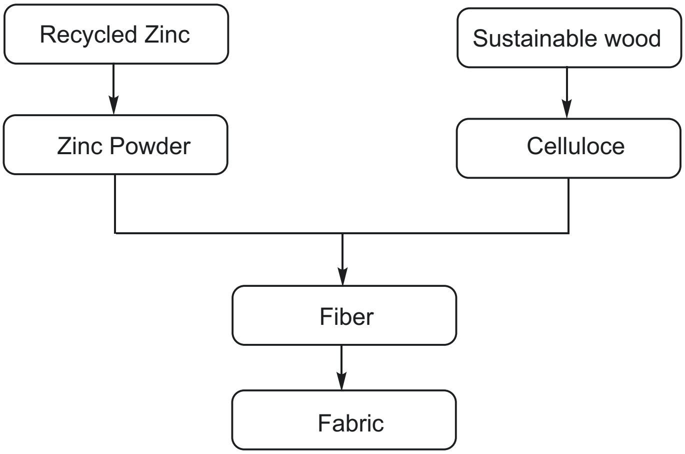


Fig. 12 Production of Smart Cell® sensitive [61, 62]

effects. It has a better antiodor with antibacterial properties; therefore, it is sold with *“Sleep well protected by Zinc” slogan* [61, 62].

Polylactic Acid Fibers

The world's foremost commercially effective biodegradable and eco-friendly artificial polymer is polylactic acid (PLA). The fabrication of PLA is done by polymerizing lactic acid monomer manufactured by carbohydrate fermentation of corn dextrose frequently. Polymerization does not require solvent and it can be prepared from biomass. The petroleum-based polymers which are not sustainable are generated to lessen the solid waste as emerging new alternative. PLA polymer family is so attractive due to its thermoplastic, biodegradable, compostable, and manufactured from renewable resources; additionally, it also possesses mechanical and obstacle behavior comparable to synthetic polymers. Various application in the field of medical, textile, and packaging industries are shown by versatile material PLA which is also utilized for any purpose from sweatshirts to blister packs. Within extensive study in technical textiles, it also brings a trendy arrangement of attributes to packaging, stiffness, clarity, low temperature heat seal ability, and with a fascinating mixture of barrier properties. By changing conventional packaging with PLA, thermoformed packaging for just by four products, 4900 metric ton of greenhouse gases released into the Earth’s atmosphere is avoided. For applications of biomedical and tissue engineering are attracted by numerous innovative domains created by PLA polymers. If crystallization of PLA polymer is avoided, their degradation rate inside the body can be controlled due to its nature of nontoxic, biocompatible, and metabolized easily. Based on these two characteristics, PLA polymers make them an exceptionally striking bioabsorbable material. Lactron, the PLA fiber was introduced by the Kanebo from Japan in 1994. Foremost the viscon rayon was mixed to obtain nonwoven. PLA’s continuous manner with low cost manufacture was patented by the Cargill Dow LLC (NatureWorks LLC) polymers in 1997. The biggest plant for manufacturing the PLA fibers and plastics recently is Nature works LLC. Production of PLA are done under various company with different trade names such as Kanebo Gohsen Ltd (Lactron® for both textile fiber and polymer), Shimadzu Corp (Lacty® as polymer), Toray Industries (Ecodear® for both textile fiber and resin products), Unitika (Terramac® as textile fiber), Kuraray (Plastarch® as textile fiber), and Mitsui Chemicals (Lacea® as resin products). Renewable sources like corn starch or sugar beets derived to obtain Poly (lactic acid) (PLA) which is linear and hydrolysable aliphatic polyester. Based on the products of nature, the PLA is a first fiber which is melt spinnable and thermoplastic in nature which has property of high strength and high modulus. PLA has a molecule chain of helical structure. Simple hydrolysis of eater bond readily degrades PLA; furthermore, catalyst is not required to hydrolysis reaction. During the hydrolysis reaction depending on the size of the article, isomer ratio, and temperature, the degradation takes place. Degradation takes place when nearing 200 °C while the glass transition temperature was 55 °C and melting temperature was 175 °C; consequently, it is very stress-free to dye with normal temperature as polyethylene terephthalate [69–71].

Production of PLA Fibers

Raw corns are milled to separate the starch like dextrose/sugar and then it should ferment to obtain lactic acid as that of beer or wine manufacturing. After the process of fermentation lactide, the intermediate dimer is converted from lactic acid. Through vacuum distillation, lactide is purified plenty of times to obtain the polymer and guarantees the ring opening polymerization (see Figs. 13 and 14). PLA can be altered with differing the molecular weight and structure of crystallinity based on the applications. Superior hand, drape, comfort, moisture management, UV resistance, and resilience are the properties possessed by the PLA fabrics [72].

Environmental Benefits of PLA

Fossil fuel is used to manufacture conventional synthetic fibers like PET, Nylon, and Acrylic. Conflicting to the fact of consuming 11 billion tons of fossil fuels whereas crude oil shares approximately four billion tons. When same amount of crude oil is exhausted, then by 2052, there is possibility of disappearance of crude oil. Henceforth, it is foremost essential to ensure substitute products in which one among them is PLA. From a renewable resource, one-third of energy necessary to manufacture PLA is derived. This difference makes huge variations in hydrocarbon consumption in producing synthetic fibers. From the atmosphere, the cultivation of

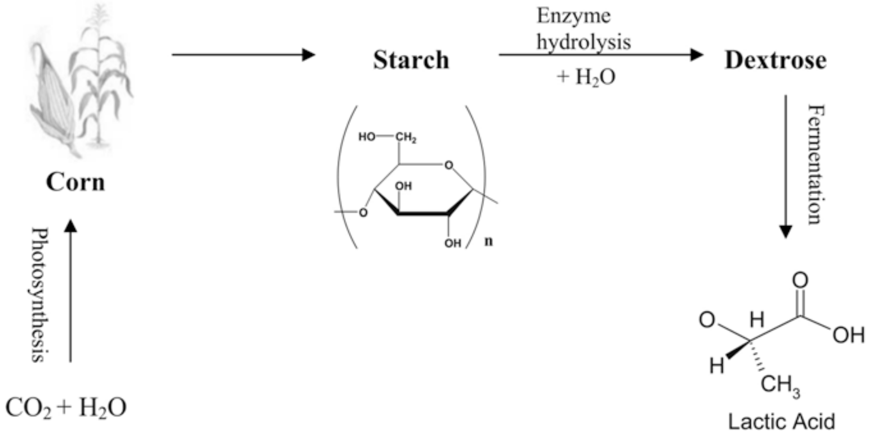


Fig. 13 Simple production route of PLA. (Reproduced from Ozan Avinc [70], with the kind permission of Springer Publications)

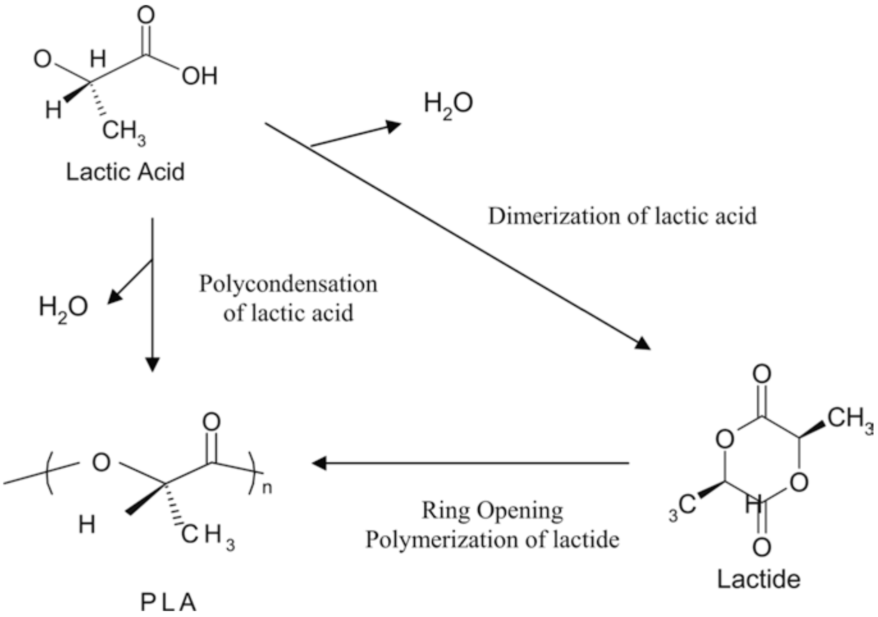


Fig. 14 Different polymerization routes of PLA. (Reproduced from Ozan Avinc [70], with the kind permission of Springer Publications)

corn helps in reduction of carbondioxide ensuring the impact to be less on global warming rather than other hydrocarbon-based fibers [69, 73].

Biodegradability of PLA

As deliberated earlier, by simple hydrolysis reaction, it can be readily degradable and also, it is possible to recycle under suitable situation. Under the process of hydrolysis, conversion of PLA into carbon dioxide and water takes place. The process of recycling supports to form lactic acid hence results are subject to treat with a different temperature from 100 to 250 °C under water. To investigate the sustainability of textile fibers, an important tool can be life cycle assessment.

Chitin, Chitosan

Chitin, poly(1,4-2-acetamido-2-deoxy-P-D-glucose), is the second most abundant natural polymer. Chitosan is the deacetylated product of chitin and both are polysaccharides that support numerous living organisms and are available indigenously in fairly large quantity as raw material [74, 75]. In last two decades, so much attention

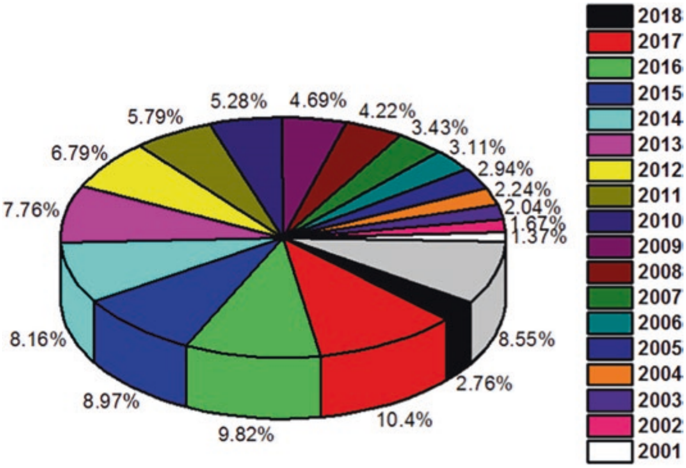


Fig. 15 Research publications in chitosan. (Reproduced from [77], with kind permission of Elsevier publications)

is given on this polymers due to the potential applications [76]. Figure 15 evidenced through increase number of publications in these decades.

For numerous medical and pharma medical application, biocompatible chitosan is used as a safe substance for the living organisms which is investigated for military use in a large scale in USA. Chitosan is formed by processing two sources with certain modification: converting into stable gel, then subsequently into paste and fine powder. Evaluation of the samples was conducted to determine the presence of metal ions to discover their purity by comparing with the imported material. It has been marketed it as a dietary supplement, used to thicken foods, paints, and make-up. It also has favorable applications as an artificial skin for burn victims. At last coagulation property of chitosan suspends the sediments in water in order to settle out. For the public viewing, most of the marine aquarium like Sea world uses chitosan to preserve their aquatic habitats crystal clear. Cellulose and chitin/chitosan have similar chemical structure as such of cotton and rayon (Fig. 16). The total production of Chitin is estimated on the earth annually to be about 1–100 billion ton [76–78].

Characterization of Chitosan

Degree of deacetylation (DD) and molecular weight (MW) are the two important structural parameters of chitosan influencing the properties solubility, enrichment ions, the mechanics of the chitosan membrane, flocculation, etc. determine its performance in physics and chemistry. Chitosan allows to constrain the growth of many bacteria, including gram-negative and gram-positive ones by the quaternary amino group which is NH_2 group in chitosan in acidic solvents.

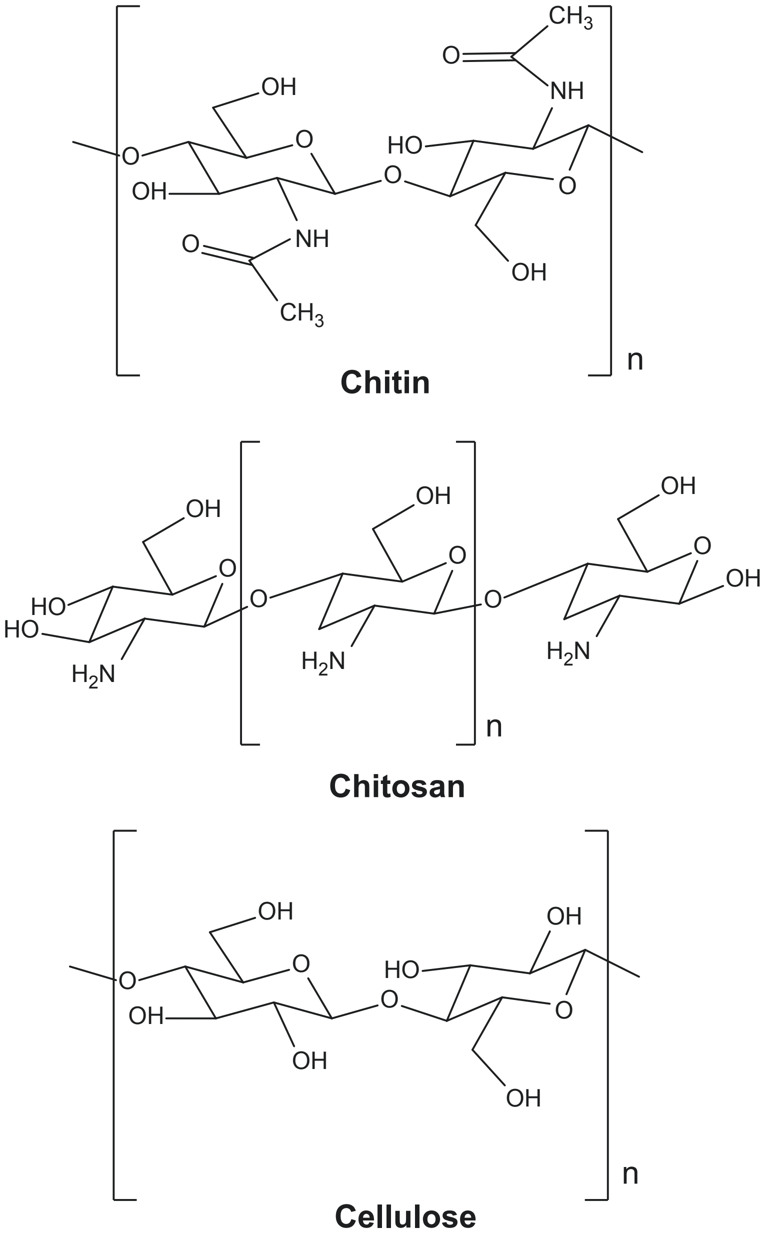


Fig. 16 Chemical structure of chitin, chitosan, and cellulose

Manufacturing

In order to remove calcium and protein, the waste shells (typically crab, but also shrimp and lobster) are grounded up and then processing is done in any of the two methods. The refined chitin is combined with lactic acid flakey product (milk acid), dried, and shredded for the dry one resulting in chitosan lactate, water soluble which will dissolve. Acetic acid and water is combine with refined chitin to produce a 1 or 2% solution of chitosan acetate, liquid product [76]. Dissolving Chitosan in aqueous acetic acid solution, a typical dope was organized and then candle filter system filters before adding to the spinning system reservoir by degassing under vacuum. Spinning head of mounded spinnerate receives it and then a dilute NaOH bath, with an immersion length of ca. 100 cm coagulates the filaments and then passes through take-up rollers, drawing system, drying rollers, and the winding up procedure as mentioned earlier. Radiant heat on chrome rollers washes and dries the filaments after the drawing was carried out in hot water at 80–85 °C depending on various occasion [76]. The various mechanical properties of cellulose/O-hydroxyethyl chitosan fibers are shown in Table 3 and the results were compared with viscose rayon.

The chitin filament with 3.1 denier and the chitin-fibroin (67:33, w/w) filament in 18.5 denier are shown in the SEM photographs (see Fig. 17) in which it has faintly scaly structure of vertical stripes. During the neutralization and dehydration processes of the filaments, filament surface with scaly structure is deliberated to be formed. Figure 18 shows the socks knitted by the Fibers containing 6% silk fibroin. The commercialization of the process has been restricted due to the difficulty in dissolving chitin in spite of producing fibers from chitin.

Table 4 shows the various physical properties of chitin filaments and its blends. Spun filament of silk fibroin was white in color, soft, insoluble in cold and boiling water, steady on heating at up to 200 °C and after over 230 °C, it converted into brown color on heating. Silk fibroin having filaments less than 10% have good mechanical property. As silk fibroin content increases from 31 to 53%, the tenacity values decrease extremely from 0.63 to 0.15 g/denier predominantly due to a shrinking of a filament of about 2/3 length through the course of air-drying.

Table 3 Physical properties of cellulose/O-hydroxyethyl chitosan fibers and viscose rayon (Reproduced from [79] with kind permission of Elsevier Publications)

Fibers	Dry tensile strength (cN.dtex^{-1})	Dry elongation at break (%)	Wet tensile strength (cN.dtex^{-1})	Wet elongation at break (%)	Moisture absorption (%)	Mass specific resistance (Ω g cm^{-2})
Viscose rayon	3.06	19.0	2.70	17.9	13.01	4.7×10^8
CHCFs-3	3.04	21.2	2.66	19.4	13.23	4.3×10^8
CHCFs-4	3.01	22.5	2.61	21.2	13.40	4.2×10^8
CHCFs-6	2.97	22.9	2.55	24.5	13.55	4.0×10^8

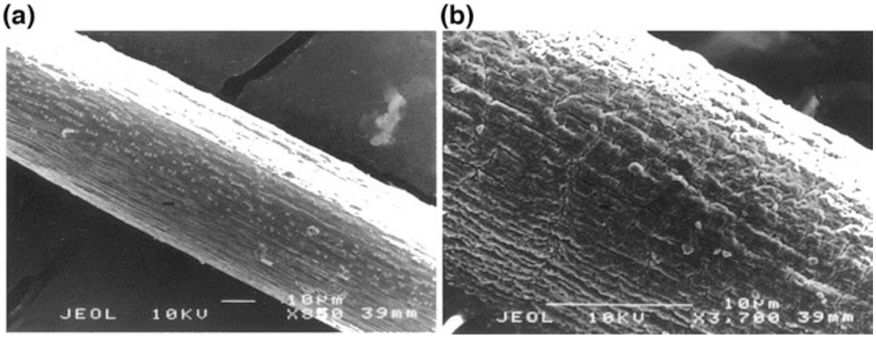


Fig. 17 The rough and serrated surface of chitin (**a**) and chitin-fibroin blend fibers (**b**). (Reproduced from [80] with kind permission of Elsevier Publications)

Fig. 18 Produced knitted sock from chitin/fibroin blend fibers. (Reproduced from [80] with kind permission of Elsevier Publications)

Silver Containing Chitosan Fibers

A varied range and cherished property of metal ions within chitosan matrix giving polysaccharide are used for medical applications [82]. The SEM image of silver containing chitosan is shown in Fig. 19. In the spinning dope, AlphaSan RC5000 particles contained in silver is blended by it. This image indicates that the inside the fiber the particles enclosing RC5000 were found to be in consistently scattered in which it acts as the reservoir for the sustained release of silver ions [83].

Alginate Fiber

The reaction of alginic acid and sodium hydroxide (NaOH) is neutralized to yield seaweed by a biodegradable fiber, Alginate. Marine brown algae (ascophyllum, durvillaea, ecklonia, laminaria, lessonia, macrocystis, sargassum and turbinaria) are the

Table 4 Physical properties of blend fibers of cellulose/silk fibroin and cellulose/chitin/silk fibroin (Reproduced from [81] with kind permission of Elsevier Publications)

Cellulose (%)	Silk fibroin (%)	Chitin (%)	Tenacity (g.denier^{-1})	Elongation (%)
47	53	0	0.15	0.8
69	31	0	0.63	30.7
90	10	0	1.08	35.0
94	6	0	1.15	29.7
98	2	0	1.20	33.8
80	11	9	0.93	25.0
41	43	16	0.70	20.6
11	12	77	0.85	28.6
0	0	100	1.11	13.4

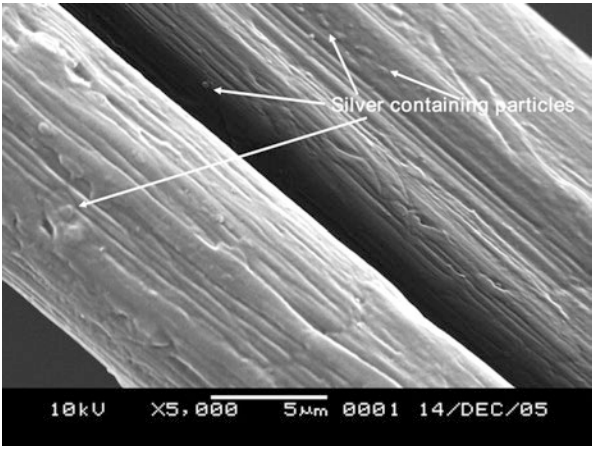
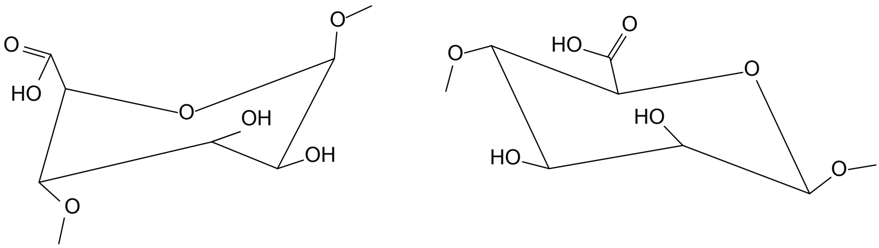


Fig. 19 SEM Photomicrograph of the silver containing chitosan fiber. (Reproduced from [83], with the kind permission of Wiley Publications)

raw materials of alginate fiber. Huge quantity of water is hold by the alginate fibers due to its excellent gel forming property. In general, medical textiles precisely in wound healing products, gels, foams and absorbing nonwoven materials use the alginate fibers. Natural alginate is converted into water soluble sodium alginate by treating it with NaOH after extracting alginate from raw seaweeds for the production of fibers. It is then treated with calcium chloride to get precipitate after numerous filtrations. Powder is made by drying and crushing the precepted alginate and dissolved in water and fed in the wet spinning. Spinneret forces the dope solution into the spinning bath of calcium chloride acting as a coagulant. Spinning bath precipitates the fibers and then to the first set of rollers [84]. Chemically the alginate fibers are polymeric acids which is composed by two monomers is called L-guluronic acid (G) and D-mannuronic acid (M). The chemical structure of both the polymeric acid is described in Fig. 20.



L-guluronicacid(G)

ß-D- mannuronic acid (M)

Fig. 20 Chemical structure of two polymeric acids (monomer) of alginate fiber

The combinations of these polymeric acid fibers have the unique properties, if alginate fibers having high G content (extracted from seaweed) makes calcium binding ability strong, resulting less absorbance than the M content alginate fibers. Meanwhile, high M content *(extracted from the leaf fronds of the seaweed)* fibers can easily modify the calcium ions by sodium ions, resulting the better absorbency and swelling properties.

Production of Alginate and Chitosan Blend

By using multifunctional extruder with conventional wet spinning technique, Knill et al. [85] attempted to yield alginate/chitosan filament. Figure 21 shows the detailed description of fiber production. Spinneret extrudes spinning dope solution of different viscosity under pressure into a bath containing either hydrochloric acid and/or calcium chloride to afford the conforming alginic acid and/or calcium alginate filament. In the between of first and second set of rollers, the resultant filaments were drawn which is then passes through a water washing bath. In order to remove excess liquid, the filaments are placed between rollers to get squeezed, wound up, removed from the extruder and placed in a treatment bath which comprising of unhydrolyzed and/or hydrolyzed chitosan (AcOH) for 10 min, soaked with deionized water and dried using acetone baths of growing concentrations (50–100% v/v). After manufacturing of initial filament, as an uninterrupted process Chitosan treatment, water washing, and acetone drying can also be performed directly. At last, separation of filament is done by hand and conditioned (24 h at ambient temperature).

In Fig. 22, it is shown that the SEM images of fibers of alginate/chitosan regarding the stimulus of three various chitosan's molecular weights (low, medium, and high) and three adjustable retention times, respectively. A heavily rugged figure displays the fibers comprising low and medium molecular weight chitosan revealed from the image contrarily chitosan with high molecular weight shows smooth and less rugged surface morphology. The formation of structure of polyelectrolytes varies with respect to their concentration and molecular weight. It is shown that chains reallocate to a PEC conformation nearer to stability (Table 5).

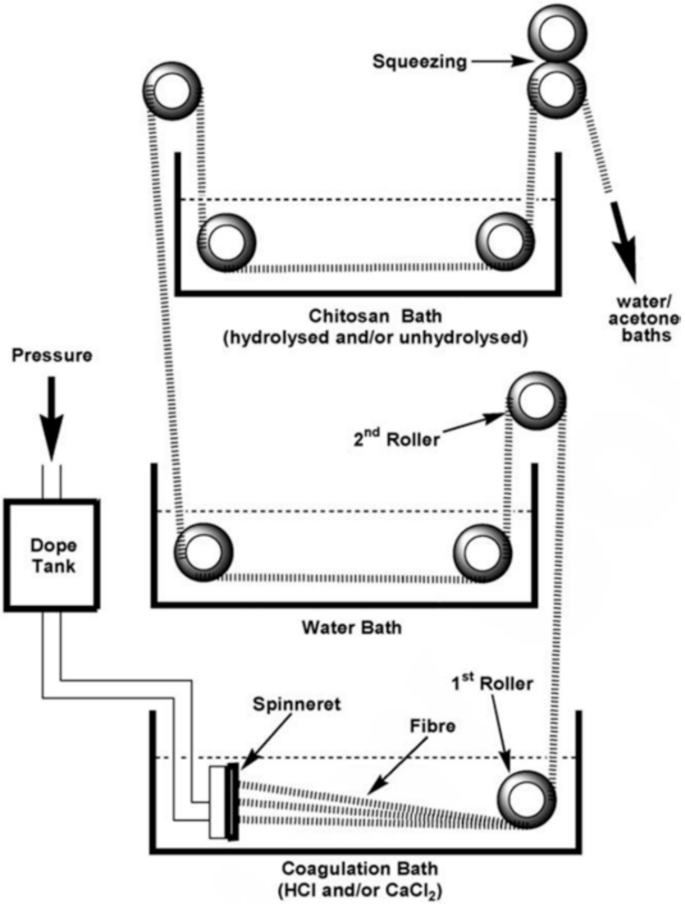


Fig. 21 Wet-spinning of chitosan/alginate blend fibers. (Reproduced from [85] with kind permission of Elsevier Publications)

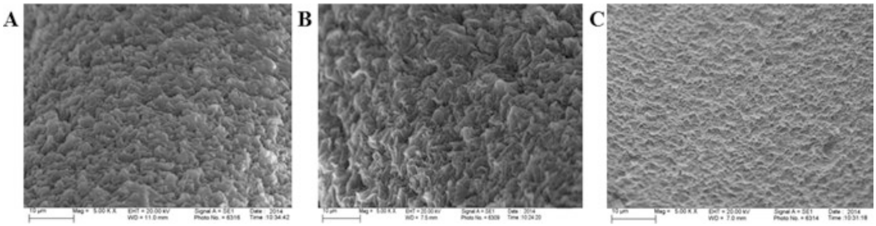


Fig. 22 Scanning electron micrographs of alginate-chitosan fibers prepared using low (**a**), medium (**b**), and high (**c**) molecular weight chitosan. (Reproduced from [86] with kind permission of Elsevier Publications)

Table 5 Some physical properties of chitosan/alginate fibers (Reproduced from [85] with kind permission of Elsevier Publications)

Dope (% w/w)	Draw ratio	Concentration	Moisture (% w/w)	Elongation (%)	Tenacity (cN. tex^{-1})
Sodium alginate	1.18	6%	11.9	20.5	2.5
Alginate + unhydrolyzed chitosan	1.18	6%	11.7	29.3	2.7
Alginate + unhydrolyzed chitosan	1.18	6%	10.7	19.2	1.5
Sodium alginate	1.18	4%	11.9	10.1	1.4

Conclusion and Recommendations Going Forward

This chapter discuss various sustainability in regenerated fibers from production to uses. Due to many advantages and potential applications, the regenerated fibers are alternatives (i.e., some extent) to the synthetic and natural fibers. In the point of sustainability with respect to all these regenerated fibers, still there are some issues associated. For example, a tiny quantity of NMMO is discharged in the wastewater which is really harm to the aquatic life. Regarding, all regenerated fibers were produced from the wood pulp with managed forest; however, there is no data related to number of trees utilized to produce the fibers as well as the number of trees planted in these days. For the future design for the production of fibers, we must keep in mind followings:

- Goods manufactured by sustainable design should possess eco-friendly without harming nature. Meanwhile, it should also satisfy the properties of fashionable products also maintaining the aesthetic beauty.
- The output should possess the featured qualities like multitasking, improvised in benefits rather than custom product manufactured. It should satisfy the necessities all time favorable rather than the trendy fashion which fades as time passes.
- This contextual explains that the products of sustainable design should be formulated to minimize the utilization of natural resources and less effect to the environment during the process of manufacturing and consumption.

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Use of Roselle (*Hibiscus sabdariffa*) in Composite Materials for Sustainability

Munir Taşdemir, Çiğdem Gül, and Emine Dilara Kocak

Abstract There is a growing research interest in bio-based products due to the rapid consumption of natural sources and synthetic production activities that are responsible for environmental pollution. The Food and Agriculture Organization (FAO) of United Nations, or the Common Fund for Commodities (CFC), for leaving a clean environment for future generations and disposing of harmful chemicals has foreseen the use of herbal-based materials; thus, legislation on the use of natural materials and wastes has been adopted by governments in this context.

Nowadays, plant-based materials are generally used to produce light composites. In this study, roselle (*Hibiscus sabdariffa*) fiber was employed to reduce carbon footprint and increase sustainable production. For this purpose, *Hibiscus sabdariffa* fibers which are shorter than 10 mm dissolved in 20% NaOH solution in which microfibrils are obtained. Thereafter, microfibrils are mixed with polypropylene to produce composite material. Polypropylene is the lightest polymer known to have a density of 0.90 g/cm^3. The most important feature of polypropylene is its high friction resistance. This material is often mixed with herbal-based materials. The main aim of this study is to increase the mechanical properties of the proposed material as well as the cost-effective production. Mechanical (tensile, compression, hardness, notch impact) and non-flammable properties of composite structures were measured. We observed that there is a strong correlation between the number of waste materials and an increase in mechanical properties.

Keywords Sustainability · *Hibiscus sabdariffa* · Polypropylene · Composite · Natural fibers · Carbon footprint

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Introduction

Environmental issues are very critical importance for the future of humanity and they are currently being addressed by many scientists. Synthetic production activities increase environmental problems. Material science had to follow a sustainable path since the end of the twentieth century due to increasing environmental concerns. Approaches to producing sustainable, renewable, environmentally friendly materials are called "green materials, green chemistry." Green chemistry is the design of chemical products and processes that reduce or eliminate the use or production of hazardous substances [1]. Plant-based natural fibers used in the production of green materials are widely used in all industries, especially in the production of green composites. Petroleum is a fossil fuel that is estimated to last only 50–60 years at the current consumption rate [2].

Increasing awareness of the limitation of greenhouse gas emissions caused by gases such as CO_2 in the atmosphere and the fact that fossil energy resources are finite leads to the development of new materials based entirely on renewable resources. A goods' carbon footprint is the sum amount of greenhouse gases that is expressed in kilograms of CO_2 equivalents, it spreads during its life cycle [3] and total annual greenhouse gas emissions, arrived 53.5 Gt CO_2 in 2017 [4]. The increase in CO_2 in the atmosphere causes various environmental problems, especially the world's climatic changes. Besides, excessive use of petroleum-based polymers leads to a significant reduction in storage capacity. Therefore, raising awareness on the elimination of non-degradable solid wastes has increased efforts to develop fully degradable materials in nature.

The increasing concern toward the prevention of ecocide and the need for eco-friendly materials have caused growing attention about polymer composites from sustainable natural sources and biodegradable plant materials [5]. Figure 1 shows the life cycle of sustainable textile materials.

For this chapter's purpose, the studies carried out to improve the plant-based in composite materials. This review focuses on plant fiber-based green composites. General research on plant fiber composites was done by some researchers. Different fibers, especially bast fibers and its composites, were investigated previously. In this study, an attempt has been made to point out the plant fiber-based bio-composites. The mechanical properties of composites were also investigated.

Composites are multifunctional materials that are created by a combination of suitable properties of two or more materials in a single material or by combining them at a macro level to create new features [7]. They are favored in lots of engineering applications such as automotive, building, biomedical, and aerospace. Glass, carbon, and aramid fibers are generally used as reinforcement material due to their high strength and modulus. Although glass fibers are greatly used in reinforcing plastics due to good mechanical properties and low cost, they are not recyclable and they cause health risks when inhaled [8]. Table 1 shows the mechanical properties of E-glass, carbon, and aramid fibers.

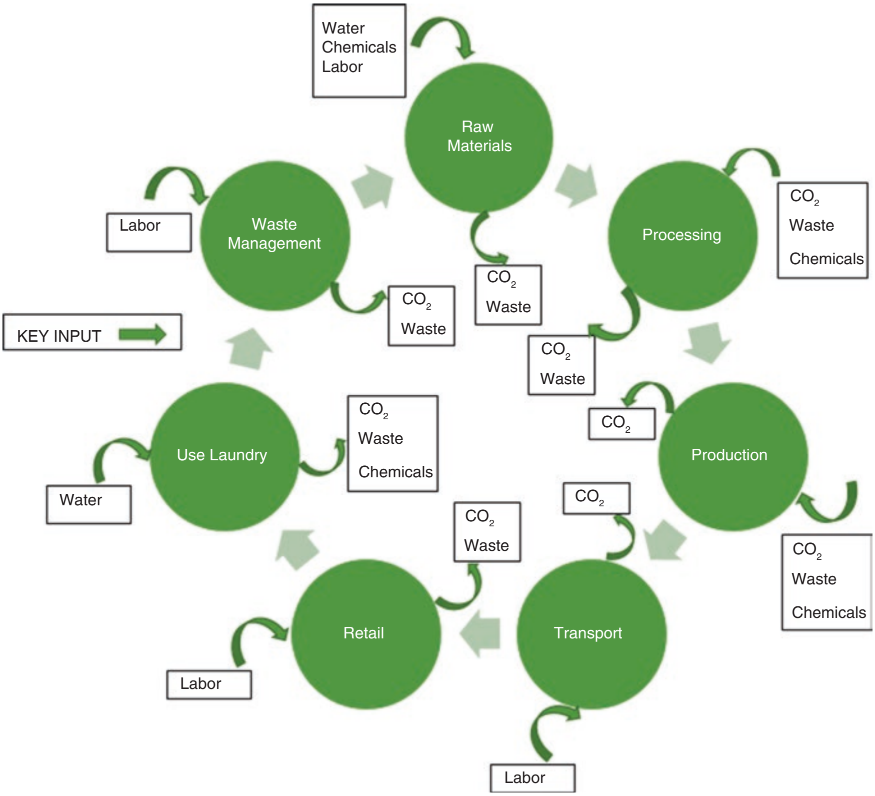


Fig. 1 Phases of the textile product life cycle and outputs [6]

Table 1 Mechanical properties of E-glass fiber, carbon fiber, aramid fiber

Fiber	Density (g/cm^3)	Tensile strength (MPa)	Young's modulus (GPa)	Reference
E-glass	2.58	2.000	80	[9]
Carbon	1.85	2.900	525	[9]
Aramid	1.44	3.600	131	[10]

Natural fibers have been used in various applications throughout man's history. There has been an exciting increase in the use of natural fibers to produce a new kind of eco-friendly composite recently. Natural fiber-reinforced composites are composed of two components that are reinforcement and matrix. Figure 2 shows that natural fibers are mainly divided into three groups as animal fibers, plant fibers, and mineral fibers.

There is a wide range of plant fibers that use as reinforcement materials in composites. Natural fibers can be preferred alternatives to synthetic fiber reinforced composites due to low cost, low-density, renewable, eco-friendly, non-toxic, and good-specific mechanical properties [13, 14]. Two kinds of natural fibers are

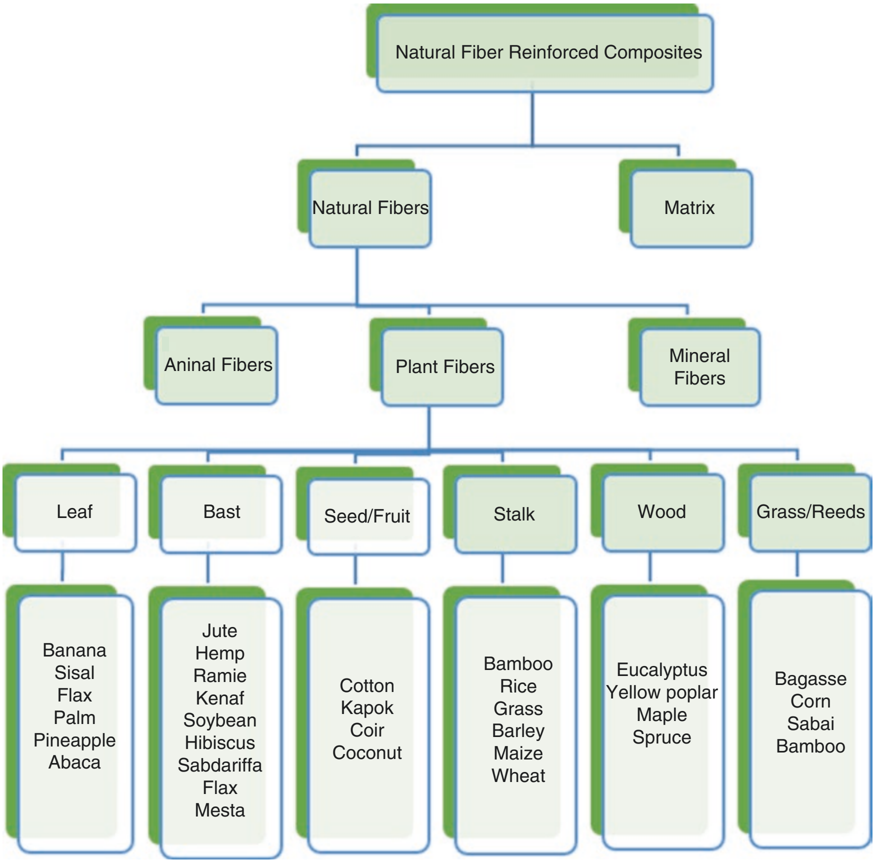


Fig. 2 Plant fibers types [11, 12]

Table 2 Chemical composition of various plant-based bast fibers

Group	Fiber type	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Reference
Bast	H. sabdariffa	58–64	20	6	[17]
	Banana	59.3–60.6	10.2–12.4	17.5–18.9	[18]
	Flax	75.2	4.8	8.6	[19]
	Hemp	75.1	8	2	[19]
	Jute	45–71.5	13.6–21	13–26	[17]

described for the production of fiber-reinforced polymers; these are plant-based fibers and animal-based fibers. As plant-based fibers are abundant in the natural environment, prices are relatively lower than synthetic fibers [15]. Plant-based natural fibers consist of cellulose, hemicellulose, lignin, pectin, and other waxy substances [16]. Tables 2 and 3 show the chemical compositions and physical properties of various plant-based natural fibers (Table 4).

Table 3 Physical properties of some natural fibers

Fiber type	Density (g/cm^3)	Diameter (μm)	Reference
Hibiscus sabdariffa	1.38	40–90	[20]
Banana	1.48	17–23	[21]
Flax	1–1.5	80–250	[22]
Hemp	1.5	17.8–21.6	[23, 24]
Jute	1.3–1.5	15.9–20.7	[24]

Table 4 Mechanical properties of some natural fibers

Fiber type	Young’s modulus (GPA)	Tensile strength (MPa)	Elongation (%)	Reference
Flax	27–80	345–1830	1.2–3.2	[24]
Jute	11–32	400–800	1.8	[25, 26]
Hemp	30–60	350–800	1.6–4.0	[26]
Banana	20	529–914	4.5–6.5	[27]
H. sabdariffa	17	147–184	5–8	[28, 29]

Hibiscus sabdariffa fiber is one of the natural bast fibers used as a reinforcement material in composites for lightweight structures [30, 31]. This plant is affiliated with the Malvaceae family that has more than 300 species in the world [32]. There are two most known species: *Hibiscus sabdariffa* and *Hibiscus cannabinus*. *Hibiscus sabdariffa* is widely cultivated in Tanzania, Indonesia, Sri Lanka, Malaysia, Borneo, Africa, Sudan, Egypt, the Philippines, Brazil, Australia, Mexico, and Hawaii and Florida of the USA [33, 34]. It is an annual plant that can grow up more than 2 m [35]. *Hibiscus sabdariffa* has a dark green to red cylindrical stems. Its leaves are between 7.5 and 12.5 cm long and they are green with reddish veins size [36, 37]. *Hibiscus sabdariffa* has two essential types: *Hibiscus sabdariffa* whose flowers are yellow and its calyces are red or green. Fresh *Hibiscus sabdariffa* calyces contain fiber (2.3 g/100 g), β-carotene (300 mg/100 g), calcium (1.72 mg/100 g), iron (57 mg/100 g), phosphorus (36.30 mg/100 g), and ascorbic acid (14 mg/100 g) [38], whereas dried *Hibiscus sabdariffa* calyces contain great amount of ascorbic acid among 360–280 mg/100 g [39]. Dried *Hibiscus sabdariffa* calyxes are shown in Fig. 3a, b.

Nowadays, many researchers are interested in *Hibiscus sabdariffa* fibers as reinforcement materials in composites. Kenaf and jute fibers have been extensively used especially in the fabrication of automotive parts. Due to similar physical and chemical properties, *Hibiscus sabdariffa* fibers can be used for the same purpose [36]. The density of *Hibiscus sabdariffa* fiber is 1.38 g/cm^3 and fiber diameter ranges from 40 μm to 90 μm; these values depend on the age of the plant. The low density of the natural fibers owes to exist of a lumen (hollow structure) in the fibers. The low density of the fiber is an advantage for natural fibers that enable the production of lighter composites [20, 40]. SEM images show the variation of the hollow lumen layer of *Hibiscus sabdariffa* fibers according to plant age (see Fig. 4) [16].

Fig. 3 (**a**) *Hibiscus sabdariffa* calyxes. (**b**) *Hibiscus sabdariffa* power

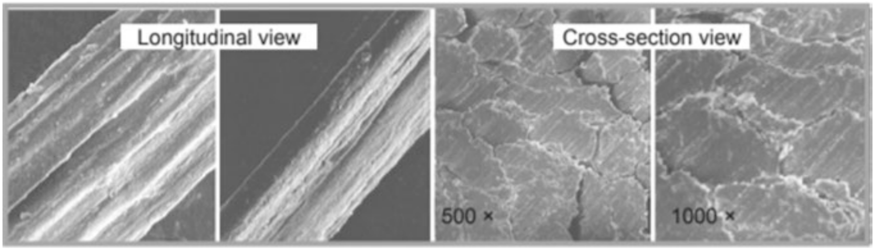


Fig. 4 Surface and cross section morphology of Kenyan *Hibiscus sabdariffa* fiber [41]

Scanning Electron Microscopy (SEM) of Hibiscus sabdariffa

SEM is used to define and analyze impurities on the surface of the fibers. The surface morphology of the crack examples was examined with SEM. Figure 4 shows the cross section of the lumen layer of *Hibiscus sabdariffa* fibers.

Mwasiagi et al. examined the surface of the *Hibiscus sabdariffa* fiber. It can be seen that cross sectional and longitudinal view of *Hibiscus sabdariffa* fiber in Figure 4. The lengthwise view showed several split-like lines throughout the fiber, which could be an indicator of fiber groups being kept together by an adhesive material.

FT-IR Characterization of Hibiscus sabdariffa

Fourier transform infrared spectroscopy (FT-IR) is a physicochemical analytical technique and molecular bond characterization is done by the FT-IR technique. The functional groups in the structure of organic compounds are determined in terms of their type, state, bonding sites.

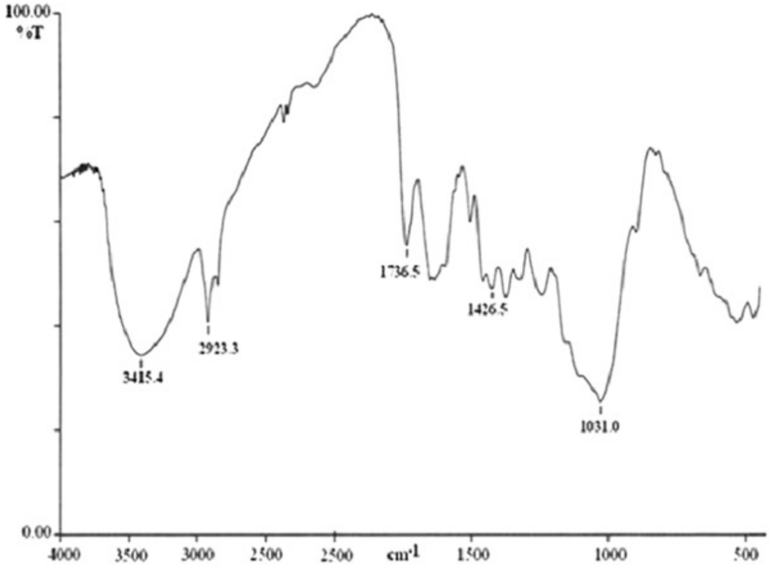


Fig. 5 FT-IR spectra of *Hibiscus sabdariffa* raw material in the range of 500–4000 cm [42]

The FT-IR spectrum of the untreated *Hibiscus sabdariffa* fibers in Fig. 5 shows a wide peak at 3415.4 cm^{-1} due to bonded OH groups and at 2923.3, 1426.5, and 1031.0 cm^{-1} due to –CH_2, C-C, and C-O extension, respectively.

TGA/DTG/ DTA of Hibiscus sabdariffa

Thermal analysis of polymers typically involves a combination of various techniques, including well-established thermogravimetric analysis (TGA), differential thermal analysis (DTA), differential scanning calorimetry (DSC). Thermal analysis of polymers includes a composition of various techniques such as thermogravimetric analysis (TGA), differential thermal analysis (DTA) and differential thermo gravimetric analysis (DTG). The TGA determines the frequency and amount of weight change of samples against temperature and time [43]. These methods provide a certain knowledge of thermal stability. It is very important to verify that the fibers used in the composites are resistant to the temperature applied in the production of the material. Figure 6 points out the curves for differential weight loss for *Hibiscus sabdariffa* fibers as the temperature increases. It shows that hemicellulose starts to decompose in the range of 225–350 °C, cellulose starts to decompose at 350 °C, and finally lignin started to decompose at 375–400 °C.

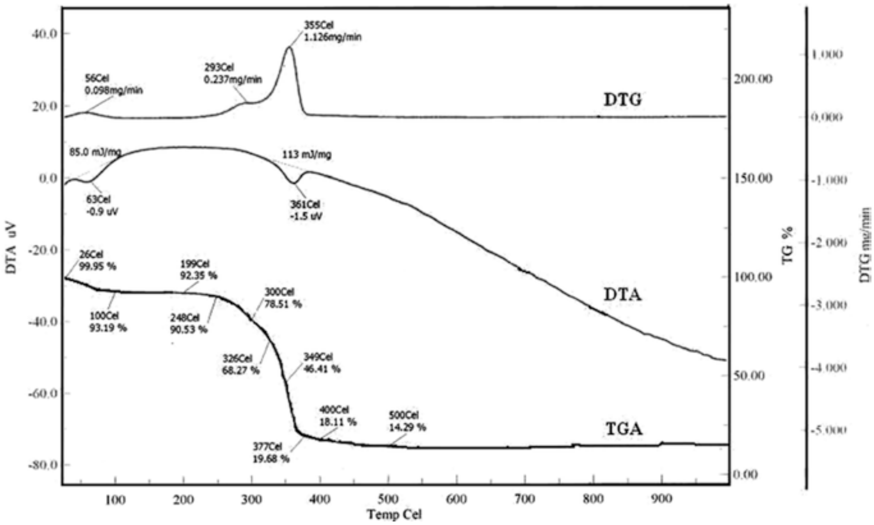


Fig. 6 TGA/DTA/DTG analysis of raw *Hibiscus sabdariffa* fiber [44]

Table 5 Polymers used as the matrix for composites

Thermoplastic polymers	Thermoset polymers
Polypropylene (PP)	Polyurethane
Polyethylene (PE)	Polyester
Acrylonitrile-butadiene-styrene (ABS)	Phenolics (PH)
Polyvinyl chloride (PVC)	Epoxies (E)
Polybutylene terephthalate (PBT)	Bismaleimides (BMI)
Polyetheretherketone (PEEK)	Cyanate esters (CE)
Polyetherketoneketone (PEKK)	Polyimides (PI)
Polyphenylene sulfide (PPS)	
Polyetherimide (PEI)	
Nylon	
Cellulose acetate	

Natural Fiber Reinforcement Composites

Natural fiber-reinforced composites could be cheaper, tougher, and environmentally friendly. The polymer matrix used in the composites is divided into two types as thermoplastic and thermoset according to the bonding type. Thermoplastic polymers are which can be molded, melted and again remote without changing their physical properties. Thermosets are hard and three-dimensional cross-linked plastics due to the irreversible curing reaction. Thermoset composite components are used in a wide range of applications in sectors such as automotive, aerospace, and constructions [45]. The classification of the polymers used as the matrix in the composites is shown in Table 5.

Recently, matrices used with natural fibers are polypropylene (PP), polyethylene and poly(vinyl chloride) [46]. Polypropylene (PP) is a thermoplastic material produced as a long polymer or chain by polymerizing propylene monomers. Figure 7 shows that the general formula of polypropylene.

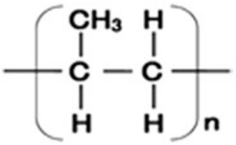
Because of the asymmetric form of propylene, the characterization of polypropylene is a rigid situation. This is a cause of structural isomers and stereochemical isomers in the polypropylene chain. Structure isomerism scientists describe the olefin carbon with the methyl group as the "head" of the monomer and the other olefin carbon as the "tail" of the monomer [47]. Most commercial PP (90–95%) is isotactic PP (iPP) produced by the Ziegler–Natta catalyst via head-to-tail participation of propylene monomer [48].

The stereochemical isomerism present in the polypropylene indicates the positioning of propylene monomers in the chain. When all of the methyl groups are arranged in one side of the chain, it is referred to as the "isotactic" configuration, and if they are on both sides of the chain it is referred to as the "syndiotactic" configuration, a random configuration of methyl groups are known as "atactic" polypropylene [47]. Figure 8 shows three basic structures for polypropylene: (a) isotactic, (b) syndiotactic, and (c) atactic.

Polypropylene polymer is a lightweight polymer (density of 0.90 g/cm^3). It has perfect chemical resistance, good mechanical properties, and cost-efficient; thus, polypropylene is preferred for various industrial applications [49]. Mechanical properties of polypropylene can be alternated depending on the application area. The mechanical properties of polypropylene can be improved by using different fillers and reinforcements. Natural fillers and reinforcements are generally polar but polypropylene is nonpolar. Therefore, one of the consequences of poor adhesion between the fill surface and the polymer matrix is the poor mechanical properties of the composites. To overcome the above-mentioned problem, maleated polypropylene can use in fiber-reinforced polypropylene [50]. The maleic anhydride groups of maleated polypropylene (MAPP) and hydroxyl groups of cellulose molecules link to each other with ester bond; thus, the mechanical properties of the composite material are improved. Figure 9 shows the bond structure formed between the surface of the lignocellulose fiber and the maleated polypropylene (MAPP).

Production of natural fiber-reinforced composites has always been a challenge due to their low stability during processing. Conventional manufacturing methods such as compression molding, injection molding, and vacuum infusion are used for the production of natural fiber reinforced composites [51]. Injection molding is one of the most important manufacturing processes for polymeric products.

It is observed from the literature survey that natural fibers were used as reinforcement materials in composite structures and following studies can be shown as



$$\left(-\overset{\displaystyle CH_3}{\underset{\displaystyle H}{\overset{|}{\underset{|}{C}}}} - \overset{\displaystyle H}{\underset{\displaystyle H}{\overset{|}{\underset{|}{C}}}} - \right)_n$$

Fig. 7 General formula of polypropylene

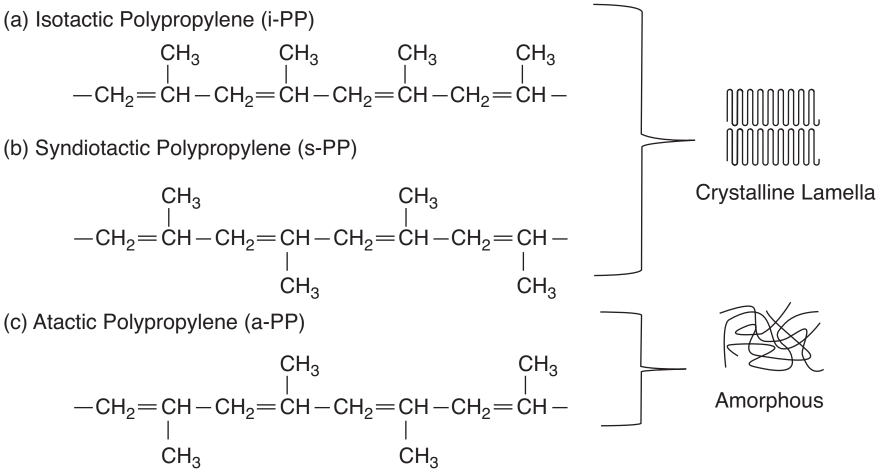


Fig. 8 The three basic structures for polypropylene (**a**) isotactic, (**b**) syndiotactic, and (**c**) atactic

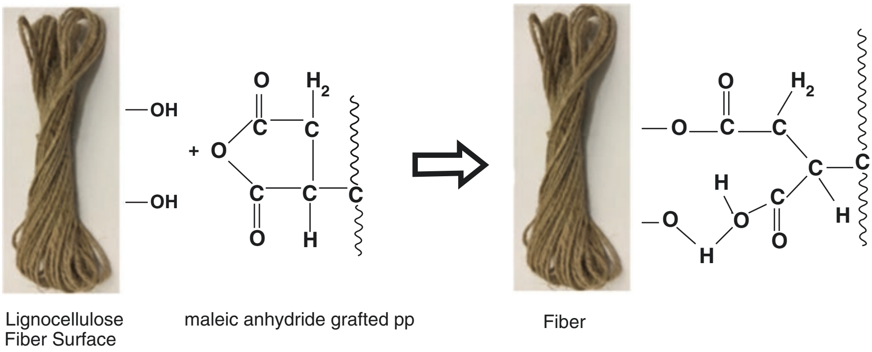


Fig. 9 Schematic description of the maleic anhydride with the lignocellulose fiber surface

examples for this purpose: natural fibers (sisal, kenaf, hemp, jute, and coir)/PP [52], *Hibiscus cannabinus*/PP [53], *Hibiscus cannabinus*/HDPE and HDPP [54], *Hibiscus cannabinus*/PP [55], oil palm EFB/*Hibiscus cannabinus*/PP [56], *Hibiscus sabdariffa*/iPP [57], *Hibiscus sabdariffa*/acrylic resin [58], *Hibiscus cannabinus*/PP [59], ramie/MAPP [60], hemp/PP [61], sisal/ PP [62], bagasse/PP [63], sabai/ PP [64], kapok husk/iPP [65], spruce fibers/PP [66], pineapple/PP [67], abaca/PP [68], palm/ PP [69], banana/PP [70], coconut/PP [71], bamboo/PP [72], and eucalyptus/PP [73].

In this study, it was aimed to obtain lightweight, environmentally friendly composite materials by using natural plants as reinforcing elements. *Hibiscus sabdariffa* was selected as the natural plant. *Hibiscus sabdariffa*/PP/MAPP composites with different loading of 10, 20 and 30 wt% were prepared via the injection molding method. Mechanical properties of the *Hibiscus sabdariffa*/PP/MAPP were evaluated. This study purposes to increase *Hibiscus sabdariffa* loading in the PP matrix to enhance the mechanical properties of *Hibiscus sabdariffa*/PP composites. Up to now, most of the works have done on the *Hibiscus sabdariffa*/PP composites with different techniques but the studies related to injection molding technique are limited. Finally, tests were performed to determine composite mechanical properties and results were evaluated.

Materials and Methods

Blends Preparation

Dried *Hibiscus sabdariffa* calyxes were bought from herbalist market in İstanbul. *Hibiscus sabdariffa* calyxes are ground in the mill. The size of the *Hibiscus sabdariffa* particles was observed to be 400 μm. Polypropylene supplied from Slovnaft Tatren IM 1579 Impact Copolymer (Bratislava, Slovakia), Maleic anhydride polypropylene (MAPP) is produced by grafting MA to PP (Bondyram 1001 CN, Polygram Group, Ramon, Israel).

Production Techniques

Extruder

Rotary screw extruder machines push the polymer material through the feed groove into the melting sleeve. This is done by controlling the correct melting temperatures for the polymers.

Twin-screw extruder makes production in the pressure of 20 Bar and 193 rpm at a temperature of 85–190 °C.

Injection Molding

The injection molding method was used to produce PP and *Hibiscus sabdariffa* composites. Two types of samples (PP and *Hibiscus sabdariffa*/PP composites) were shaped via Arbung injection molding. Different weight percentages, 10, 20 and 30 wt% combinations of *Hibiscus sabdariffa*/PP/MAPP composites were used. MAPP weight percentage is fixed 10 wt% for all combinations (Tables 6 and 7).

Table 6 Blends ratio

Groups	PP + MAPP	*Hibiscus sabdariffa*
1	100%	–
2	80% + 10%	10%
3	70% + 10%	20%
4	60% + 10%	30%

Table 7 Molding conditions in injection molding

Parameter	Value
Injection temperature	210–230 °C
Injection pressure	40 Bar
Time (in molding)	10

Mechanical Characterizations

The mechanical characterizations of pure PP and *Hibiscus sabdariffa*/PP composites were defined using a Zwick universal tensile tester. Tensile strength tests were performed with Zwick impact tester in accordance with ISO 527-2. Impact tests were performed with Zwick impact tester in accordance with ISO 180, TS 1005, ASTM 2782 Standards. Melt Flow Index (MFI) tests were performed according to ASTM D 1238 standard on Zwick 4100 test device.

Result and Discussions

Mechanical Properties

In this study, mechanical properties (e.g., tensile strength, elongations, elasticity modulus, Izod impact, hardness, and MFI) are measured. It is observed that mechanical properties are increased with increasing fiber content in the polymers.

Tensile Properties

The effect of the mixture ratio on tensile strength was investigated. Figure 10 shows the tensile strength of PP/*Hibiscus sabdariffa* composites. The highest tensile strength value is observed in the composite containing 20% by weight of *Hibiscus sabdariffa* plant particles, while the increase in fiber content appears to lead to a decrease in the strength value. Khoathane et al. reported that increasing the amount

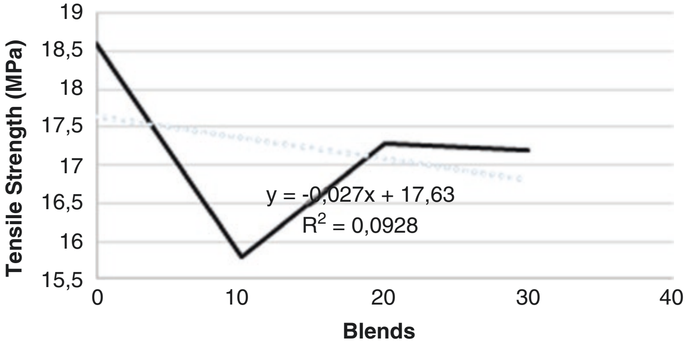


Fig. 10 Tensile strength (MPa) value of *Hibiscus sabdariffa*/PP

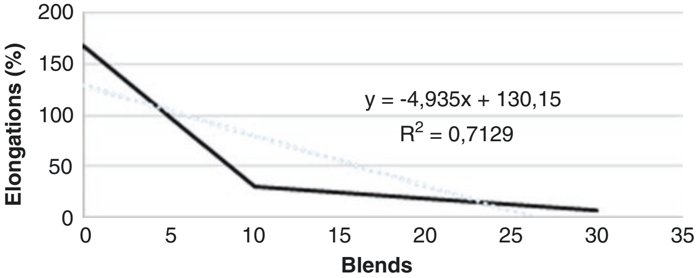


Fig. 11 Elongation (%) value of *Hibiscus sabdariffa*/PP

of lignocellulosic fiber in composite resulted in an increase in tensile strength [11, 74]. The study in the literature is in line with our study.

Figure 11 shows the percent elongation value of PP/*Hibiscus sabdariffa* composites. The highest elongation value was observed in the composite containing 10 wt% *Hibiscus sabdariffa* plant particles, while the increase in fiber content appears to reduce elongation. In principle, the elongation decreases when the hardness of a material is increased via join reinforcing fibers. Cordin et al. reported that increasing the amount of lignocellulosic fiber in composite resulted in a decrease in elongation [75]. The information in the literature supports the results obtained in our study.

Figure 12 shows the elasticity modulus value of PP/*Hibiscus sabdariffa* composites. The highest elasticity modulus was observed in the composite containing 30% by weight of *Hibiscus sabdariffa* plant particles whereas the elasticity modulus increases with increasing fiber content. Pupure et al. reported that the composites have good elasticity modulus [76]. The information in the literature supports the results obtained in our study.

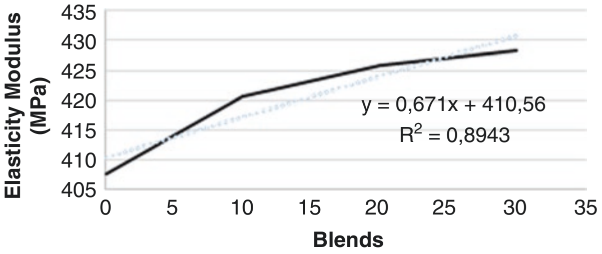


Fig. 12 Elasticity modulus (MPa) value of *Hibiscus sabdariffa*/PP

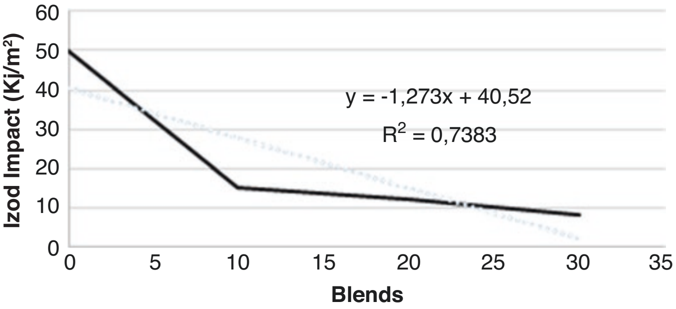


Fig. 13 Izod impact (Kj/m^2) value of *Hibiscus sabdariffa*/PP

Figure 13 shows the Izod impact value of PP/*Hibiscus sabdariffa* composites. The highest Izod impact value was observed in the composite containing 10 wt% *Hibiscus sabdariffa* plant particles, while the increase in fiber content appears to decrease Izod impact. Nourbakhsh et al. examined the effect of fiber content on poplar fiber PP composites containing 2% MAPP. As fiber content increased in composite, Izod impact value decreased due to poor interfacial adhesion [77]. The information in the literature supports the results obtained in our study.

Figure 14 shows the hardness value of PP/*Hibiscus sabdariffa* composites. The highest hardness was observed in the composite containing 30% by weight of *Hibiscus sabdariffa* plant particles while the increased hardness as fiber content increases. Gupta et al. reported that average hardness values increased with an increase in fiber loading [78]. The information in the literature supports the results obtained in our study.

Figure 15 shows the melt flow index value of PP/*Hibiscus sabdariffa* composites. The highest melt flow index was observed in the composite containing 30% by weight of *Hibiscus sabdariffa* plant particles while the increase melts flow index as fiber content increases. Ramli et al. reported that the MFI of the composites increased with increasing binding agent content. Composites via MAPP provide minimum fiber debonding [79].

The information in the literature supports the results obtained in our study. Average hardness values increased with an increase in fiber loading.

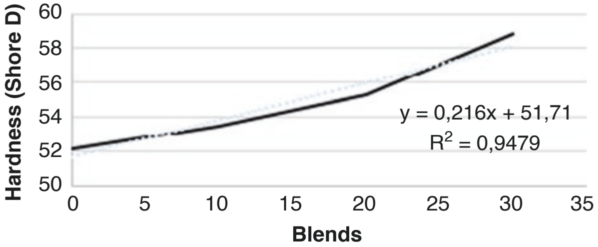


Fig. 14 Hardness (shore D) value of *Hibiscus sabdariffa*/PP

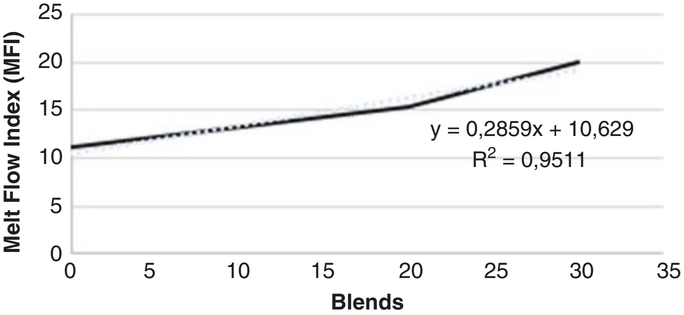


Fig. 15 Melt flow index value of *Hibiscus sabdariffa*/PP

Conclusion

Mechanical properties such as tensile strength, elasticity modulus, hardness, and melt flow index of *Hibiscus sabdariffa* reinforced polymer composites have been investigated. *Hibiscus sabdariffa*/PP composites with different fiber loadings of 10, 20, and 30 wt% were prepared in an injection molding machine. The effects of MAPP on *Hibiscus sabdariffa*/PP composites were investigated in terms of mechanical properties. The tensile strength and elasticity modulus improved with increasing *Hibiscus sabdariffa* contents. The elongation decreases with an increase in fiber content. As fiber content increased in composite, Izod impact value decreased. MFI of the composites increased with increasing binding agent content. The sum of this research are as follows:

1. In recent years there has been an increase in the use of natural plants to produce sustainable environmentally friendly and biodegradable materials. In this study, we produced environmentally friendly biodegradable and lightweight materials.
2. It has been examined that composite with fiber loading increasing mechanical properties. These results propose that the *Hibiscus sabdariffa* fiber reinforcement composite can be pointed out in different fields such as automotive and aerospace.

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Recycling of Marine Litter and Ocean Plastics: A Vital Sustainable Solution for Increasing Ecology and Health Problem

Sedat Kumartasli and Ozan Avinc

Abstract Marine litter is a crucial health and environmental issue in the global sense for not only humankind but also for cetaceans, marine life, and other flying and land animals. It is known that marine litter has significant environmental, economic, health, and aesthetic effects. Marine litter is a permanent, manufactured, or processed solid material which is discarded, disposed, or abandoned from any source into marine and coastal environments. It can be composed of the wastes and particles of abandoned waste textile products, synthetic garments and their fragments, fishing nets, fishing lines, industrial product wastes and industrial plastic production wastes such as plastic bottles and plastic containers (mostly made from synthetic polymers), vehicle tire dusts, and breakdown of litter and cosmetic products. In most cases, plastics are one of the most important components of marine litter because of their very slow decay rates. It is stated that approximately 90% of the marine litter is composed of plastic material wastes and 5–13 million tonnes of plastic waste litter are released to the marine-related environment per year. The amount of plastic waste in the seas is likely to continue to increase, mainly due to the negative increase in plastic consumption (about 9% per annum) and the inadequacy of its reuse, recycling, and waste management practices. The entanglement and ingestion of marine litter directly damage wild animals and their environment. Accumulation of marine litter on the seabed, accumulation of trash, and seagrass deposits in coral reefs cause damage to the natural habitat and damage the ecosystem. Plastic entanglement and ingestion problems by the animals are the main issues with macroplastics. On the other hand, plastic ingestion and accumulation problems by the animals are the main issues with microplastics. Microplastics in marine litter can be generated through microbeads, pellets, abrasion of especially car tires, textile materials and textile products, the decay of mesoplastics and macroplastics, and so

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on. Microfibers and microfibrils, which may be generated during ordinary home laundry cycles due to the agitation and beating nature of the washing process and end up in sewage, are also a subcategory of microplastics. Ingestion of microplastic and microparticle marine litter can cause many health problems. Microplastics in the sea enter the body of living sea creatures. As a result of these marine organisms, such as fishes, being consumed by humans, these microplastics and their remnants enter the human body and cause further health problems. Plastic materials enter to the seas and oceans end up on ocean floor, sea sides, beaches, and ocean surfaces. Unfortunately, degradation of these plastic waste litters in the marine environment needs centuries. Various measures are taken to remove the plastic wastes from the seas and seashores. Coastal cleaning activities and cleaning nets taken to the coasts are some of the most commonly used methods. The most common approaches for collected marine litter can also be storage or incineration. However, these methods may not be always ideal solutions because of limited storage space and pollution risks. The most likely solution for the destruction of plastic marine litter is the plastic recycling technologies commonly used in the processing of industrial wastes. The waste plastic and plastic parts collected from the seas and seashores are separated from each other by various methods and then each type of the recovered polymer, such as polyethylene terephthalate (PET) polymer, polypropylene (PP) polymer, and polyamide (PA) polymer, can be included in the recycling processes at their relevant recycling facilities. Plastic recycling technologies can typically be classified in three ways: mechanical recycling, chemical recycling, and thermal recycling. In this chapter, marine litter and recycling of marine litter and ocean plastics are comprehensively reviewed. First of all, the information regarding marine litter sources, marine litter types, and the contribution of synthetic fibers to marine litter via laundry (washing) cycles is given. Then, the ecological and socio-economic effects of marine litter are discussed. Afterward, the precautions against marine litter and recycling of marine litter (mechanical recycling, chemical recycling, and thermal recycling) are mentioned. Finally, the recent commercial developments for marine litter recycling are covered.

Keywords Marine litter · Ocean plastics · Micro fibres · Thermal recycling · Chemical recycling · Laundry

Introduction

Marine litters (marine debris) are the wastes discharged by humans to coastal or marine environments resulting from onshore or offshore activities [1]. Most marine litters are made of plastics [2]. Today, marine litter has become a major and lasting environmental problem threatening the ocean and seas [3]. Litter that is left, discharged, or forgotten directly to coasts and marine environment, or indirectly transported through rivers, sewers, erosion, winds, and streams threatens marine life [4]. Plastic/polystyrene is the most abundant litter in coastal and marine areas [5]. Due to its low density, light weight, durability, easy processability, and low cost, plastic/polystyrene has started to be used in all areas of daily life in the twentieth century [6]. Since the 1950s, plastic/polystyrene production has enhanced by ~8.6% year-on-year to approximately 322 million tonnes per year [7]. Since that time the amount of plastic in the environment has enhanced radically [2]. Due to the increasing population and consumption needs, plastic is a cheap, durable, easily processable, lightweight, low density synthetic material that has entered all areas of daily life after the 1950s, and in 2013 the annual production of plastics on a global scale reached approximately 300 million tonnes [7]. Between 4.8 and 12.7 million tonnes of land-based plastic waste are discharged into the oceans each year [8]. Approximately 2–5% of this production ends at sea and constitutes 60–80% of marine litter [6, 9].

The serious ecological and socioeconomic effects of marine litter are known. Plastics adversely affect not only water ecosystems but also societies and economies [10, 11]. Economic activities, such as maritime, fishing, aquaculture, and tourism, are directly influenced by plastic pollution and the total negative impact on the oceans is estimated to be at least $8 billion per year.

There are different categories for the size of marine litter plastics; macroplastic (>25–50 mm), mesoplastic (5–25 mm), microplastic (100 μm–5 mm) nanoplastic (<100 μm) litters [12, 13].

Macro (>5 cm), meso (5 mm–5 cm), micro (100 μm–5 mm), even nano (<100 μm) litters according to their specific gravity of the water column and the bottom of the water can be found at the bottom of the most important hazards for the world's oceans and seas [12, 13].

In order to get rid of the damages of marine litter and prevent further growth of the problem, various institutions, organizations, and organizations established policies asked their members to comply with these policies [5]. In this context, the Marine Strategy Framework Directive (2008/56/EC), issued by the European Parliament in the field of Marine Environment Policies, requested Member States to ensure or maintain an Environmental Situation (ICA) by 2020 at the latest by the European Union (EU). Among the 11 identifiers defined for the identification of the IAE, the identifier includes 10 Marine Solid Wastes [14].

Marine litter is described as any permanent, processed, produced solid waste which is lost, released, discharged, drained, eroded, flooded, or transported to coastal and marine environment by wind or rivers by people, as a result of conscious or unconscious behavior [15]. Increasingly, waste accumulated around the sea or ocean threatens the lives of marine organisms [6]. Today, it is estimated that 6.4 million tonnes of marine litter enter our oceans and seas every year and approximately 8 million items of marine litter enter the oceans and seas every day. According to the calculations, 13,000 pieces of plastic/polystyrene trashes are estimated to float on every square kilometer of the ocean surface [4].

According to the calculations, 10% of the annual plastic/polystyrene production ends in the seas and constitutes 60–80% of the marine litter and 50–80% of the beach litter [6, 15]. According to research conducted worldwide, the most common materials we encounter as marine litter are as follows:

- Cigarette butts
- Covers
- Plastic/polystyrene beverage bottles
- Plastic/polystyrene bags
- Food packages/product packaging
- Cups, spoons, forks, knives, and plates
- Glass bottles
- Pipette and mixer
- Beverage cans
- Paper bags
- Synthetic fibers

Sources of Marine Litter

Marine litter is a permanent, manufactured, or processed solid material which is discarded, disposed, or abandoned from any source into marine and coastal environments. It is accepted that marine litter is of land origin or marine origin considering the ways of reaching the sea (Table 1) [15]. Marine litter can be composed of the wastes and particles of abandoned waste textile products, synthetic garments and their fragments, fishing nets, fishing lines, industrial product wastes, and industrial plastic production wastes, such as plastic bottles and plastic containers (mostly made from synthetic polymers), vehicle tire dusts, and breakdown of litter and cosmetic products. Humans and human activities are the source of many marine litters, intentionally or accidentally. Marine litter originates from two sources on land (land-based resources) and marine environment (marine-based resources). Marine origin wastes, sources of commercial shipping, ferry, passenger, tourist activities, wastes thrown from research vessels, wastes formed, leaving the damaged goods to the sea, the loss of nets used in fishing activities at sea, abandoned worn-out hunting materials used in the package after hunting, such as sack, case, and foam box, waste

Table 1 Marine litter resources [15]

Land-based marine litter resources	Marine origin marine litter resources
Urban discharge	Merchant ships, ferries, and passenger ships
Garbage and waste transport (by water or land)	Fishing vessels
Industry and production	State ships
Waste and garbage from wrong waste management	Personal ships
Natural events	Drilling platform
Rainwater discharge	Natural events

left to the sea. Again, oil and gas platforms and aquaculture activities may be other factors that constitute marine wastes [16].

Therefore, most marine or ocean-based marine litter resources come from commercial ships, ferries, passenger ships, fishing vessels, military fleets and research vessels, pleasure craft, offshore oil and gas platforms, boreholes, and aquaculture facilities. Land-based marine litter sources originate from coastal and inland sources, including coasts, piers, harbors, marinas, docks, and rivers. Distribution and storage of marine litter are highly influenced by regional topography, including ocean currents, tidal cycles, wind, and seabed topography [17].

Environmental threats of marine litter, attachment, and consumption are the main forms of direct damage caused by marine litter for natural life, while other threats include drowning at the seabed and degradation along with mechanical wear. Parts of marine litter can also carry invasive species across the oceans. Furthermore, marine litter can damage fishing vessels and nets, power plants, and seawater treatment plants. Pollution of coasts (requiring cleaning and removal, closure of beaches due to public health) and pollution of commercial ports and marinas (resulting in cleaning and removal) may also be attributed to the economic damage caused by marine litter. Marine litter also harms human health through accidents caused by divers encountering submerged litter, as well as medical waste (physical injury and illness) on water and coasts containing medical waste. Sea litter is one of the problems that affects tourism negatively leading to visual and aesthetic problems [18]. As also aforementioned, according to estimations, the total amount of marine litter entering the oceans every year is approximately 6.4 million tonnes worldwide and about 8 million items of marine litter entering the oceans and seas every day, and 13,000 pieces of plastic litter float on every square kilometer of the ocean surface [4].

Marine litter has become an all-pervasive pollution trouble affecting the world's oceans. Plastic and synthetic materials are the most common type of marine litter and the marine environment is highly contaminated with plastic litter [19]. There are two types of microplastic: intentionally made primary microplastics (e.g., lumps or microbeads) and secondary microplastics, which are fragmented parts of larger objects [20]. The use of plastics and other synthetic materials is increasing rapidly. As the usage areas of these materials have been developed, applied, and accessible to more people, the amount of plastic waste entering the marine environment has increased [21]. This increase is the same as the production level in the last 50 years. But it has accelerated the storage rate in the last 20 years of the twentieth century, and plastics are now the most common pollutants of beaches and ocean waters around the world. Land-based wastes consist of direct abandonment, forgetting, disposal as well as inadequate management of landfill sites, tourism, coastal activities, filling, discharging, waste from industrial enterprises, wind, flood, sewage, and rivers. About 20–40% of the wastes in the marine environment, while land resources account for about 60–80% [13, 15]. However, the main source of marine litter may vary from region to region [13, 15].

Contribution of Synthetic Fibers to Marine Litter via Laundry (Washing) Cycles

Cheap, short life apparel and clothing also called as “fast fashion” is an immense contributor to sea and ocean plastic pollution [22]. Microplastic particles are characteristically relics of larger plastic items, broken down over time into smaller bits and pieces [23–25]. Textile materials based on synthetic fibers are also a significant source of microplastics, since they release fibers every time when they are laundered or washed [26]. Indeed, when one washes synthetic garments, many microfibers (microscopic synthetic fibers) are released from the clothing during the laundry cycle and some of them end up in our waterways and eventually in rivers, seas, and oceans [27]. For instance, a single fleece jacket may unleash to one million fibers during a wash cycle. In the case of a pair of nylon socks, this number could go as much as 136,000 fibers. It was reported in a study which was financed by the European Union that washing machines in Europe alone flush 30,000 tonnes of synthetic fibers into waste water each year [22]. Microplastic diversity, prevalence, and size of parts vary according to different parts of the world, but the fact that the release of these particles into the environment during the routine operation of daily life remains unchanged. An important source for microplastics, for example, is plastic fibers and particles which mix with water from garments and detergents during washing, which are also exposed to water resources, plants, land, and aquatic animals through contaminated waste waters. Microplastics consist of polyester and acrylic fibers and dyestuffs used in textile industry. Sediment samples taken from habitats receiving wastewater discharges and sewage wastes contain these particles intensively. Studies examining waste water samples of domestic washing machines have shown that a single garment could produce approximately 1900 microplastic fibers per wash [28, 29]. The number of microfibers unleashed from a classic 5 kg wash load of polyester fabrics is estimated to be over 6,000,000 depending on the type of detergent utilized [30]. It is also reported that microparticles generation in the marine environment due to textile materials and textile products were 190,000 tonnes in 2016 [31]. For instance, in another study, it was stated that approximately 26–4300 mg microparticles were generated per washing cycle and up to 700,000 fibers could be released to the canalization from an average 6 kg wash load consisting polyester, acrylic, polyester/cotton shirts, and jackets [31]. For instance, uptake and effects of microplastic textile fibers on freshwater crustacean *Daphnia magna* were studied in order to examine the resultant effects on such creatures [32]. In this research study, the ingestion and influences of ground polyethylene terephthalate (PET) textile microfibers (length range: 62–1400 μm, width 31–528 μm, thickness 1–21.5 μm) on *D. magna* after a 48 h exposure and subsequent 24 h of recovery in microplastic fibers free medium and algae were examined. Most of the PET fibers taken by *D. magna* were about 300 mm, however, there were also very large twisted microplastic fibers around 1400 mm in the gut of the *D. magna*. Exposure to these fibers led to increased mortality of daphnids after 48 h only in the case where daphnids were not prefed with algae previous to experiment, however, no influence was found when daphnids were fed before the experiments. On the other hand, irrespective of the feeding type, daphnids could not recover from microplastic fibers exposure after additional 24 h incubation period in a microplastic fiber free medium with algae [32].

Effects of Marine Litter

Like all ecosystems, marine ecosystems are based on a balance. Interventions to the ecosystem due to various external factors cause changes in the ecosystem. Marine litter also changes the balance of the marine ecosystem and poses a threat to living beings as well as socioeconomic and human health [6]. There is also an enhancing concern about the potential negative effects and risks of (micro) plastics on organisms and human health [33–35].

The vital importance of plastics for modern life due to their satisfying characteristics and the possibility of their mass production availability, and therefore in return the production and use of plastics is rapidly increasing. If the current situation continues to increase the production rates by 5% per year, according to estimations by 2050, unfortunately 33 billion tonnes of plastic will be accumulated in the world [36]. The existence and accumulation of marine litters result in ecological and socioeconomic effects.

Ecological Effects

Marine litter, both in macro and micro dimensions, changes the physical and chemical characteristics of the aquatic environment leading to destruction in the ecological balance of environment and damages to living things [21]. Plastic/polystyrene accumulations in coastal and marine areas have a number of negative effects that can lead to digestion, excretion, reproductive problems, restriction of living movement through entanglement, or even termination of vital functions in organisms as a result of consumption of food [6, 13, 35, 37, 38]. In addition, plastic/polystyrenes can also affect biodiversity by creating substrates for living life, moving pathogen/invasive species to currents and winds where they do not belong [39, 40]. Although plastic/polystyrene litter accumulates in the benthic area may act as artificial reefs, they also cause habitat loss for many other living creatures [6, 37].

Abandoned, lost, or discarded hunting tools (monofilament fiber nets and rope nets), traps, baskets, and so on create significant danger for marine life. Hunting activities continue and these abandoned, lost, or discarded hunting tools are great threat for living things because of their long deterioration processes [41]. Known as ghost hunting, it has been reported that sponges, corals, crabs, fish, sea turtles, and marine mammals are seriously affected and sometimes these damages may lead to even deaths [42]. For instance, monofilament nets and rope nets can cause dangerous situations for animals. Plastic/polystyrene bonds containing nets, drinking cans, and other food packaging materials are particularly dangerous for mammals and birds [43–45]. It is known that up to 45% of the marine mammals on the red list (the International Trade Convention on Endangered Species, CITES, the list of threatened species) circulate or swallow marine litter [17, 44]. In 1991, a study was carried out on the coast of Ukraine; 194 mutur (*Phocoena phocoena*), 18,424 turbot (*Psetta maeotica*), 143 sturgeon (Acipenser spp.), 401 spur dogfish (*Squalus acanthias*), and 1359 stingray (*Raja clavata* and *Dasyatis pastinaca*) were found entangled in bottom gillnets. In another study conducted in 2002, 35 mutur (*P. phocoena*) caught in illegal gals and fancy nets were reported in the Exclusive Economic Area of Romania [46, 47].

In addition to hunting vehicles, synthetic and plastic/polystyrene materials, which are encountered as marine litter, also affect the growth, development, and nutrition processes of living organisms [6, 13, 48]. On the other hand, plastic waste pieces reaching the seas cause the death or suffering of the mammals, sea turtles, reptiles, fish, and seabirds by obstructing their digestive canals [6, 21, 29, 43, 49–51]. For example, turtles eat plastic/polystyrene bags, which they think are jellyfish, and birds feed themselves and their offspring with plastic/polystyrene, which they think are fish eggs or crabs. Creatures that fill their stomachs by eating garbage are exposed to hunger and die from insufficient nutrients. It is known that 44% of all seabirds consume plastic/polystyrene [6]. In addition, edible substances can block the organism's breathing canal and cause it to die slowly.

Particularly plastic/polystyrene is divided into smaller pieces and microplastic is formed and consumed by marine creatures. Many studies have been reported by the presence of microplastic litter in the coasts, seabed, and seawater [29, 54–57]. On 14 May 2019, Victor Vescovo went to 10,927 m (35,853 ft) to the bottom of the Challenger Deep which is the southern end of the Pacific Ocean's Mariana Trench as part of a mission to chart the world's deepest underwater places. Unfortunately, even this deepest ever dive also witnessed "plastic bag" at bottom of Mariana Trench [58].

These microplastic litters have been found in many species, from the smallest to the largest creatures that feed on them [49, 59–61]. These microplastic litters found in marine organisms enter the food chain through transmission from one organism to another and threatens human health by consuming contaminated seafood. Accumulation of marine litter also damages habitats by covering and disrupting habitats [62]. They stated that more than 100,000 lobster traps, which are lost every year, especially in storms, pose a significant threat to seagrass beds and coral reefs. Some of the marine litters are composed of chemical and medical wastes which are disease causing. These harmful litters harm to marine organisms as well as to humans through feeding, contamination, and sinking [13, 48, 63, 64].

According to the nature of the material constituting marine litter is located at various depths. In particular, the plastic/polystyrene litter that makes up 60–80% of marine litter can float and can cover long distances with currents [12, 18, 43]. It was reported by some studies that after entering marine environment various bacteria and microalgae were observed on marine litter biofilm [3, 65, 66]. In addition, some invertebrates that reach different ecosystems by clinging to marine litter may invade and damage this new environment in which they do not belong [67, 68].

Plastic wastes today also have a significant harmful effect on marine organisms. Since albatross, seagull, yelkouan, and storm birds consume feeds as a result of feed supplements. It is known that many organisms of these species are affected. For instance, 44% of all seabird species consume plastic and 267 marine organisms around the world are affected by plastic waste [6]. Colonization of plastic marine litter by sessile organisms can also threaten marine biodiversity by transporting alien species in the ocean environment. The collection of plastic litter at the seabed is also another potential hazard for marine ecosystems. The accumulation of these wastes prevents the gas exchange between the water covering the sediment and the water in the pores, causing disturbance and suffocation of benthic organisms [13, 48, 69].

It was stated in many different studies that the presence of plastic micro-trashes in the coasts, seabed, and seawater has been reported, and the presence of plastic micro-litter has been reported in many marine species from zooplanktonic organisms to invertebrates, fish, seabirds, and marine mammals [45, 54–56, 58–61]. It has also been reported in the experimental studies that plastic micro-trash is consumed by the infiltrators at the base of the food web and transferred to trophic level [70–72]. As plastics are known to absorb hydrophobic contaminants, digestion of degraded plastic particles and particles increases the concern for toxicity. In addition to those added to plastics during production, there are complex problems that require extensive research on compounds absorbed from nature by plastics [69].

Socioeconomic Effects

Plastic litter in the world's oceans causes serious environmental problems, since mechanical erosion at sea and degradation by chemical erosion is minimal [73, 74]. The very slow degradation of these products and the gradual increase in the amount of garbage lead to an impressive increase in the amount of the world coasts and oceans [21]. Following their accumulation on the beaches, the plastic materials are exposed to ultraviolet (UV) radiation and the physical process controlled by the wind, current, wave, and tidal event and enter a marine environment in a wide range of sizes from micrometers to meters and are divided into smaller pieces called microplastics when their diameter is less than 5 mm [34, 70, 74–76]. Degradation (and therefore partial destruction) of ecosystems through marine litter could lead to major economic losses [77–79]. Plastic/polystyrene garbage may cause negative effects on tourism by causing an aesthetically undesirable appearance in the coastal area and may even cause injuries and threaten human health [1, 79]. Sea litter pollution in our seas and coasts and the images caused by this pollution cause tourists not to prefer those countries. It is expected that the tourism sector and fishery industry will be disrupted due to marine pollution caused by marine litters. It is expected in the long run that small-, medium-, and large-scale enterprises that have financial profits from the tourism and fishing sectors will also be affected immensely since marine litters damage aquatic life forms and deteriorate the ecosystem leading to deterioration in the food chain and consequently affecting the fish stocks. Therefore, national economies may suffer from these situations. Expansionist and invasive species, which have succeeded in crossing other ecosystems by adhering to microplastic and marine litter, can suppress the existing ecosystem and cause economic damage [12, 67, 68]. Damage to fishing, fishing boats and fishing nets, congestion and damage at the water inlets of seawater treatment plants, closure of beaches due to public health by polluting beaches, and pollution of commercial ports and marinas are some of the economic losses caused by marine litter [80, 81]. Again, marine litter can be attached to the propellers of boats and ships underway, causing damage to the engine components, resulting in economic losses for ship owners. In addition to this, physical injuries and diseases caused by medical wastes are examples of other problems [18].

Consumption of polluted marine organisms has also an impact on individual human health and litter on polluted beaches can cause epidemics in society [82, 83]. The health budget spent for the treatment and prevention of the diseases can also adversely affect the economy [80]. In addition, the money spent for the solution and disposal of the garbage problem that has formed and continues to increase day-by-day, loss of labor force is a burden on the economy as well [18].

Precautions Against Marine Litter

Although marine litter may seem to be more problematic for some certain countries, it is a global problem which threatens the whole world sustainability [6]. Of course, the best way to hamper marine plastic pollution is to stop it at its source. Therefore, countries need to incentivize companies to decrease the utilization of wasteful, difficult-to-recycle plastic packaging in favor of reusable, easily recyclable, and compostable options. All products need to be produced with environmental perspective and community health in mind. Environmental pollution caused by industries and the amount of waste can be minimized by providing financial resources for education, planning, good governance, state supervision, and environmental protection, but unfortunately it cannot be completely destroyed in the short run. However, both natural resource waste and waste problem can be reduced while economic inputs can be increased. Preventing the rapid depletion of natural resources and transforming the generated wastes from being a threat to the environment and human health into an input for the economy via waste management strategies all over the world constitutes the basis of the sustainable economic approach which is an increasingly adopted as a priority policy objective. For this reason, national wills, international organizations, and unions determine common strategies for the solution of the problem and ask their members to act in accordance with the determined strategies [5]. The Marine Strategy Framework Directive [14] issued by the European Parliament in the field of Marine Environment Policies requires that

Table 2 Qualitative good environmental condition descriptors [14]

Qualitative good environmental condition descriptors	
T1	Biodiversity
T2	Alien species
T3	Fishing
T4	Eutrophication
T5	Seabed integrity
T6	Hydrographic conditions
T7	Pollutants
T8	Sea food pollutants
T9	**Marine solid wastes**
T10	Energy and noise input
T11	Food chains

member states be established in the EU's seas to ensure or maintain the IAE by 2020 at the latest. In this framework, it is aimed to achieve and maintain the point of impact (POI) targets in order to achieve a measurable and significant reduction in the amount of litter in the marine environment. As shown in Table 2 [14], 11 EU POI identifiers have been identified by the EU.

In order to assess the environmental status of the waters of the member and candidate countries of the European Union, they try to achieve this goal by preparing phased strategies for seawater. It is known that there are many new initiatives and formations to prevent and dispose of marine litter. These positive efforts are expected to increase day-by-day worldwide.

Moreover, the collection and recycling processes of ocean plastics and marine litters that are harmful to sea creatures, birds, humans, and other living beings should be seen as an inevitable end to sustainability leading to cleaner environment and therefore world for future generations.

Recycling of Marine Litter

Plastic materials enter to the seas and oceans end up on ocean floor, sea sides, beaches, and ocean surfaces. Unfortunately, degradation of these plastic waste litters in the marine environment needs centuries. Various measures are taken to remove the plastic wastes from the seas and seashores. Methods, such as coastal cleaning activities, cleaning nets taken to the coasts, are still some of the most commonly used methods. The most common approaches for collected marine litter can also be storage or incineration. However, these methods are not always ideal solutions because of limited storage space and pollution risks. The most likely solution for the destruction of plastic marine litter is the plastic recycling technologies commonly used in the processing of industrial wastes. Marine litter can be collected and then separated. First of all, plastics and other kind of wastes are separated. Then, the waste plastic and plastic parts collected from the seas and seashores are separated from each other by various methods and then each type of the recovered polymer, such as polyethylene terephthalate (PET) polymer, polypropylene (PP) polymer, and polyamide (PA) polymer, can be included in the recycling processes at the relevant recycling facilities. Plastics that are more suitable for use in textile products can be sent for recycling process. Plastic waste journey to end up with the rebirth of new textile material is shown in (Fig. 1) as an example.

From an environmental point of view, closed-loop and open-loop approaches are used for waste management. Closed-loop approach is the use of the recycled product in the same product production after the closed-loop customer use. For instance, in this approach, PET flakes obtained from waste PET bottles should also be used in PET bottle production. Open-loop approach means that the recycling material can be used in different areas of use. For example, waste PET bottles can be used in the textile, automotive, and construction sectors to create different materials rather than bottles. Especially in the recent years, waste PET bottles have been researched for recycling and possible application areas. For example, recycled PET can also be used in the material production area and plastics industry. On the other hand, if the same substance is produced from the environmentally recycled product, this is more environmentally valuable. However sometimes, wastes are washed with chemicals during recycling and therefore may not reach sufficient purity values for the next

Fig. 1 From plastic wastes to the rebirth of new textile materials

production of PET bottles or other products [85]. Therefore, it is stated that the use of the recycled polymer in food products and food contact products due to possible contamination of the recycled polymer can be harmful for health [42]. It would be more appropriate to produce products from recycled plastics and polymers in different areas (rather than food contact products) with open-loop instead of closed-loop production. Textile and fiber sector is the leading one of these possible sectors to reuse the recycled plastics and polymers. Since it is estimated that 60–85% of the collected and recycled PET wastes are used in polyester filament and staple fiber production in textile industry. Therefore, the fibers to be produced from recycled PET polymer and other plastic products contribute more to the environment including the closed-loop approach. Since the usage of recycled PET polymer can play an important part in the creation of the final textile product, such as garment, and can be a substitution of the wholly virgin PET polymer usage in the textile product [86]. There are three main recycling methods known as mechanical, chemical, and thermal recycling. In the textile industry, recycled PET polymers can be utilized in many different applications. For instance, mechanically recycled PET bottles and plastics are generally used in nonwovens and short fibers and chemically recycled PET bottles and plastic wastes are mainly used in the filament industry and the composite industry.

Mechanical Recycling

Material recycling is a technique where waste plastics are reprocessed into similar or different plastic products without the modification of its initial chemical structure. In this procedure, waste plastics are initially processed into ingots or pellets through shredding, melting, and granulation and afterward these ingots or pellets are processed into new plastic products [87]. Mechanical recycling consists of melting down the old plastic (separated and cleaned) and using it to make new products. Collected, sorted, and processed granules can be used in different applications, such as new textile materials, heat and sound insulation materials, flower pots, video tapes, and road markers. Recycling is possible at a positive cost/benefit balance of separate collection and sorting in stages to reach pure fractions of certain polymers, and due to needs of the market for high quality recyclates [88].

Chemical Recycling

In the chemical recycling technique, waste plastics are recycled as, among other products, plastic raw material, fuel oil, and industrial feedstock, which are obtained by changing the chemical structure through various chemical processes [86]. Substances resulting from this decomposition are evaluated again as industrial raw materials. Chemical recycling of plastic waste is considered to be a very promising process in the manufacturing of valuable chemicals and fuels. The present attention is not only in recovering energy or in mechanical recycling but also in the fabrication of valuable products, such as monomers or petrochemical feedstocks. Indeed, chemical recycling options exist for some feedstocks, such as PET, polyurethane (PUR), and nylon [88].

Thermal Recycling

The thermal recycling uses the heat energy obtained from combustion of waste plastic. Heat energy resulting from incineration could be utilized for numerous aims, comprising electricity generation, power generation, and cement manufacturing. Even though the power plants often base upon fossil fuels (coal and oil) for their energy source, power plants which utilize waste as an energy source are becoming a popular alternative. Waste plastics are good energy sources for such plants since they possess a high calorific value, akin to that of coal and oil. Waste plastic could also be mixed with wastepaper and wastewood to fabricate fuel pellets named as RPF (Refuse Paper and Plastic Fuel). RPF possesses a high calorific level and hence could be utilized as an alternative energy source to fossil fuels. It could also be manufactured at a low cost and is recently in great demand by the paper, steel, and cement sectors [86].

Recent Commercial Developments for Marine Litter Recycling

Many different companies now collect marine litter, ocean, and ocean coastline plastics and produce new textile products and other kind of products from these wastes in order to protect to environment leading to more sustainable world for future generations.

One of the players in the eco-fashion market is the Spanish company EcoAlf. In order to obtain the recycled raw materials, this fashion company cooperates with an international network and frees oceans from plastic waste. According to EcoAlf, 250 boats a day bring a total of 1.3 tonnes of marine waste ashore for EcoAlf [89]. The fishermen along the Spanish coast also participate by handing in their old waste nets to EcoAlf's collection points instead of throwing them into the sea or to the bin and moreover fisherman take a part in recycling process via carefully separating the plastic rubbish from the fishes. It is reported that this remanufactured thread is then used to make fabrics leading to many different textile products. EcoAlf company started its business in Spain. The proximity to the Mediterranean Sea led them to think about endowing a second opportunity to these materials which instead could stay in our seas and oceans for more than 400 years. This company utilizes all the plastic materials and fishing nets hiding on the seabed as the primary textile raw material for the next textile products. EcoAlf recycles 1 tonne of plastic every day and has recycled and reused over 70,000,000 plastic bottles and 60 tonnes of fishing nets for the creation of their recycled plastic fashion yarn. EcoAlf reports that 1 m of textile fabric can be produced from either 70 plastic bottles or 135 g of fishing nets [89, 90].

As a result, EcoAlf company has saved 20% in water, 50% in energy, and 60% in greenhouse gas emissions by utilizing plastic bottle wastes via recycling in their textile fiber production. On the other hand, the same company has made 27 and 28% savings on natural resources and greenhouse gas emissions, respectively, by utilizing fishing net wastes via recycling in their textile fiber production and therefore, most importantly, this company makes a significant contribution to the prevention efforts of marine pollution via recycling and reusage of these waste fishing nets [89, 90]. Five old plastic bottles were sourced from the Mediterranean Sea and then these waste bottles were utilized to produce each pair of Shao sneakers by Spanish fashion brand EcoAlf leading to zero-waste process. Here, this discarded plastic is processed into a textile yarn, which is utilized to produce the black knitted upper sole that fits the wearer akin a sock. It is stated that the outer sole is also manufactured from a type of algae which grows in excess in lakes and rivers, which EcoAlf company transforms into a flexible foam which allows easy movement. According to this brand, removal of the algae from lakes and rivers also permits clean water to circulate appropriately, supporting plant and animal life [91, 92].

Another example is New York City-based Bionic which uses old plastic bottles recycled from the ocean coastline and turns them into yarns and fabrics for clothing. The company has partnered with several different clothing brands, including G-Star and O’Neill. Since its inception in 2009, it has been established to incorporate yarn into a variety of products, from denim jeans to snowboard jackets. Bionic Yarn is creating durable fabric yarns from up to 100% recovered plastic bottles, lately from other ocean plastic waste as well. In the last 3 years, this company has turned more than seven million plastic bottles into new yarns that have been sold to its partners, such as G-Star and O’Neill. Plastic bottles are chiefly well suited to fabricate new textile materials since they comprise the same polymers as polyester [27, 93].

Sports fashion giant Adidas has also turned a hand to the plastic masses in our seas and oceans. The company collaborated with Parley for the oceans to produce running shoes made partly from plastic waste found on the beaches [94]. Adidas released its “Parley” version of its popular running shoes that turns ocean plastic waste into a thread that is woven into running shoes. Each shoe utilizes about eleven PET bottles and incorporates it all throughout the shoe [93, 95].

Nylon waste from landfills and oceans around the world is converted to ECONYL® regenerated nylon and it is precisely the same as brand new nylon and could be recycled, recreated, and remoulded again and again. It was recently announced that Prada also now uses these ECONYL® nylon yarn from discarded materials and products in their woven fabrics, bags, backpacks, and so on [96].

Norton Point is an eyewear company and they have developed the first line of eyewear produced from recovered high-density-polyethylene (HDPE) ocean plastics. HDPE is a consumer plastic utilized in millions of different products around the world and is one of the most common plastics one can come across nowadays [97].

These developments are important steps for environment, human health, and world sustainability and these promising steps are expected to expand and increase day-by-day.

Conclusions

Marine litters (marine debris) are the wastes discharged by humans to coastal or marine environments resulting from onshore or offshore activities. Marine litter is a crucial health and environmental issue in the global sense for not only humankind but also for cetaceans, marine life, and other flying and land animals. Marine litter can be composed of the wastes and particles of abandoned waste textile products, synthetic garments and their fragments, fishing nets, fishing lines, industrial product wastes, and industrial plastic production wastes, such as plastic bottles and plastic containers (mostly made from synthetic polymers), vehicle tire dusts, and breakdown of litter and cosmetic products. Approximately 90% of the marine litter is composed of plastic material wastes and 5–13 million tonnes of plastic waste litters are released to the marine related environment per year. The amount of plastic waste in the seas is likely to continue to increase, mainly because of the negative increase in plastic consumption (about 9% per annum) and the inadequacy of its reuse, recycling, and waste management practices.

The entanglement and ingestion of marine litter directly damage wild animals and their environment. Accumulation of marine litter on the seabed, accumulation of trash, and seagrass deposits in coral reefs cause damage to the natural habitat and damage the ecosystem. Plastic entanglement and ingestion problems by the animals are the main issues with macroplastics. On the other hand, plastic ingestion and accumulation problems by the animals are the main issues with microplastics. Microplastics in marine litter can be generated through microbeads, pellets, abrasion of especially car tires, textile materials and textile products, the decay of mesoplastics and macroplastics, and so on. Microfibers and microfibrils, which may be generated during ordinary home laundry cycles due to the agitation and beating nature of the washing process and end up in sewage, are also a subcategory of microplastics. Ingestion of microplastic and microparticle marine litter can cause many health problems. Microplastics in the sea enter the body of living sea creatures. As a result of these marine organisms, such as fishes, being consumed by humans, these microplastics and their remnants enter the human body and cause further health problems. Plastic materials enter to the seas and oceans end up on ocean floor, sea sides, beaches, and ocean surfaces. Unfortunately, degradation of these plastic waste litters in the marine environment needs centuries.

Although marine litter may seem to be more problematic for some certain countries, it is a global problem that threatens the whole world sustainability. The most likely solution for the destruction of plastic marine litter is the plastic recycling technologies commonly used in the processing of industrial wastes. The waste plastic and plastic parts collected from the seas and seashores are separated from each other by various methods and then each type of the recovered polymer, such as polyethylene terephthalate (PET) polymer, polypropylene (PP) polymer, and polyamide (PA) polymer, can be included in the recycling processes at their relevant recycling facilities.

Indeed, the collection and recycling processes of ocean plastics and marine litters that are harmful to sea creatures, birds, humans, and other living beings should be seen as an inevitable end to sustainability leading to cleaner environment and therefore world for future generations. Therefore, recently, many different companies (e.g., EcoAlf, Bionic, Adidas, Aquafil, and Norton Point) now collect marine litter, ocean and ocean coastline plastics and produce new textile products and other kind of products from these wastes in order to protect to environment leading to more sustainable world for our grandchildren. These developments are important steps for environment, human health, and world sustainability and these promising steps are expected to expand and increase day-by-day.

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Sustainability in Polyurethane Synthesis and Bio-based Polyurethanes

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Abstract Increasing environmental problems and economic and environmental problems associated with global warming, waste management problems, decreasing fossil resources, fluctuations in oil prices, and dependence on oil have led to an increase in research for renewable and sustainable new materials that are friendly to our health and environment. These studies can be focused on certain materials by looking at the width of the application areas. One of these materials is polyurethane (PU).

PU draws attention about sustainability because it is one of the most important polymers and has a wide range of application areas. It has versatile and excellent physical, chemical and mechanical properties that increase demand in various areas such as foam, elastomer, adhesive, liquid crystals, sealants, ink, paint, and coating applications. Good flexibility, elongation, high impact and tensile strength, high abrasion resistance, good weather resistance, excellent gloss, color protection, and corrosion resistance are some of its attractive features.

Recently, the use of green materials and sustainability have made it possible to highlight the presence of natural materials that are alternative to synthetic materials. Natural products have been searched for PU synthesis and many studies have shown that natural products can be used in the production of polyol.

Vegetable oils among renewable resources are one of the cheapest, most abundant and renewable natural materials that can be used in many industrial applications. PUs can be synthesized by partial or complete replacement of polyols from renewable sources such as vegetable oils with petrochemical polyols. There are many studies in the literature on polyol production from different vegetable oils such as soybean oil, castor oil, corn oil, rapeseed oil, palm oil, karanja oil, andiroba oil, and cottonseed oil.

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In this chapter, the composition, raw materials, and properties of PU materials used in textile and other sectors are explained and the possibilities for bio-based PU synthesis are mentioned. First of all, vegetable oils used in polyol synthesis will be examined. The structure and modification of these oils will be explained. After that, polyol synthesis from oils and polyurethane synthesis from vegetable oil-based polyols are emphasized.

Keywords Sustainability · Textile · Biodegradable · Vegetable oil · Triglyceride · Bio-based polyol · Isocyanate · Polyurethane

Introduction

Boundedness, environmental problems, and unstable high cost of oil have led researchers to find alternative ways to produce today's materials. In addition to ecological concerns such as environmental safety and recyclability, consumers' expectation for lighter, more energy-efficient and more sustainable products has increased the interest in green materials. Thus, the issue of the use of renewable resources instead of petroleum has come to the agenda and has begun to spread to a wide area with many advantages [1]. Some "environmentally friendly" or "green" technologies have been developed with particular attention to the overuse of renewable sources such as vegetable oils [VEGO], as well as to reduce or eliminate the use of volatile organic compounds [2]. Vegetable oils are cheap, easily accessible, nonhazardous, and most importantly biodegradable [3]. Besides these features, in view of environmental and energy problems, triglyceride oils are expected to play an important role in enabling polymers to be synthesized from renewable sources. Polymers forming triglyceride oils can be prepared using a variety of strategies. The choice of strategy for the success of polymerization depends on the structure of oil and monomer. The presence of the fatty/fatty acid chain in the polymer structure improves some physical properties of the polymer in terms of flexibility, adhesion, water, and chemical resistance. Because of their sources and structural properties, triglyceride oils can be widely used. Biocompatibility and/or biodegradability play an important role in bio-applications. Even these factors make triglyceride oils essential raw materials for use in various future applications [4].

Many oil-based polymeric resins are used as polyols for PUs, a polymer group that is of interest to researchers and industrialists due to their excellent property profile and properties that can be tailored to specific requirements [3].

PUs can be synthesized by partially or completely replacement of polyols obtained from renewable sources with petrochemical polyols. Structure–property relations of the obtained PU can vary depending on the type of triglyceride, the degree of crosslinking, and the structure of the isocyanate (–NCO) group [5].

In this chapter, vegetable oils used to obtain biodegradable polyols are mentioned and their structure, properties, and modification processes are examined.

Polyol synthesis from vegetable oils by some modification methods and after that the synthesis of bio-based polyurethane from these polyols is explained. Information about the usage of bio-based polyurethane materials obtained is given.

Polyurethanes

PU, first synthesized by Otto Bayer in Germany in 1937, forms a wide range of polymers with urethane linkage. The reaction of isocyanate groups (–N=C=O) with polyhydroxyl groups yields PUs containing urethane group (–NH–CO–O–) and functional groups such as ester, ether, urea, and amide. The structure consists of a soft part formed by polyols and a hard part formed by isocyanate and chain extenders. This copolymer structure allows this polymer to be used in many applications. The soft part gives the PU elastomeric properties, while the hard part provides high mechanical properties. The properties of the PU are adjusted by the ratio of this hard portion to the soft portion and the types of reactants used in the synthesis (Fig. 1).

In PU block copolymers, the hard segments particularly affect the modulus, stiffness, and tear strength, and it determines the upper usage temperature with its ability to stay connected at high temperatures. By using the most rigid, bulky and symmetrical diisocyanate, PUs with the highest modulus, tear, and tensile strength levels are obtained. The diisocyanate residues in the polymer affect the ability of the polymer chains to sequence themselves and the development of the interchain structure by hydrogen bonding. The low temperature properties of PU elastomers are moderately affected by the diisocyanate used. Flexible (soft) blocks primarily affect the elastic nature and low temperature performance of the product and also make significant contributions to the hardness, tear strength, and modulus.

PUs are generally synthesized in two steps. In the first step, diols, compounds with two hydroxyl compounds, and isocyanates are reacted to form the prepolymer, and in the second step, the polymer is finally chain-extended with diamines or diols. Schematic diagram of PU synthesis is given in Fig. 2 [6].

PUs are excellent materials in terms of high tensile strength, abrasion resistance, weather resistance, low temperature resistance, and wide stiffness range [6, 7].

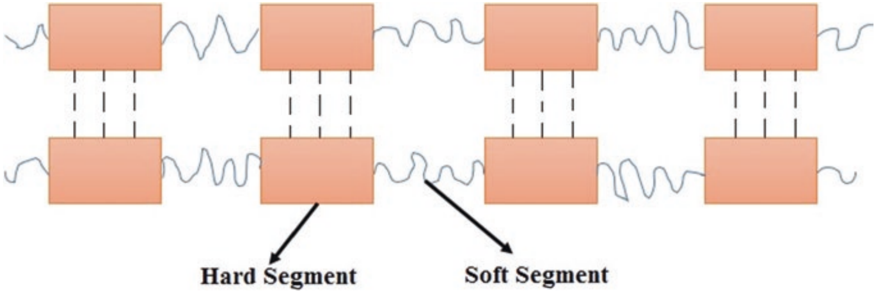

Fig. 1 Soft and hard segments of PU

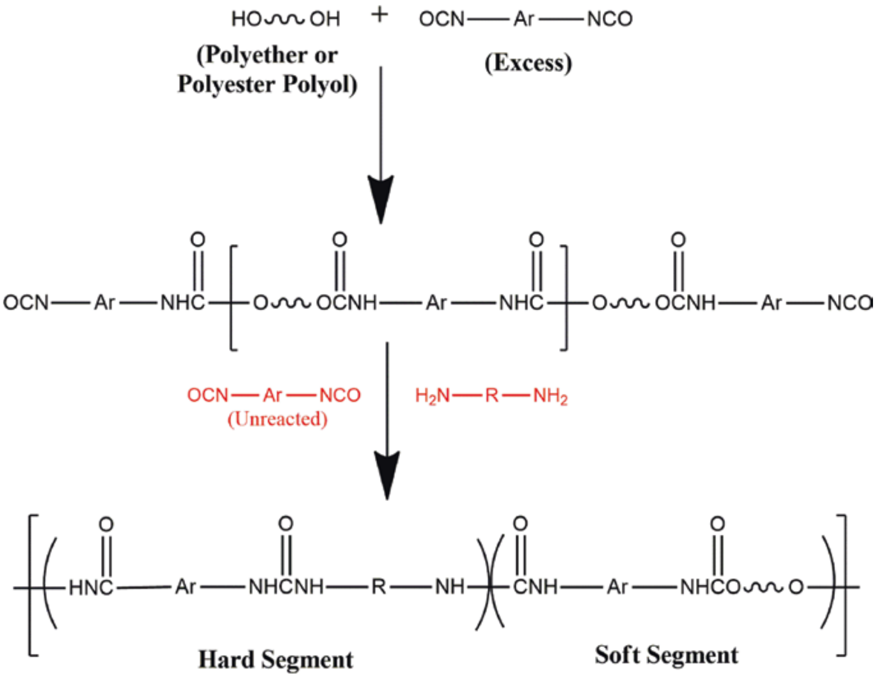

Fig. 2 Schematic diagram of PU synthesis [6]

By changing factors such as the structure of raw materials, reaction conditions, and the ratio of –NCO/–OH, it is possible to synthesize PU materials with the desired properties for certain applications [5, 8]. The PU chains may have a linear, lightly branched, or crosslinked network structure. This versatility in PU synthesis with a wide range of products such as flexible foam, rigid foam, elastomer, adhesive, coating, fiber, composite, and sealing material offers a wide range of applications.

Raw Materials

The raw materials used in PU production are examined in four groups. These are isocyanates, polyols, chain extenders and crosslinkers, and catalysts.

Polyols

Polyols are compounds whose main chain is hydrocarbons such as polyether and polyester [9]. Most are derived from petroleum-based chemicals and have a molecular weight of 400–5000. Some polyols used in PU synthesis are homo- or copolyesters, homo- or copolyethers, polyester-polyethers or polyisobutylene polyols.

Polyether polyols constitute a large portion of the polyols used in PU production. It is divided into four groups: polyoxyalkylene polyols, graft polyols, (polymer polyols), PHD polyols, and polytetramethylene ether glycol (PTMEG) [10].

Polyester polyols for urethane and related polymeric foams include aliphatic and aromatic polyesters and are the first polyols used in PU production. Aliphatic polyesters are prepared by polycondensation reaction of dibasic acids (such as adipic acid, phthalic acid, and sebacic acid) with glycols (such as ethylene glycol, propylene glycol, diethylene glycol, 1,4-butanediol, and 1,6-hexanediol). These polyesters have high viscosity and low functionality. On the other hand, aromatic polyesters are prepared by transesterification of recycled polyethylene terephthalate (PET) [10].

Isocyanates

One of the main components used in PU synthesis is isocyanates. Toluene diisocyanate (TDI), diphenylmethane diisocyanate (MDI), naphthalene 1,5-diisocyanate (NDI), and hexamethylene diisocyanate (HDI) are the most commonly used.

Isocyanates containing the reactive groups –N=C=O can be commercially divided into three categories: (1) aromatic, (2) aliphatic and cycloaliphatic, and (3) specific isocyanates [11]. Aliphatic isocyanates were first synthesized by Wurtz in 1849, while aromatic isocyanates were first prepared by Hoffmann in 1950 with the symmetrical diphenyloxamide prolysis [10]. Aromatic isocyanates are more reactive. They also form a tighter polymer chain, resulting in the formation of a high melting point PU. However, they are not resistant to light and they gradually turn yellow [12]. They are used in the preparation of isocyanate-based foams. Since foaming reactions require high reactivity, aliphatic isocyanates that react slowly with OH groups are not used [10].

TDI is obtained by phosgenation of diaminotoluene obtained by reduction of nitrotoluene. Commercial TDI products are mixtures of 2,4 and 2,6 isomers in weight ratios of 80/20 or 65/35. The melting point of these mixtures is in the range of 5–15 °C and the melting point of pure 2.4 TDI is around 22 °C. TDI with an isomer ratio of 80/20 is used mainly for flexible foams, but not for the preparation of polyisocyanurate foams. The modified TDI and undistilled TDI are often used for hard urethane foams and partly for semi-hard foams. Since they are toxic materials, they should not be used without taking the necessary precautions [10].

The MDI group represented by pure 4,4-diphenylmethylene diisocyanate (Fig. 3), polymeric diphenylmethylene diisocyanate (PMDI), and modified diphenylmethylene diisocyanate is obtained by phosgenation of the aniline condensation product with formaldehyde. The polymeric and oligomeric MDI are liquid and have an average functionality of from 2.3 to 3.0. They are essentially 4,4′-isomer based and have small amounts of 2,2′-isomer and 10% of the 2,4-isomer. Pure MDI (or monomeric MDI) is obtained by distillation of a crude reaction product and is used in elastomers and coatings. Polymeric MDI, which has recently been used in flexible foam technology, is used in rigid and semi-rigid urethane foams as well as polyisocyanurate foams [10].

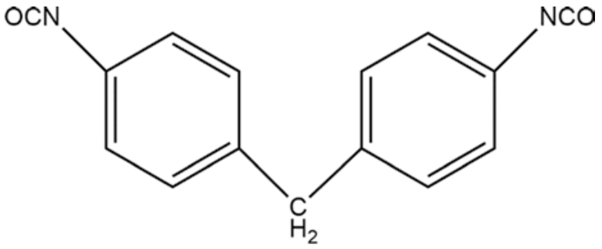

Fig. 3 Chemical structure of diphenylmethylene diisocyanate

$$NCO-(CH_2)_6-NCO$$

Fig. 4 Chemical structure of hexamethylene diisocyanate

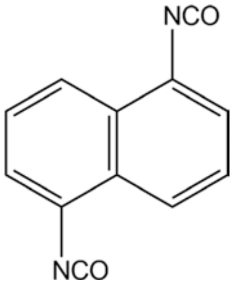

Fig. 5 Chemical structure of naphthalene 1,5-diisocyanate

Hexamethylene diisocyanate (HDI) is a light-resistant isocyanate group due to its aliphatic structure (Fig. 4).

Naphthalene 1,5-diisocyanate (NDI), first produced in Germany, is a solid compound with a melting point of 128 °C (Fig. 5).

Chain Extenders and Crosslinkers

Chain extenders, which are reactive polyfunctional structures with low molecular weight, are obtained from difunctional structures, while crosslinkers are obtained from high functional structures. Aromatic or aliphatic diols and diamines can be used as chain extenders. Some commercially used chain extenders are ethylene diamine, 1,4-butanediol, and ethylene glycol.

The structure of chain extenders and the amount of crosslinking are factors that affect the structure of the PU. Chain extenders improve the physical properties of the material and increase the molecular weight. The aliphatic or aromatic structure of the chain extender is also effective for the material to be soft or hard. The amount of crosslinking is also effective in the amount of elongation and resistance to the applied force.

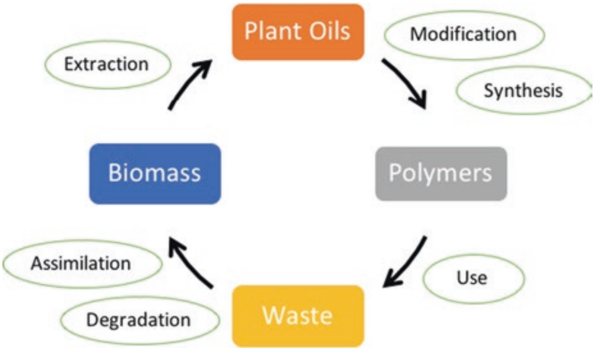

Fig. 6 Life cycle of vegetable oil-based polymers [4]

In some studies, PU can be synthesized without chain extenders. In this case, the isocyanates react with polyols in stoichiometric proportions.

Catalysts

In PU synthesis, there is a need for catalyst as the reaction rate decreases when the size of the substituted group in the structure of high molecular weight alcohol increases. Co-naphthenate and dibutyltin-dilaurate are some of them.

Vegetable Oils Used in PU Synthesis

Recently, due to environmental concerns and dependence on depleted resources, the use of renewable resources in the preparation of various industrial materials has acquired currency, and various researches have been done on this subject [2, 4, 13–16]. Bio-renewable materials such as cellulose, starch, protein, natural oil, and sugar are of interest as potential raw materials [16].

Vegetable oils also have the potential to be an alternative source for the production of polymeric materials. They can be used as a renewable raw material in the preparation of polyols used to produce bio-based PU foams. Among the vegetable oils, flaxseed, sunflower, castor oil, soybean, oiticica, palm, tall, and rapeseed oils are widely used in the synthesis of oil-modified polymers. Depending on the geographical location of production facilities, the preference of vegetable oil type used in polyol production may vary. For example, canola and sunflower oils in Europe, palm and coconut oils in Asia, and soybean oil in North America [17].

Life cycle of vegetable oil-based polymers is shown in Fig. 6 [4]. Vegetable oils are converted into polymers for specific application areas by applying certain processes. Waste, produced at the end of product life, is turned into biomass by degradation and/or assimilation, and then vegetable oils are extracted.

Vegetable oils have become an area of interest as platform chemicals in polymeric materials for both academic and industrial research, due to their universal availability, biodegradability, low prices, physical and chemical stability, as well as economic and environmental benefits [3, 4, 13, 15, 16, 18–22]. The outstanding properties of vegetable oils are their unique chemical structure with their unsaturated zones, epoxies, hydroxyls, esters, and other functional groups, as well as their natural flowability. They enable various chemical transformations to produce low molecular weight polymeric materials in a variety of applications [18]. In addition to these advantages, their reactive functionality also makes vegetable oils attractive monomers for polymer chemistry. However, their use as monomer presents difficulties due to their heterogeneous and variable structure [13].

Structure and Modification of Vegetable Oils

The essential building blocks of vegetable oils are triglycerides. Triglycerides are highly functionalized molecules and therefore they are used in the synthesis of crosslinked polymers by two main approaches. First, it takes advantage of naturally occurring functional groups present in triglycerides such as internal double bonds, alcohols or epoxides which can be polymerized using different methods. The second strategy is based on chemical modifications before the polymerization. This approach solves the disadvantage of the low reactivity of natural triglycerides (usually containing only double bonds) by the addition of easily polymerizable functional groups and thus extends the synthetic possibilities [15]. Triglyceride is an ester product obtained from a glycerol molecule and three fatty acid molecules [4, 13, 15–17, 19, 20, 22–24] (Fig. 7).

One of the most dominant parameters affecting fatty acid and oil properties is the degree of unsaturation. The average degree of unsaturation is measured by the iodine value. It is calculated by the amount of iodine (mg) that reacts with the double bond for 100 g of the sample under the specified conditions. Triglyceride oils are divided into three groups based on their iodine value (IV): drying (IV > 130), semi-drying (100 < IV < 130) and non-drying (IV < 100) oils [2–4].

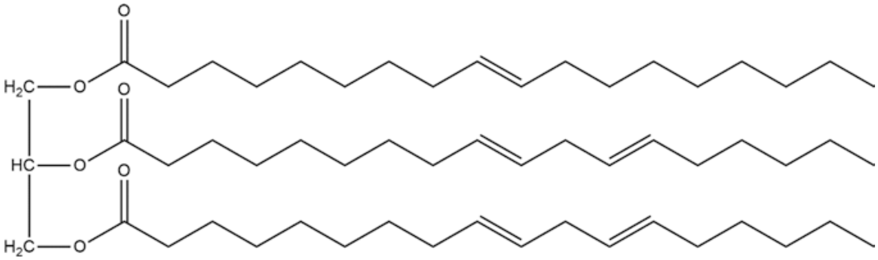

Fig. 7 Schematic presentation of triglyceride structure of vegetable oils

Highly unsaturated vegetable oils indicate the presence of more carbon–carbon double bonds and are more prone to polymerization by some polymerization methods such as cationic, free radical, and thermal methods. These oils make it possible to obtain polyol with high hydroxyl functionality, thus PU with high crosslinking density, high thermal, and mechanical properties can be synthesized [21, 23, 24]. For example, soybean oil and flaxseed oil have relatively high unsaturation compared to other vegetable oils; therefore, these two types of vegetable oil are often used to synthesize polymers [21].

Fatty acids account for 94–96% of the total weight of a molecule of triglyceride oil [4, 15]. Some of the most common fatty acids in natural oil compositions are saturated fatty acids such as palmitic (C16: 0) and stearic (C18: 0) and unsaturated fatty acids such as oleic (C18: 1), linoleic (C18: 2), and linolenic (C18: 3) (Fig. 8) [4, 5, 13]. Saturated fatty acids do not have double bonds, while unsaturated fatty acids have one or more double bonds [4, 13].

The fatty acid model varies depending on product, growth conditions, seasons, and purification methods, but each of the triglyceride oils has a specific distribution of fatty acids [4, 13]. For example, the fatty acid composition of cottonseed oil is oleic acid (18: 1) 17.6%, linoleic acid (18: 2) 54%, linolenic acid (18: 3) 0.3%, and myristic acid less than 1%. In the content of the karanja oil, oleic acid (18: 1) is

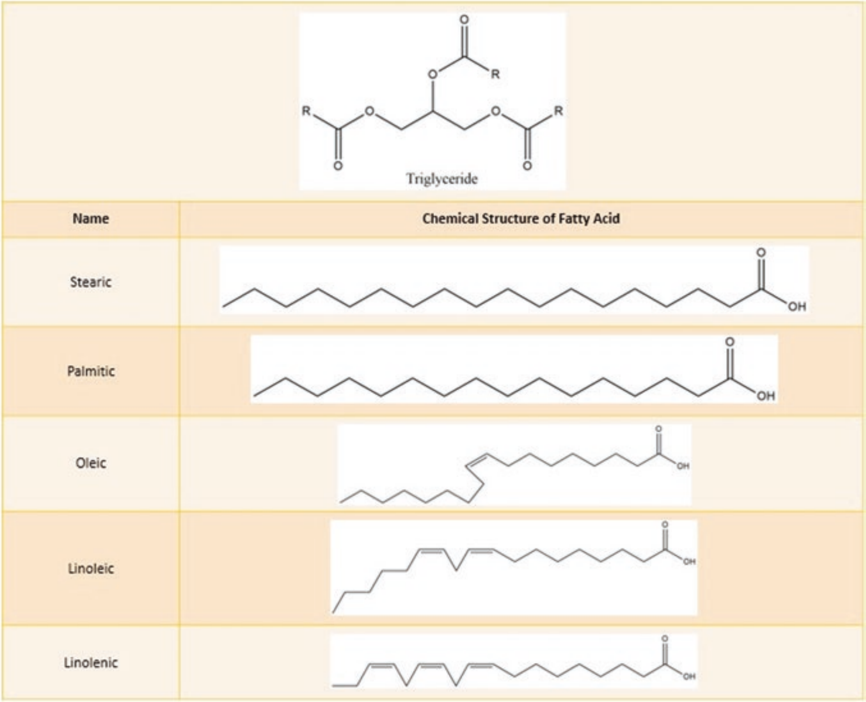

Fig. 8 Structure of triglycerides and the five most common fatty acids

44–72%, linoleic acid (18: 2) is 10–18%, and linolenic (18: 3) and myristic acid are absent. While the basic fatty acid content of the carrageenan oil is oleic acid, the basic fatty acid content of cottonseed oil is linoleic acid with 54%. Both linoleic acid and oleic acid are unsaturated fatty acids and are therefore suitable for conversion to polyol by epoxidation [3]. Linseed oil is mainly composed of linoleic and linolenic acids. In castor oil, the majority of fatty acids are ricinoleic acid (12-hydroxy-9-octadecenoic acid) [4].

Depending on the fatty acid distribution in the structure of triglyceride oils, the physical and chemical properties vary greatly, and a wide variety of polymers with different structures and functions can be obtained [4, 19]. For example, flaxseed oil is widely used for the preparation of dye-binding agent because it is composed of reactive unsaturated fatty acids which cure by atmospheric oxidation. Castor oil is an important reactant for transition polymer networks (IPNs) because it contains hydroxyl groups that can react with isocyanate and carboxyl groups.

To produce linear, branched, or crosslinked polymers, it is possible to select the fatty acid distribution function of oils by computer simulation and molecular coupling. Materials prepared in this manner can be used to produce pressure-sensitive adhesives, elastomers, rubbers, and composites [4].

For the use of vegetable oil-based fatty acids in PU applications, various specific methods have been developed to convert an inexpensive, readily available and renewable raw material into valuable monomers and other natural raw materials [5]. Triglycerides contain several chemically modifiable reactive sites containing double bonds, allylic positions, and ester groups (Fig. 9) [16, 17, 19, 21, 22]. If vegetable oils containing high fatty acids are used in PU synthesis, it is essential to modify them first. There are many methods used in chemical modification of oils. Some of these are transesterification, transamidation, hydroformylation, hydrolysis, ozonolysis, hydrogenation, photochemical oxidation, thiol–ene coupling, epoxy ring-opening epoxidation, and hydrogenation (Fig. 10) [5, 13, 16, 22].

One of the main reactions for polyol synthesis from vegetable oils is epoxidation followed by reaction of epoxy groups with different ring-opening reagents such as water, alcohol, glycerol, 1,2-propanodiol, and acids [22]. Epoxidation is one of the

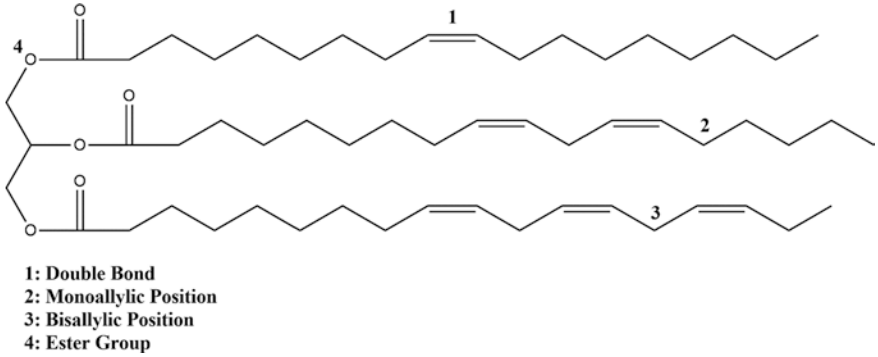

Fig. 9 Structural representation of triglyceride and reactive regions

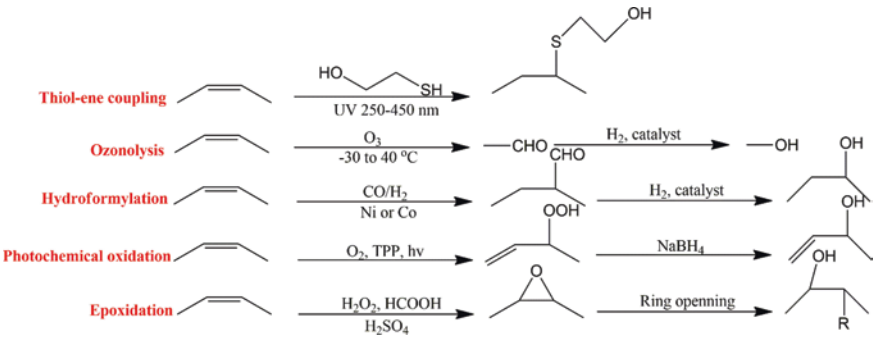

Fig. 10 Synthesis of vegetable oil-based polyols

most commonly used methods of functionalizing carbon–carbon double bonds and can be performed very efficiently in many ways. Polyols are obtained from epoxidized vegetable oils by oxirane ring-opening reactions using a wide range of active hydrogen containing compounds such as alcohols, inorganic and organic acids, amines, water, and hydrogen. The properties of the polyols obtained by epoxidation and subsequent oxirane ring-opening reactions vary depending on the raw material characteristics and the type of ring-opening agents. During reaction with a nucleophilic reagent, oxirane ring opening in fatty acids and fatty acid esters makes it possible to convert into product containing long chain polyols. Oxirane groups are generally introduced into the fatty acid chain, which poses an obstacle in ring-opening reactions. Groups in this position are less reactive, so it is necessary to increase the reaction temperature using concentrated inorganic acids. High pressure may also be required in some cases. Oxirane ring-opening agents are divided into three main categories: alcohols, acids, and hydrogen [23]. For example, in a study with canola oil, oxirane ring opening and transesterification of epoxidized canola oil was achieved using a strong acid catalyst (such as sulfuric acid) and excess diol. Transesterification effectively removes glycerol from the polyol, resulting in lower molecular weight and viscosity and higher hydroxyl number than the polyol obtained by oxirane ring opening [23, 25–27].

In one study, the development of thermoset plastics with an optimal solvent-free epoxidation process from plant-based oils (e.g., flaxseed, soybean, cottonseed, peanut oils) was emphasized.

The epoxidation of vegetable oils was carried out economically by reacting the double bonds of fatty acids with hydrogen peroxide [28].

In one study, various chemical modifications of bio-based materials, synthesis of various PU coatings from these modified materials and their potential applications were discussed. The PU obtained with bio-based diisocyanate synthesized from fatty acids has similar physical properties to that obtained from oil, and in some cases even higher tensile strength. Cardanol (from CNSL liquid) based polyols were used to obtain bio-based PU coatings. The CNSL-based cyclic carbonate (CC-cyclic carbonate) is effectively used as a precursor for the synthesis of isocyanate-free PU

(NIPU). Terpene-based PU coatings have excellent impact strength, water resistance, pencil hardness, adhesion, and flexibility. The bio-pitch and heavy oil obtained from the distillation of eucalyptus tar is used to produce renewable polyols [22].

Vegetable oil-based polyols can also be obtained by thiol-ene reactions; hence, this is a simple one-step reaction for the addition of primary hydroxyl groups [16].

Use of Vegetable Oils in PU Synthesis and Bio-based PUs

Increased environmental problems, environmental and economic problems associated with global warming, waste management problems, declining fossil resources, fluctuations in oil prices, and oil dependence have led to the search for sustainable, renewable, applicable materials that are friendly to our health and the environment [17, 22, 29, 30]. Numerous research studies have been conducted focusing on the application of bio-based components for the production of plastic foams, composites, coatings, fillers, or adhesives [17, 22].

The main strategy of the European Commissions in achieving one of the targeted sustainable development objectives is to reduce greenhouse gas emissions up to 20% by 2020 and up to 80% by 2050 [31]. The development of bio-based renewable resources can also limit carbon dioxide emissions [17].

Recently, the use of green materials, which have become frequently on the agenda, has made it possible to highlight the presence of natural materials that provide alternatives to synthetic materials. Despite its significant benefits, PU also has disadvantages such as poor degradability and toxicity. Therefore, researchers have focused on the production of bio-based polyols and PUs from more environmentally friendly and renewable sources [3, 8, 22, 26, 31–33]. Bio-derived materials such as vegetable oils, cashew nut shell liquid (CNSL), terpene, eucalyptus tar, and other bio-renewable sources are a rich source of precursor for the synthesis of polyols and isocyanates used in the production of “greener” PU materials. [22]. Among renewable sources, vegetable oils are one of the cheapest, most abundant and annual renewable natural materials that can be used in a wide range of industrial applications [17, 22].

There are many studies in the literature on the production of polyols from different vegetable oils. In one study, the polyol obtained from soybean oil was used as a natural source to form an environmentally friendly PU foam [34]. In a study in which PU was synthesized by reacting polymeric isocyanates and polyols obtained from soybean oil, biocomposites were obtained by the addition of nanocellulose fibers and their characterizations were performed [35]. In another study, castor oil was used to obtain polyol [36]. In a study, petrochemical polyol was modified with rapeseed or palm oil-based polyols and their characterizations were carried out. A softer and less elastic PU foam was obtained with 30% palm oil-based polyol and the compressive strength of the final product was found to be high. PU obtained with 50% rapeseed oil-based polyol has improved compressive strength and reduced elongation at break. As a result, it has been proposed that low density oil modified foams can be used to replace high density petrochemical materials and thus the use of raw materials and the price of the final product can be reduced [37]. In one study, two biodegradable PU adhesives were synthesized from aliphatic HDI and aromatic MDI diisocyanates, 1,4-butanediol as chain extender, soy-based polyol, and 1,4-butanediol polyadipate blend. In MDI-based PU adhesives, up to 22% by weight soy-based polyols meet the adhesive quality requirements for footwear, whereas in HDI-based adhesives only soy-based polyol content not exceeding 7% by weight can meet these requirements [26]. In another study, polyols from castor oil (CO) were synthesized with diethanolamine (DEA) and triethanolamine (TEA) in a molar ratio of 1:1–1:3, and then biobased rigid PU foams having a renewable content of 25–35.6% were obtained. The tensile strength, modulus of elasticity, and glass transition temperature of PU coatings are high for samples obtained from CO/DEA polyols, but the highest breaking elongation was observed in PUs derived from CO/TEA polyols. When the CO/DEA and CO/TEA molar ratios increase from 1 to 3 in the temperature range 150–350 °C, the thermal stability of the PUs obtained from these polyols decreases. The presence of polyethylene glycol improves the degradability of bio-based PU foams in the presence of fungi, while increased CO content decreases biodegradability [27]. In a study on obtaining PU coatings by epoxidation of cotton seeds and carrageen oils using hydrogen peroxide and Amberlyst resin, the final product has shown very good thermal stability and coating properties such as dryness of touch, gloss, pencil hardness, adhesion, impact resistance, and chemical resistance. It has also been concluded that PU resins based on cottonseed and carrageenan oil have excellent potential for use in the formulation of coating binders [3]. In another study, bio-based polyol was obtained by esterification reaction of fat and rosin acids from tall oil with diethanolamine for cleaner synthesis of rigid PU foam. This polyol has a hydroxyl value of 273.9 mg KOH/g and a moisture content of 0.12% [31]. In a study, polyol was obtained with enzymatic glycerolysis from andiroba oil, which is distinguished by its numerous medical properties such as anti-inflammatory, antimicrobial, and repellent, and then flexible PU foam was synthesized. PU foam was prepared with andiroba oil polyol (AOP) or AOP/glycerol blends, hexamethylene diisocyanate biuret, dibutyltin dilaurate as catalyst, and water as blowing agent. Due to the low average functionality of AOP, the production of dimensionally stable foams was possible only in combination with glycerol [38]. In a study, it has been shown that soybean oil-based functional polyols can be produced as promising alternatives to conventional polyols to obtain PU coatings with the desired properties. A technology platform consisting of a series of efficient and quantitative thiol–ene reactions has been proposed for the preparation of functional and sustainable polyols [30]. In another study, PU resin was obtained by using castor oil-based polyol and diphenylmethane diisocyanate (MDI) and reinforced with sisal fibers to obtain composite material. This composite material has been shown to have a higher storage modulus and lower damping factor and glass transition temperature than the composite material obtained with normal PU resin [36]. A study was carried out to make a detailed assessment of the integrated impact on a corn-based polyol system and the environment. Modeling was conducted to evaluate the environmental impact in four polyol production stages: raw material cultivation, corn-based polyol production, use of these products, and disposal process. Findings from systemic simulation can be used to identify environmental pollution bottlenecks in the process. The results have showed that multiple scientific and technological advances in polyol production can reduce one third of the production cost per ton compared to petrochemical polyols and can significantly reduce adverse environmental impacts [39]. In one study, the development of new types of hard PU foams (RPUFs) containing flaxseed oil (LO) as a natural modifier was investigated. The aim of this study was to determine the effect of flaxseed oil on foam morphology and physical properties. As a result, it has been found that the addition of 5% flaxseed oil improves the mechanical and thermal properties of the material and higher amounts of flaxseed oil, such as 10% and 15%, can reduce the basic properties of foams [17].

Renewable sources are used as much as possible to reduce the use of environmentally hazardous chemicals such as isocyanate and other petroleum-derived chemicals. In addition to obtaining polyol from biomaterials, it has also been worked through the synthesis of polyisocyanate-free PU. In a study of obtaining isocyanate-free PU from lignin and soybean oil, the reaction was carried out in three steps. The purchased epoxidized soybean oil was carbonated and the resulting oil was then reacted with the 3-aminopropyltriethoxysilane (APES) coupling agent. The prepared urethane monomers were polymerized with lignin. In this polymer, while the aromatic structure of lignin functions as a hard segment, the polysiloxane–Si–O–Si– bonds formed by the self-condensation of APES molecules function as soft segments. The content of lignin and soybean oil in the polymers is as high as 85% by weight. Thus, the use of toxic and environmentally harmful materials can be avoided as much as possible [40].

Use Areas of Bio-based Polyurethanes

PUs are one of the polymers that have the largest and most diverse applications due to their wide range of performance properties. They have unique properties such as good flexibility, elongation, high impact and tensile strength, high wear resistance, good weather resistance, excellent gloss, color protection, and corrosion resistance. PU properties vary depending on the structure, composition, molecular weight, amount of crosslinking, and proportion of hard and soft moieties of monomers. They may also exhibit different structural properties in different forms such as film, foam, elastomer, adhesive, fiber, leather, liquid crystals, sealing materials, ink, paint, coating, and hydrogel [3, 5, 41–45].

Among all products obtained from PU, foams are versatile polymeric materials with a wide market, which can be classified as flexible, semi-rigid or rigid depending on their mechanical performance properties and densities. PU foams are widely used in various industries such as automotive, furniture, construction, refrigerants, chemical pipelines, transportation systems, packaging, and manufacturing.

Foams are used in the roof and facade coatings of factory buildings and industrial buildings (especially in the construction of all yarn and other textile factories since they do not perspirate and keep the humidity in balance), in shelters and prefabricated structures created after natural disasters due to ease of application and high production capacity, in the insulation of pipes in the groundwater (geothermal) transmission lines, low density foams inside the tubes, fixing of doors and windows for filling and gluing, cold storage of fresh vegetables and fruits, dairy products, cheese, etc., the construction of cold rooms and cold stores of vehicles such as aircraft, trains, steamers, ships, mobo type shelters used in construction sites, temporary offices and offices, guard shelters, packaging operations, interior parts of automobile seats, cushioning, etc., in all areas for heat insulation, in all areas where sound insulation is required, in shoe production, in panels and other forms in upholstery sector [8, 17, 31, 46, 47].

Among organic coatings, PU coatings have excellent wear resistance, toughness, low temperature flexibility, corrosion resistance, and chemical resistance, so they are used in a wide variety of applications from automobile finishing to industrial maintenance and chemical resistance [3, 22]. It is also often used as an adhesive in joining different materials in the footwear and automotive industry [44].

PUs are also used in biomedical field in different forms such as film, hydrogel, and foam. For example, PU membranes can be used as wound dressings due to their excellent blood compatibility and physical properties. PU has a structure that allows the passage of oxygen and carbon dioxide and restricts the passage of liquid as well.

The oxygen permeability may vary depending on the chain flexibility of the PU. It is known that chain flexibility can be achieved by high molecular weight polyols and non-aromatic isocyanates used in PU synthesis. In a study, a mixture of mono- and diglyceride (partial glyceride) prepared from vegetable oil and containing functional hydroxyl group was reacted with aromatic HMDI and/or aliphatic MDI to obtain PU in solvent environment. Membranes of different structure were synthesized with the ratio of HMDI:MDI isocyanate compounds 1:0 (PU1), 0.5:0.5 (PU2), 0:1 (PU3), 1:1(PU1 and PU3 mix). As a result of the experiments, according to O_2, N_2, and CO_2 gas permeability, membrane PU4 was determined as the best membrane. All samples were generally found to have “homogeneous structure” and “good flexibility” properties. As a result, the film and permeability properties of the PU4 membrane were found to be suitable for wound dress purposes [48]. In another study of wound dressing, partial glyceride was obtained with flax oil and glycerine, and then it was reacted with diisocyanate compounds and PU was synthesized. Hexamethylene diisocyanate (HMDI) and diphenylmethylene diisocyanate (MDI) were used as diisocyanate to obtain PU HMDI-MDI and PU HMDI. As a result of the tests, it was found that PU HMDI-MDI is thermally more stable and has higher crosslinking density due to its benzene ring. PU HMDI was found to have a more homogeneous crosslinking structure, higher mobility, and faster degradation. When these two types of PU are compared, PU HMDI-MDI with superior mechanical properties and longer biodegradation time may be preferred. As a result, the obtained oil-based PU films without adding any additives have been suggested as a suitable material for use as the antibacterial wound dressings [49]. In a study about

PU hydrogels, polyols were obtained by using different ratios of castor oil (HY)/polyethylene glycol (PEG) and they were reacted with hexamethylene diisocyanate (HDI) and triethylamine as crosslinker (TEA), and 1,4-butanediol (BDO) as chain extender. It was found that as PEG/HY ratio increased, density of polymer increased, and Tg values and contact angle decreased. The increase in the amount of HY provided a more homogeneous crosslinking but decreased the crosslinking density. Polymers with high PEG content are more hydrophilic. As a result, it is predicted that the obtained polymers can be used for wound dressing applications [50].

Conclusion

Because of increased environmental problems, declining fossil resources, fluctuations in oil prices, and oil dependence, it is aimed to limit the use of petrochemical materials and to further improve the use of green materials instead. This also makes it possible to reduce the cost of materials, which attracts the attention of the producers. In this respect, it has been proved by different studies that different materials can be obtained from many vegetable oils.

In this chapter, it is focused on the synthesis of bio-based PU and for this purpose, it is explained how polyol synthesis from vegetable oils can be performed. Polyol with different properties and therefore PU for different application areas are synthesized from vegetable oils of different structure. Therefore, after determining the material to be produced for which application area, it should be investigated which types of oils can meet the desired properties and production should be performed accordingly. Considering the environmental concerns, evaluation of oil wastes may offer greater advantages besides the advantages of using vegetable oil. Waste oils will be prevented from damaging the environment and production will be realized at minimum cost. Further research should be carried out on this subject and PU synthesis from waste oils should be supported by experimental applications.

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Textile Industry Insights Towards Impact of Regenerated Cellulosic and Synthetic Fibres on Microfibre Pollution

Songyi Yan, Celina Jones, Claudia E. Henninger, and Helen McCormick

Abstract The purpose of this chapter is to investigate a current topic that has received increased academic and media interest: microfibre pollution (MFP). It contributes to knowledge by exploring how microfibre pollution is defined from an industry perspective and what challenges and/or solutions are associated with it. This research is qualitative in nature and supports its findings with ten in-depth semi-structured expert interviews. Although this could be seen as a limitation, the chapter provides valuable insights that can be explored further in the future. Findings indicate that (1) MFP lacks a clear-cut definition and a key distinction between what is considered as problem and challenge, and (2) tackling MFP needs to integrate multiple stakeholders to take actions throughout the entire product life cycle. Implications identified concern current communication practices that provide both scientific facts and practical solutions.

Keywords Microfibre pollution · Textile industry experts · Perspectives · Regenerated cellulosic fibres · Impact · Alternatives

Introduction

The current fast fashion model, which sees stock turnover on a fortnightly basis, has led to hyper consumption. In order to satisfy the fashion-appetite on the consumer side, manufacturers need to find ways to produce more garments at a low cost [1–4]. Garments currently available in the industry are predominantly made from man-made fibres, including regenerated cellulosic fibres (e.g. viscose, Lyocell) and synthetic ones (e.g. polyester, polyamide, acrylic) [2, 5]. The issues that surround the fast fashion model, which include, but are not limited to, labour rights violations,

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microfibre pollution (MFP), and burning unwanted stock, has led to an increased awareness of sustainability [4]. To explain, sustainability in the textile industry has been made a top priority on a national and international basis [6]. As such, it is vital to understand what underpins sustainability and how it can be achieved across the supply chain, including raw materials. Concerns that have been associated with raw materials can vary from fabric waste, to recyclability of fabrics, to chemicals being used in the production and finishing stages and, more recently, to microfibre pollution [7–9].

This chapter explores the impact of regenerated cellulosic and synthetic fibres on microfibre pollution from an industry perspective, through interviewing experts within the remits of the textile and fashion industry and academia. The following research questions are addressed:

- How is MFP defined from an industry perspective?
- What are the key challenges of MFP?
- What are potential alternatives to reduce MFP according to industry experts?

Background

In the textile industry, fibres are grouped into two major categories: natural and man-made fibres. Natural fibres are classified as either those created from plant-based raw materials (cotton, flax, etc.) and or animal-based ones (wool, silk, etc.). Figure 1 provides a visualisation of man-made fibres most commonly used within the textile industry [5].

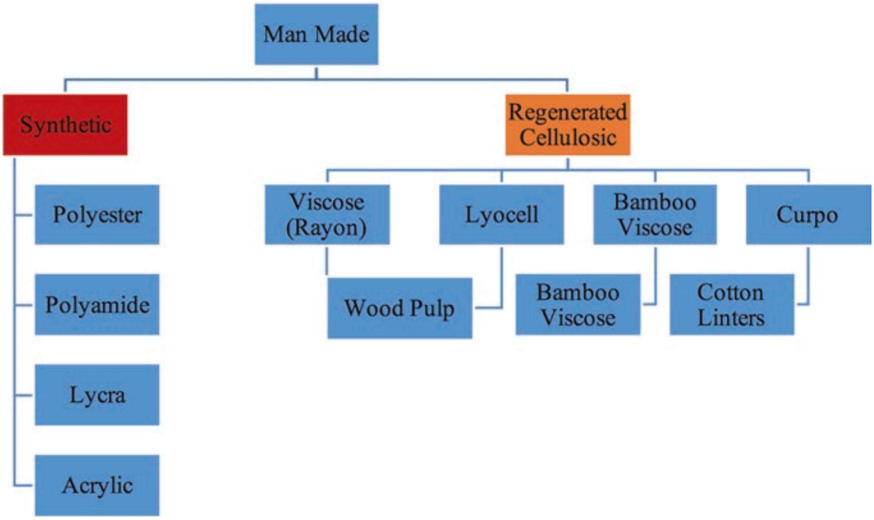

Fig. 1 Groups of man-made fibres within textile industry. (Adapted from [5], p. 276)

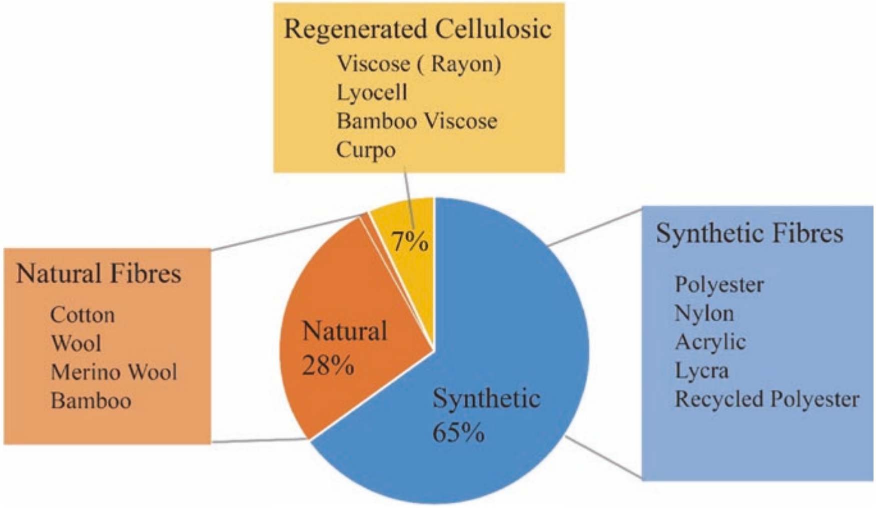

Fig. 2 Share of world textile market by fibre type in 2019 and Most commonly used fibre types in textile industry. (Adapted from [5, 11])

Within the global textile market (Fig. 2) synthetic fibres dominate the industry taking up a total of 65%, yet regenerated cellulosic fibres are dramatically increasing and see a current market share of 7% [10].

An explanation for the increased uptake of regenerated cellulosic fibres is the fact that their raw materials are associated with hygroscopicity, comfortable wear and ‘easy’ biodegradation [12]. Although polyester to date dominates the market within the fashion and textile industry, especially in the sportswear market [13], more and more regenerated cellulosic fibres are used in the production process of a variety of garments (e.g. sportswear; maternity wear) as they are linked to ‘well-being’. For example, yoga clothing has seen a dramatic change in fabrics such as viscose (rayon) and Lyocell, as a more ‘natural fibre’, which can be linked to the yoga core message to ‘promote active relaxation’ ([14, 15], p. 27). Fast fashion retailers, such as H&M, have also increased the use of regenerated cellulosic fibres in their maternity lines [16], which could link to healthier lifestyles and wanting to protect newborns and children from any harmful materials/substances. Companies such as Bamboo Clothing and Komodo predominantly use bamboo, which is ‘smooth and luxurious to the touch’ [17] and marketed as having a ‘lower environmental impact’, being ‘chemical and pesticide free’ and ‘antibacterial’ [17, 18]. The latter aspect however has not been scientifically proven; although bamboo itself may have antibacterial properties, creating bamboo viscose is a process involving the use of toxic chemicals, which can change these properties [19, 20]. Moreover, some companies have been scrutinised for emphasising the ‘lower environmental impact’ of bamboo and being ‘chemical and pesticide free’ in marketing campaigns, as the feedstock and production process lacks transparency and traceability across the supply chain requiring, as indicated previously, chemical additives that can be harmful to the environment [15, 21]. Yet, overall, the trend to move away from 'plastics' to more 'natural' fibres (e.g. Lyocell, cupro and piñatex) continues to increase [22], which could also be explained due to the price of viscose and Lyocell being relatively low compared to the cost of cotton [23]. Additionally, there is an increased use of blends within the garment and textile industry of synthetics/cellulosic fibres. By blending fibres such as polyester/viscose companies can make use of the best performance properties of both fibres, whilst at the same time enhance the appearance, durability, comfort, maintenance, cost and overall performance of a garment. However, the main drawback of blends is the end-of-life treatment, as it is not always possible to split fibres and recycle them appropriately [2, 22].

Microfibres and Microfibre Pollution

According to the literature and recent media (e.g. [8, 24–26]), the term *microfibre* can have different meanings depending on the context (Fig. 3).

Within a textile manufacturing context, the term *microfibre* refers to fabrics/materials that have a textile linear density of one denier or less and possess valuable properties, such as softness, durability and high absorbency. Focusing on the performance properties of these microfibres, it may not be surprising that they are commonly used within the fashion industry. According to the literature covering the textile manufacturing context, microfibres are seen to be value adding materials that are purposively created to produce garments and textile with specific performance properties [2, 24]. To reiterate this further, some regenerated cellulosic fibres (e.g. Lyocell) have a natural fibrillation process that produces microfibres that lead to valuable performance properties, such as an appealing fabric touch, often referred to as 'peach skin' effect [27].

Yet, recent media has portrayed microfibres in a negative way in that they are described as pollutants that are released predominantly from synthetic clothing during the aftercare process (e.g. laundering) and destroying aquatic life (e.g. [26, 28, 29]). Within the pollution context microfibres are characterised as 'tiny threads of synthetic textiles, size <5 mm and mostly released from the process of laundering'

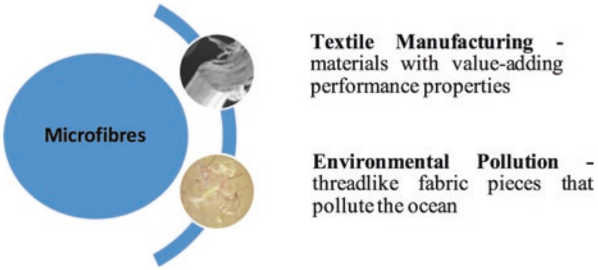

Fig. 3 When 'microfibres' used in different context. (Authors' own)

([30], p. 9; [31], p. 188). Yet, more recently the term was 'applied to particles that are <1 mm in size' ([32], p. 1191). Various studies solely refer to synthetic fibres when it comes to microfibre pollution, whilst others also incorporate regenerated cellulosic fibres, which further distracts from clarity on what microfibres are. Some studies have investigated microfibre shedding, which is seen to be a key source of pollution, yet it remains unclear how much 'shedding' is seen as being polluting and what the standard shedding rate is that is used as a baseline to make these judgements. Moreover, recent research [8, 30, 33] of developing and standardising the test and analytical methods of microfibre shedding during the laundering process have predominantly focused on synthetic textiles, thereby excluding regenerated cellulosic fibres. Henry et al. [24] state that there are considerable variations in the quantity of fibres released from different types of synthetic textiles. For instance, acrylic releases more microfibres than polyester, whilst there is almost no difference in the microfibre shedding rate between virgin and recycled polyester. However, in terms of shedding rate, cellulose-based fabrics shed more microfibres than polyester fabrics [29]. This could be due to the natural fibrillation process that happens in the production process of certain regenerated cellulosic fibres such as Lyocell, which enhances microfibre production and consequently shedding [27].

Thus, it can be said that the amount a material sheds seems to be dependent on the washing machine used, the washing method applied, the material being washed (synthetic, regenerated celluloses) and the physical properties of the material (cut, seam) [32, 34]. Although the term *microfibre* seems to be intuitively understood and associated with a negative connotation, currently there is no clear-cut definition of the term. Within this chapter microfibres in the context of pollution are understood as, threadlike pieces measuring more than 1 μm and less than 5 mm in size. Microfibres can fall within three categories of fibres (Fig. 4).

Figure 4 indicates that microfibre pollution can come from 'natural' sources (e.g. cotton, wool), 'regenerated cellulosic' fibres (e.g. viscose, Lyocell), or synthetic fibres (e.g. polyester, acrylic). However, Henry et al. [24] reiterate that there is a

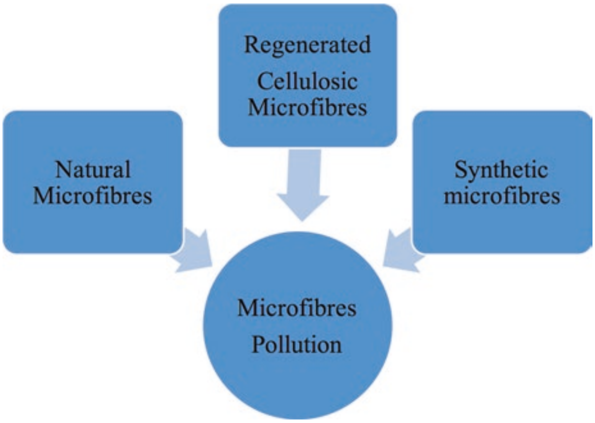

Fig. 4 Three types of microfibre when used in pollution context. (Adapted from [24])

need for future research to address this gap by developing a definition of what 'microfibres' are, in order to enhance data sharing and communication strategies. This will be addressed in this chapter.

Currently, within the microfibre pollution context, the majority of research investigates the pollution process from the 'laundering—wastewater treatment plant—ocean' pathway [31], yet microfibres can be released during the production, use, maintenance and end-of-life disposal stages [30]. Authors [29, 31] indicate that microfibre pollution could be controlled by applying some of the following strategies: washing clothes in front load washing machines, loaded fully, washing at low temperature and at a low spin speed and for shorter times, reduce the amount of detergent used, etc. Yet, it is questionable whether this is always feasible within both consumer households and industrial contexts. Some products such as Cora Balls and the Guppyfriend Bag were developed to catch the microfibres during the laundering process; however, there is no further information telling users of these products how to dispose or treat those entangled microfibres after washing. This implies that although there are intentions to take microfibres out of the laundering process and thus prevent them from entering the wastewater treatment system and ultimately the ocean, consumers are hindering the process by simply emptying the captured microfibres into the sink spoiling efforts made to reducing their impact (e.g. [35]). Thus, addressing fundamental questions on how we produce, use and dispose of our clothing in a more sustainable way might be more effective in reducing microfibres release in the long term [24].

Dris et al. [36] further indicate that atmospheric fibre shedding is another alternative to microfibre dispersive pathway. To explain, detached fibres are randomly dispersed from the fabric/textile and settle in both indoor and outdoor environments. Thus, microfibre pollution could start from the textile manufacturing stage and does not necessarily occur only during consumer maintenance stage. Through the whole manufacturing process of yarn to fabrics, it is possible that fibres are released into the air; an example is the natural fibrillation process in production process of regenerated cellulosic fibres, such as Lyocell, which has previously been mentioned [27]. The shedding rates and contamination of air and water may also pose health and safety risks for textile factory workers [37].

Although microfibres, in contexts of both textile manufacturing and as pollutants, have received increased interest, the majority of attention has focused on synthetic microfibres, which could be due to the fact that the textile and fashion industry is currently dominated by these man-made synthetic fibres [5, 11]. Synthetic microfibres, fall within the microplastic category as the raw materials used to produce them are plastic- and petroleum based (e.g. [36]). A further explanation for focusing predominantly on synthetic microfibres could be due to the fact that these plastics are coated in hazardous chemicals and are resistant against degradation. On the contrary, natural fibres and regenerated cellulosic fibres are associated with biodegradability; thus they have received relatively little attention when it comes to microfibre pollution.

Sanchez-Vidal et al. [25] and Halstead et al. [38] report that the major type of microfibre found on the seafloor sediments is cellulosic microfibres, which concerns both natural cellulosic (e.g. cotton, linen) and regenerated fibres (e.g. rayon). To reiterate this further, previous studies have highlighted that twice as many cellulosic microfibres (which include natural and regenerated cellulosic fibres) can be found in deep-sea sediments, where viscose accounts 56.9% of microfibres, which is twice as abundant as polyester [8, 24, 25, 29, 39]. An explanation as to why regenerated cellulosic fibres may have been overlooked is that they are associated with biodegradability [30]. Yet what has been overlooked is the fact that the chemicals used in the textile manufacturing process could be realised through these microfibres in deep-sea sediments [24, 40].

In summary, there are gaps in the literature that investigate alternative sources, pathways and impacts of other types of microfibres, or more specifically regenerated cellulosic fibres. Thus, the present research explores the impact of both regenerated cellulosic and synthetic microfibres on microfibre pollution from an industry perspective. This chapter addresses this contextual gap (ibid.), by investigating regenerated cellulosic and synthetic fibres and their impact on MFP from an industry perspective.

Methodology

This research is exploratory in nature and utilises a qualitative research methodology in form of in-depth semi-structured interviews. Interviews have been carried out with ten experts in the field of textile science and the fashion industry. The authors ensured that there is an even distribution of experts/professionals with a textile technical background, and those who have an invested interest in the fashion market and business area. In addition, majority of them are with academic background, whilst others are working within the industry. Table 1 provides a brief overview of participants in terms of their background and length of interview.

Although the small sample could be seen as a limitation of this research, it has to be highlighted that this research does not intend to generalise the findings, but rather

Table 1 Summary of interview participants

Participant	Background	Interview duration (min)
Expert #1	Industry—Fashion	58
Expert #2	Academia—Fashion	55
Expert #3	Industry—Fashion	60
Expert #4	Academia—Textile science	75
Expert #5	Academia—Fashion	50
Expert #6	Academia—Textile science	50
Expert #7	Academia—Textile science	45
Expert #8	Academia—Fashion	55
Expert #9	Academia—Textile science	60
Expert #10	Industry—Fashion	60

provide insights into microfibre pollution (MFP) from the point of view of experts. This study is part of a wider project that focuses on microfibre pollution, and as such the findings presented are based on the first part of the project, which will inform and guide the directions of future research.

Purposive sampling and snowball sampling are used to recruit experts in the field of textile science and the fashion industry, thereby ensuring an even distribution of experts with a technical background, who know about the first stage of the production process (e.g. raw materials sourcing, manufacturing) and those that have an invested interest in the latter stages (e.g. aftercare, laundering). Although the sample size may be seen as a limitation, the results provide an insight into a new and emerging phenomenon that currently lacks research and a clear-cut definition. As such, this chapter provides thinking points and areas of further exploration. To explain, the present research does not consist of the hypothetical explanation of a research question; on the contrary, it aims to generate themes, patterns and categories that can be developed into theory out of the interview data through the process of coding.

Interview transcripts and notes are analysed and coded by applying grounded analysis approach, which refers to Easterby-Smith et al.'s [41] seven steps guide of familiarisation, reflection, open coding, conceptualisation, focused re-coding, linking and re-evaluation. In order to ensure consistency and inter-coder reliability, the researchers coded parts of the data set independently, before discussing the emerging themes and patterns. Any discrepancies were carefully explored and the full data set analysed by the first author of this chapter.

Findings

The following section presents the findings in accordance with the questions posed in this research, whilst at the same time discusses them in light of literature presented.

How Is MFP Defined from an Industry Perspective?

One of the objectives of this chapter was to get an insight into how fashion and textile technology experts understand microfibre pollution (MFP); as such they were asked to provide their perceptions of MFP. An interesting observation that can be reported is the fact that a majority of participants intuitively discussed fibres and textiles made from synthetic fibres as one of the key areas linking to microfibre pollution: *It's basically like mini shape of plastic fibres, I guess they are caught in the sea quite a lot* (Expert #1).

Only two interviewees indicated that MFP does not only stem from synthetics but also occur from other fibres: *any clothing does not matter what material is, as you wear it and as you wash it, those fibres start to untangle from the garment. So* *any clothes has this kind of microfibres release issue* (Expert #4). Further into the interview Expert #4 highlights that a reason as to why the attention is more on synthetics when it comes to MFP is the fact that *with polyester and synthetic fibre, those fibres are plastics so they came out from the clothing and get into wastewater stream, and they do not breakdown* (Expert #4). This implies that microfibres from regenerated cellulosic and natural materials are seen to be less of a problematic concern in comparison to their synthetic counterparts as regenerated cellulosic and natural materials are seen to have biodegradable characteristics, which concurs with what has been found in the literature [12, 30]. What should be noted here is that within this sample of experts, the biodegradability of natural and regenerated cellulosic fibres was uncontested—this will be further discussed in the next section. To reiterate this further, although the experts are aware of the use of chemicals in the process of manufacturing regenerated cellulosic fibres, the pesticides utilised to grow natural fibres, such as cotton, and/or dyes and other coatings with which garments and accessories may have been treated in order to correspond with the new trends in the fashion industry, these were seen to be less problematic as MFP from synthetic fibres. Thus, our findings concur with Henry et al. [24] and Liu et al. [40], who highlight that this fact—chemical use within the textile manufacturing process—has been widely overlooked and are here seen to play a less prominent role when it comes to the impact of regenerated cellulosic and natural fibres on MFP.

From the interviews, it further became apparent that there was a feeling of frustration surrounding the topic area as although research exists that addresses areas of MFP *there is so little known about where microfibres come from, within the research areas, there are many reviews of reviews focus on synthetic ones, and without real research ha(ving) been done* (Expert #2). The quote supports a current gap in the literature in that past research has focused on microfibre shedding as a key pollutant, yet currently the industry is lacking a standardised approach of measuring shedding rates, as currently there is no baseline to measure this against [8, 30, 33].

Both Experts #4 and #9 further highlight that there is an issue in how MFP is portrayed in the media, as it seems to predominantly be centred on the ‘laundry—wastewater—ocean’ pathway of pollution and synthetics: *we hear a lot from the media that microfibres from synthetic clothes and go into the wastewater streams and then into ocean. However, it is not just existing single pathway as ‘from washing machine to wastewater streams to ocean’, there are microfibres floating in the air […] plus, not only synthetic fibres are doing this, every type of fibre can shed microfibre* (Expert #4). Expert #9 elaborates that not all microfibres are necessarily from the shedding process but rather they can also *come from the manufacturing process.*

In summary, our data has indicated that the expert sample for our chapter intuitively defined microfibre pollution to be predominantly caused by synthetic fibres and thus is defined in line with microplastic pollution. Although regenerated cellulosic and natural fibres are also shedding microfibres, these seemed to be linked more closely to biodegradability and seen as less of a problem, as measures can be in place that enhance biodegradability. What emerged dominantly from the data set is the frustration of what is currently known and how this knowledge is communicated, as media outlets seem to only highlight microfibres as pollutants rather than also as valuable raw materials that are utilised within the textile and fashion industry.

What Are the Key Challenges of MFP?

The second objective of this chapter was to understand associated challenges with MFP. Various experts indicated that MFP is not the only problem that needs to be addressed, but also the toxins used within the production and manufacturing process, as was alluded to in the previous section. Expert #3 states: *so there is another conversation that comes out in parallel of the microplastics debate, which is all of the toxic additives that are used for clothes for a variety of purposes, and what happens to that once garments are washed and disposed.* This implies that it is not only microfibres that can be released in the washing process but also potential chemicals or colour particles that can have a negative impact on ecological health and wellbeing. Further industry challenges that have been raised are: *natural fibres should be biodegradable, man-made ones could be more difficult, because they have arti compounds with it. They are also treated with something to have certain properties, even just dyes, those treatments can be toxic, for instance, waterproof coating is toxic, and they might not be biodegradable. Moreover those treatments may also prevent them from being biodegradable* (Expert #9). A contradiction that has to be discussed here is that in the previous section, biodegradability of regenerated cellulosic and natural fibres has not been highlighted as a problem, yet it has been discussed as a challenge. From the data, it became apparent that the expert sample chosen for this research discusses MFP from seemingly two different points of view: (1) as a problem that is under-researched and only little is known, which refers to the release of synthetic microfibres that end up in the ocean and consequently affecting marine life; and (2) as a challenge that can be more easily countered. The latter aspect links to regenerated cellulosic and natural fibres, which, as aforementioned, are theoretically biodegradable, yet due to the use of coatings, dyes and toxin may lose this property. From the data set it emerges that there is a more positive feeling about regenerated cellulosic and natural fibres in regard to MFP, as they are seen to be more ‘natural’, whilst synthetic fibres are plastics produced from petroleum [36], which takes centuries to biodegrade, if at all. Similarly to regenerated cellulosic and natural fibres, synthetic fibres can also be coated to enhance their performance properties, such as being fire resistant or water repelling, as well as fabrics also being coloured and chemically treated. This may be an explanation as to why experts discuss challenges with regenerated cellulosic and natural fibres and problems when it comes to synthetic fibres, as the microfibre shedding in the latter instance is enhanced through treatments (e.g. chemicals, dyes).

Figure 5 provides a visualisation of the findings, thereby showcasing the two different points of view of discussing challenges with and problems of microfibres. What becomes apparent here is that there is a seeming lack of consistency in terms

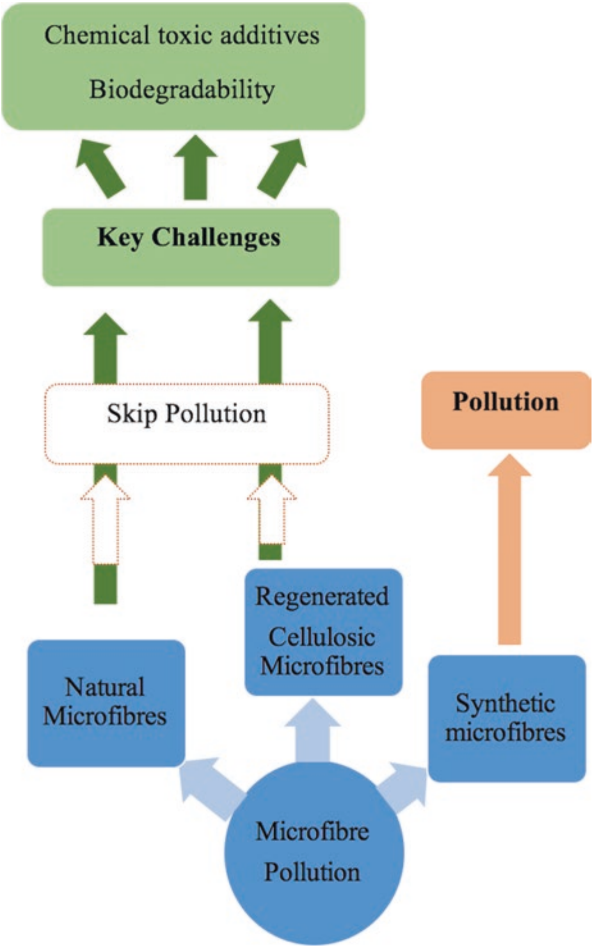

Fig. 5 Conceptual model shows how experts define MFP and its key challenges. (Authors' own)

of how MFP is defined. This supports previous research [30–32] in that without a clear definition of what microfibres are MFP cannot be communicated in a coherent manner.

Aside from more technical issues a further challenge that has been highlighted by the experts concerns consumers, in that there is a need to further integrate and educate them about tackling MFP. Although consumers can help to reduce MFP by washing their clothes at a low temperature, reducing the spins and using less detergent, experts indicate that consumers are not aware of the relationship between clothing maintenance and MFP. An explanation could be that information shared surrounding MFP predominantly focuses on scientific facts, such as shedding rates and that these microfibres can be found in deep-sea sediments, and less is communicated in terms of preventative methods and practical solutions, especially when it comes to clothing maintenance practices.

Experts indicate that ‘labelling’ may be one option on how to provide better information on how to care for garments and increase MFP awareness. Experts highlight that labels sewn in garments can provide useful information such as on material components and care instructions. Expert #2 states: *I think there is a big gap in ‘what people understand or what people know about their clothes’. You know things might be on the label, just thinking about how much of that information that people can get from label […] But I suppose there is a lot of people that do not know about them, despite the information are already there.* This concurs with a key challenge identified in the literature (e.g. [42]) in that consumers may not have the ability to decipher the message as labels in general; whether they link to environmental aspects or care instructions are not always straight forward [42]. Expert #8 further voices concerns: *if people do not understand or know about the information, for example, synthetic fibres are mainly plastics, how can they make ‘correct’ decision from that?* They call for a more straightforward approach on reporting information that allows consumers to easily identify and decipher the message at hand. *In the media lately, I have seen a lot fashion labels that might be more ethically engaged or environmentally engaged. They are trying to expand the information that they put on their labels, kind of telling you the story about the garment rather than just putting very basic key information (100% cotton, made in China…). I suppose that is the first-step for engaging with consumers.*

In addition, some experts argued that labels need to consider giving adequate information about the whole life cycle of clothes, rather than just telling consumers ‘where the garment comes from and what it is made of’, the instruction of use, or that maintenance phase is important. *I suppose there is a comparison with food addressing ethical labels; people could suddenly understand where their food comes from. But for clothing, it is not only about where the things come from, we need to think about the whole lifecycle of clothes, ‘how things can be used’. You know the use stage of clothes is crucial, the social cultural connection makes people think we have to stay clean, so people usually wear one or two times before putting it in the wash, as a result it could increase the negative impact on microfibre issue* (Expert #4). This indicates that care instructions would not only reduce MFP and thus have a positive impact on the environment but also could further prolong the lifespan of the garment. The experts unanimously agreed that whilst it is important for consumers to take responsibility and play an active part in reducing MFP, the responsibility needs to be shared, in that producers also need to be engaged in the process and make information easily available.

From the data set it becomes apparent that communication plays a vital role in addressing the issue of MFP, whether this is through introducing detailed care labels or portraying a more balanced view in the media, in terms of what is currently going on (scientific facts) and how to help prevent the impact (practical solutions).

What Are Potential Alternatives to Reduce MFP According to Industry Experts?

As highlighted in the previous sections there are various challenges with MFP stemming from the source of microfibres (regenerated cellulosic, natural, synthetic) and the resulting issues concerning biodegradability. The experts believe that more needs to be done to investigate options on enhancing biodegradability, which would dramatically reduce parts of the problem. A further issue indicted concerns communication processes and the use of inventions, such as Cora Balls and the Guppyfriend Bags, which could prevent microfibres reaching the waste water stream, yet a lack of communication and instructions might make this challenging. Expert #6 further highlights that *I do not know if there is anything available out there that can solve it (MFP)*? This suggests that more research needs to be done to tackle this increasingly pressing issue. Experts also indicate that current information on social media is predominantly *about the fact and the fear… but yet there is no solution, you feel lost actually.* It is highlighted that consumers may gain increased awareness of the issue, but if there are no solutions offered this bleak backdrop will not change in the near future, with a risk emerging that this is becoming simply a buzzword that is almost meaningless.

Expert #9 emphasises that it is important to create *some standards; could come from the measurement of those released microfibres, toxins used, and filter systems for example*; as this could provide a baseline of communication and create a more solution-based approach.

Conclusion and Implications

A key contribution of our chapter is the fact that MFP is seemingly discussed from two different points of view. In the first instance it is looked as a problem that stems from synthetic microfibres, as these are linked to microplastic pollution and associated with petroleum-based raw materials that take centuries to degrade (if at all). An alternative view is considering challenges associated with microfibres deriving from regenerated cellulosic or natural fibres, whereby solutions need to be found to enhance their natural biodegradability after treatments with dyes, toxins and coatings. As such, there is a key distinction between what is considered to be a problem and what is considered to be a challenge.

It was further highlighted that tackling MFP cannot be a single stakeholder problem, but rather needs to be addressed collaboratively by all stakeholders. This implies that companies, media and consumers all share responsibility in the manufacturing process, the way it is broadcasted, and how garments are looked after, respectively. An important implication here is that communication concerning MFP needs to be enhanced and balanced in terms of providing scientific facts and practical solutions in order to avoid MFP becoming a seemingly ‘meaningless’ buzzword.

To reiterate this further, a 'meaningless' buzzword here implies that the issue remains a key concern, yet due to the lack of available alternatives and/or solutions it cannot be tackled, thereby leading to a feeling of frustration and helplessness.

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Sustainable, Renewable, and Biodegradable Poly(Lactic Acid) Fibers and Their Latest Developments in the Last Decade

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Abstract PLA [**p**oly(**l**actic **a**cid)] is a sustainable, renewable, biodegradable, bioabsorbable, biocompatible linear aliphatic thermoplastic polyester fiber produced from 100% renewable resources like corn, starch, and rice. PLA's melt processing simplicity, sustainable and renewable source origin, exceptional property spectrum, and composting easiness and recyclable nature at the end of its lifetime have resulted in PLA fibers finding an enhancing interest and acceptance over a wide range of commercial textile sectors. PLA can find many different application types from medical and pharmaceutical applications to environmentally benign film and fibers for packaging, houseware, and apparel. PLA stands out as a potential option in many different fields for reducing environmental concerns and for a more sustainable future. In this chapter, sustainable, renewable, and biodegradable poly(lactic acid) fibers and their latest developments in the last decade are comprehensively reviewed. First of all, poly(lactic acid) is introduced. Then, the recent studies about the usage of PLA in various biomedical application types such as tissue engineering, wound dressing, drug-delivery systems, antibacterial mats, and biosensors are reviewed. Then, the information regarding the recent improvements in the wet processing of PLA fibers (such as scouring, bleaching, surface modification, and dyeing) with modern sustainable processing techniques is given. Finally, 3D printing with PLA is also mentioned.

Keywords Poly(lactic acid) (PLA) · PLA fiber · PLA biomedical applications · PLA wet processing · 3D printing

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Introduction

As people in the twenty-first century become progressively environmentally aware, environmentally friendly crops have come into emphasis. Per se, environmentally friendly textiles and eco-textiles have become an international tendency in research and advancement. Most synthetic polymers are consequent of nonrenewable petroleum incomes and incapable to degrade quickly in landfills (at present over 80% of solid waste that accrues on beaches is plastic and by 2050 the weight of the plastic wastes in the sea is expected to reach to the weight of fish) [1]. The disposal of these wastes not only reasons air pollution and underground water infection but also adds to global warming or the "*greenhouse effect*," all of which are damaging to human and animal life. Because of the high consumption of polymers and the instable price of petroleum-based materials based on oil fees, biodegradable, sustainable, and renewable polymers such as poly(lactic acid) (PLA) that called "Green Polymer" have been advanced [2, 3]. PLA *(poly(lactic acid) or polylactide)* $[(C_3H_4O_2)_n]$ is a *sustainable*, *renewable*, *compostable*, *biobased*, *biodegradable*, *bioabsorbable*, *biocompatible* linear aliphatic thermoplastic polyester [4–8] manufactured from 100% renewable resources like *corn*, *starch*, *sugar cane*, *wheat*, *sweet potato,* and *rice* [4, 9, 10].

The strategic advantages of PLA are the lower-energy consumption requirement and the lower greenhouse gas emission during production; besides, it can be biodegraded to water and CO_2 by the end of its life cycle [11]. The PLA market is estimated to spread 5.2 billion US dollars in 2020 for all of its industrial usages [12] . The chief uses are separated into areas, for instance, packaging, agriculture, electronics, textiles, biomedical, and others. Packaging applications have the maximum part (65.2%) in the worldwide market in 2014 owing to its good mechanical, thermal, and barrier properties [1, 13].

It is a polymeric helix with an orthorhombic unit cell. Lactic acid (2-hydroxypropionic acid, CH_3–CHOHCOOH) is the monomeric structural block of PLA. Lactic acid (a simple chiral molecule) is created commercially by means of a fermentation procedure from natural crops, or by the use of petrochemical feed stocks, though; the petrochemical way to lactic acid is not frugally possible now. Furthermore, the lactic acid made by the petrochemical method provides the racemic mixture of L- and D-enantiomers, which is not very beneficial in the industry. Starch (mainly corn starch) is converted to lactic acid via bacterial fermentation by a strain of *Lactobacillus* in the fermentation way. The lactic acid manufactured through this way is generally (99.5%) the L-isomer that presents the high mechanical strength into the PLA polymer after polymerization [14, 15]. Presently, high-molecular-weight PLA is usually manufactured by means of polycondensation and/or ring opening polymerization of lactic acid. The stereochemistry of PLA is significant since the stereo-regularity permits the creation of a highly crystalline PLA [16]. When the D-content is high in the polymer (>20%), a completely amorphous PLA can be attained, while highly crystalline PLA can only be got when the D- content is low (<2%). PLA has stereoisomers, for example, poly(L-lactide) (PLLA), poly(D-lactide) (PDLA), and poly(DL-lactide) (PDLLA) [13, 17]. PLLA has reached enormous attention in medical applications due to its excellent biocompatibility and mechanical properties [15, 18].

PLA is not only biodegradable, but also *bacteriostatic*, *flame retardant*, and displays *weather resistance* [19]. It should be noticed that PLA's melt processing simplicity, sustainable and renewable source origin, exceptional property spectrum and composting easiness and recyclable nature at the end of its lifetime have resulted in PLA fibers finding an enhancing interest and acceptance over a wide range of commercial textile sectors [20]. The conversion of PLA into textile constructions is difficult and depends on the structural variations in the polymer throughout various treatments [21, 22]. PLA fiber can be made into *monofilament*, *multifilament*, *short fiber*, *false twist textured yarn*, *woven fabric*, and *non-woven fabric*, which make it broadly useful in clothing and industrial fields, for instance, *weft-knitted underwear fabrics, sanitary textiles, medical textiles,* and *agricultural textiles*. Extrusion of the PLA to monofilament and multifilament could be accomplished via mainly melt spinning (mainly), dry spinning, wet spinning, and by dry/jet/wet spinning. There are separate types of all of them that are consequently reflected in fiber possessions. Due to the thermoplastic nature of PLA, it is conceivable to melt the polymer under practical situations. Its conversion to fiber with melt spinning regularly has benefits over wet spinning. It is a solvent-free method and offers a more cheap and ecological method [23]. Manufacturing speeds are generally higher than in solution spinning. Occasionally, though, melt spinning may not be probable. In here, the polymer may degrade when melting or the melt (dope) is thermally unbalanced [24]. In dry spinning solvents are removed by means of thermal evaporation, whereas in wet spinning the thickening of the polymer is carried out in a different fluid which is harmonious with the spinning solvent; nonetheless, it is not itself a solvent for the polymer [25, 26]. Yang et al. [27]. in 2019 examined the properties of PLA multifilament and its warp-knitted fabrics. Multifilament assets were experienced and associated with PET multifilament with various diameters. The 83.3 dtex PLA multifilament was approved to knit the fabric and the fabric possessions before and after dyeing was considered. Consequences presented that the mechanical characteristics of PLA multifilament were equivalent to those of PET. However, poly(lactic acid) exhibited a higher heat shrinkage rate. The dyed PLA warp-knitted fabric displays outstanding color fastness. Owing to the effect of temperature and dye particles throughout the dyeing procedure, the breaking strength, air permeability, and moisture permeability characteristics of the fabric were reduced. In contrast, the elongation at break, abrasion resistance, anti-pilling characteristics, drape, and crochet level of the fabric were improved [27].

PLA can find many different application types from medical and pharmaceutical applications to environmentally benign film and fibers for packaging, houseware, and apparel. In this chapter, the latest (especially in the last decade) technological developments on PLA fiber, their recent end-use application types such as different biomedical application types (tissue engineering, wound dressing, drug-delivery systems, antibacterial mats, etc.), the recent improvements in wet processing of

PLA (such as pretreatment, scouring, bleaching, surface modification, and dyeing) with modern sustainable processing techniques and 3D printing with PLA were reviewed in detail.

Various Biomedical Applications of PLA

The extrusion mark of PLA has high strength and modulus comparable to that of many petroleum-based polymers [28–31]. However, inherent brittleness properties of PLA and its low glass transition temperature around 60 °C have been the main restraints for its usage in variation of fields [6, 32–34]. Furthermore, PLA has some limitations for developed applications such as having a *poor toughness*, *fragility*, *poor melt strength*, *low heat bending temperature*, *narrow processing window*, and *low thermal stability*. PLA is a moderately brittle material with a less than 10% elongation at its break point, and this low toughness property confines its usage in many manufacturing tenders that need plastic deformation at higher stress levels [35, 36]. Numerous modifications including blending with nanofibers, nanoparticles, nanosheets, nanospheres, plant extracts, or drugs have been recommended for enhancing the mechanical, thermal, and physical properties of the virgin matrix and constructing PLA composites [37–39]. Various fillers have been used to overawed PLA limitations. In the structure of environmentally friendly methods and crops, there has been a rising attention on the usage of cellulose nanomaterials, viz. cellulose nanocrystals (CNCs) and nanofibers (CNFs) as natural fillers for PLA to create innovative claims other than short-term packaging and biomedical. Cellulosic nanomaterials are renewable in nature, biodegradable, eco-friendly, and these materials display high strength and stiffness. In the item of eco-friendly courses, various conventional processing systems, for example, *melt extrusion, melt-spinning, and compression molding*, have been utilized to yield PLA composites [3, 34]. These novel hybrid PLA composites develop applications of PLA in technical cases such as *biomedical field* [11, 40–42]; on the other hand it should be noticed that:

- PLA does not create toxic or carcinogenic properties in human tissues [43].
- PLA can undergo scission in the human body [15, 28, 44].
- PLA degrades to monomeric units of lactic acid as a natural intermediate in carbohydrate metabolism [45–47].
- PLA degradation rate matches with the healing time of damaged human tissues [13, 48, 49].
- PLA has similar thermal and mechanical properties to the human tissues [50–52].
- PLA has nice biological interactions with the host bone cells when implanted [4–8].

PLA composites capable for usage in various biomedical procedures (such as *tissue engineering, wound dressing, drug-delivery systems,* and *antibacterial mats*) are discussed in the coming sections [45–47, 53].

Tissue Engineering

Tissue engineering, as one of the most desirable treatment selections, comprises the elements of engineering, material and medical sciences [54, 55], and obtains regeneration possibility for virtually every tissue and organ of the human body [56–59]. Ceramics, bioactive glass, and hydroxyapatite (HA) are opportunely modified to render PLA polymer more biomimetic and able to increase human tissue regeneration [11]. In a research in 2018, PLLA nanofibers were effectively decorated by ECM derived from osteoblastic cells via decellularization of MC3T3-E1 cells grown for 2 weeks. The outcomes revealed that use of ECM on PLLA nanofibers developed mouse bone marrow stromal cell (mBMSC) adhesion, holding cell proliferation and supporting osteogenic differentiation of mBMSCs [60].

In another research in 2018, dexamethasone-loaded multilayer PLLA composite nanofiber scaffolds were fabricated for bone tissue engineering. The scaffolds have suitable surface properties. Multilayer scaffolds where the drug was in the middle layer showed the best osteogenic proliferation and differentiation [61]. In a work in 2017, Chu-Jung Su et al. [22] fabricated PLA nanofibers via a modified electrospinning process; then mats were coated with chitosan/calcium silicate (CH/CS) mixer. Chitosan is a biomaterial that has the advantages such as high biocompatibility, low inflammatory responses from host, antibacterial features, and high biodegradability. On the other hand, CS-based ceramics are typically utilized in hard tissue engineering because of a higher point of biocompatibility, bioactivity, and biodegradability. Liu et al. [30], in 2016, studied PLA nanocomposite fiber mats with graphene oxide (GO) (for improving the mechanical properties of PLA) and nanohydroxyapatite (nHA) (because of its chemical likeness to the inorganic constituent of bone [62]). nHA content (15–18 weight total percent (wt%)) is required to hold the adhesion and growth of osteoblasts on the scaffold surfaces. Tensile assessment results specified that the scaffolds with 15 wt% nHA and 1 wt% GO fillers showed higher tensile strength among the samples studied.

In a research by Hadjizadeh et al. [36] tri-fluoroacetic acid (TFA) was used as a cosolvent, in a mixture with dichloromethane (DCM) for electrospinning process of PLA. Nanofibrous mats held neural stem cell (NSC) expansion and spreading, as tested by means of AlamarBlue assay and fluorescent microscopy, correspondingly. Fibrinogen/PLA (FBG/PLA) nanofibers were made as scaffolds for vascular tissue engineering and culturing the human umbilical endothelial cells (HUVECs) [63]. The combination of thermally induced phase separation (TIPS) and electrospinning approaches was used to construct PLA/gelatin nanofiber/PRP (platelet plasma) scaffolds for peripheral nerve regeneration. The results demonstrated that when GTNF/PRP is combined to the PLA scaffolds, resulting mechanical characteristics, porosity and cell attachment, and viability in vitro were superior than pure PLA [64]. A bicomponent scaffold with a core–shell structure which combines the assistances of PLA and chitosan (CS) was equipped via electrospinning accompanied with automatic phase separation and crystallization. The mineralization of HA and culture consequences of preosteoblast (MC3T3-E1, mouse osteocalcin) cells on these scaffolds designates that the external CS component and rough nanoscale topography on the surface of the nanofibers balanced the hydrophilicity and hydrophobicity of the fibers, improved their mineralization ability, and made them more beneficial for the attachment and growth of bone cells [65]. In other investigation in 2017, researchers created PLA-based nanofibrous non-wovens that were modified utilizing two types of modifiers, namely, gelatin (GEL)-based nanofibers and carbon nanotubes (CNTs) for bone tissue engineering. Mats being composed of PLA and GEL nanofibers (PLA/GEL), as well as CNT-modified PLA nanofibers with GEL nanofibers (PLA + CNT/GEL), were produced utilizing concurrent electrospinning method (co-ES) [11].

Wound Dressing

Wound healing is a multifaceted process [66–68] that requires designing a suitable wound-healing system or dressing [69, 70] which possesses key factors like a wet wound location [71–73], avoidance of microbial action, and absorption of exudates [74–76]. Various wound dressings can be available [77, 78] but not all can meet the exact situations of an impeccable wound-healing organism to create comprehensive appropriate wound-healing procedure [79, 80]. PLA wound dressing is one of the best options [16, 21, 81–84]. In the newest research in 2018, a PLA nano-biocomposite was fabricated for acute wound dressing. Dry nanofiber bacterial cellulose (BC) sheet was coated by PLA. Bacterial cellulose is a class of peerless non-plant cellulose which is being created with the help of different types of bacteria, for instance: *Acetobacter xylinum, Agrobacterium, Gluconacetobacter, Rhizobium, Achromobacter, Alcaligenes, Aerobacter, Azotobacter, Salmonella, Escherichia,* and *Sarcina.* BC membrane is utilized for wound dressing because of its broad ultrafine network which eases wound-healing location, advances the wound exudates absorption, decreases scarring, and enhances the re-epithelialization simultaneously leading to an increase in healing rates. The BC sheets can be enhanced by using a biopolymer for providing remarkable mechanical tenacity and porous surface morphology [85]. Carvacrol (CAR) is one of the best capable vital oil components with antimicrobial activity. Scaffaro et al. [86] studied the possibility of incorporating CAR into PLA nanofibers. PLA membranes comprising regularly dispersed CAR were effectively prepared and a series of systematic examinations containing morpho-mechanical characteristics, in vitro releasement ratio, and antimicrobial/anti-biofilm activities against *S. aureus* and *C. albicans* were approved. A novel extracellular matrix (ECM) mimicking nanofibrous wound dressings from PLA and cellulose acetate (CA) was manufactured in 2017 [72]. Thymoquinone (TQ) was included into the scaffolds for avoiding prevalent medical infections, and for hastening the amount of wound closure and re-epithelialization. The TQ-laden PLA/CA wound dressings suggested several benefits like mimicking the ECM through the 3D nanofibrous structure and encouraged the cell proliferation because of the hydrophilicity and bio-activity of cellulose acetate. In another work in 2017, PLA nonofibers were utilized as a delivery system for propolis ethanolic extract (PEE) and silver nanoparticles (AgNPs) which are recognized for their famous *antiseptic* and *antimicrobial* activity that progressed wound healing. The average diameter of PLA nanofibers was 168 ± 29 nm. Adding 10 wt% or 20 wt% PEE increased the diameter to 282 ± 25 and 371 ± 25 nm, correspondingly. Also, the suspension of AgNPs caused the creation of thicker nanofibers with 254 ± 25 nm diameter. Electrospun PLA nanofibers with PEE sustained viability of HaCaT cells. Examination of antimicrobial activity proved the capacity of PLA/AgNP nano-mats for decreasing the microorganism growth [87]. Mohiti-Asli et al. [51] report effective association of ibuprofen in PLA nanofibers to produce scaffolds for the treatment of acute and chronic wounds. Nanofibrous PLA scaffolds holding 10, 20, or 30 wt% ibuprofen were constructed and ibuprofen release characteristics quantified. Degradable anti-inflammatory scaffolds having 20 wt% ibuprofen help human skin cell viability and proliferation in vitro and decrease wound contraction in vivo [51]. An effective association of curcumin (Cur) into a blend of PLA and hyper-branched polyglycerol (HPG) was implemented by Govindraj et al. [84]. for wound healing.

Drug-Delivery Systems

Various scientists have revealed the process of PLA drug-delivery systems in human body for various transdermal usages such as wound dressing and tissue engineering scaffolds [73, 83]. PLA nanofibers with a defined release with doxorubicin were created. Differential scanning calorimetry was employed to recognize the existence of DOX within nanofibers. Differential scanning calorimetry outcomes displayed that the DOX was loaded in the nanofibers effectively. In vitro drug release in phosphate buffered solution and acetate buffer for the optimized and non-optimized mats proved that diffusion is the dominant drug-release mechanism for nanofibers. The initial burst release was monitored for non-optimized nanofibers in comparison with the optimized nanofibers [88]. Dzikowski et al. [71] evaluated PDLLA (poly-D,L-(lactic acid))/PCL (poly(ε-caprolactone)) nanofibrillar matrices attained via jet spraying and having ciprofloxacin (CIF). CIF-release profiles were not controlled with the polymer blend ratios. Nevertheless, sustained release was perceived over more than 23 days. Owing to the antibiotic pH-dependent solubility, burst release was more protuberant in acidic conditions [71]. Nanofibrous PLA scaffolds holding 10, 20, or 30 wt% ibuprofen were produced, and ibuprofen-release profiles were calculated. The 30 wt% ibuprofen-loaded PLA scaffolds at 37 °C showed the highest ibuprofen release, ~0.25 mg at 336 h. At both room temperature and 37 °C, the data recommended that a direct correlation occurred between ibuprofen concentration in the scaffolds and the quantity of ibuprofen released [89]. Jiang et al. [52] considered the release behavior of tetracycline hydrochloride-loaded PLA/chitosan (PLA/CS/Tet) nanofibers fabricated using electrospinning system. The electrospinning solution was a blend of Tet, CS formic acid solution, and PLA chloroform/ethanol solution. The interface between CS and PLA in CS/PLA nanofibers was approved to be hydrogen bond. The incorporation of Tet led to a small reduction in the diameter of nanofibers with Tet content below 30%. In another research study, mefoxin (an antibiotic drug) loaded PDLLA nanofibers made with enhancing the instrumental factors such as electric field, concentration, salt addition, and feeding rate. Nanofibers were treated in a 20 mL buffer solution for in vitro drug-release examination. Complete release of the drug at 48 h was proven from the releasement profile [90].

Antibacterial Mats

Nanofibrous mats of PLA and poly(ethylene glycol) (PEG) were organized via solution blow-spinning. Terpinen-4-ol, a chief phytoconstituent from tea tree oil (*Melaleuca alternifolia*), was included to the fibers, and their antimicrobial activity against *Aggregatibacter actinomycetemcomitans* (ATCC 00078) was investigated. Nanofibers with terpinen-4-ol displayed an operative antimicrobial activity against *A. actinomycetemcomitans* [91]. Hybrid PLA/titania (PLA/TiO_2) fibrous membranes revealing outstanding air filtration performance and noble antibacterial activity were equipped with the utilization of the electrospinning method. By means of changing the composition of the forerunner solutions and the relative humidity, the morphologies of PLA/TiO_2 fibers, including the nano-pores and nanometer-scale protrusions on the top layer of the fibers, could be controlled. The spreading of nano-pores and TiO_2 nanoparticles on the surface of PLA/TiO_2 fibers was explored. Nitrogen adsorption–desorption investigation exposed that nano-pores and nanometer-scale protrusions play a significant character in refining the specific surface area and nano-pore volume of the applicable PLA/TiO_2 fibrous membrane. Filtration performance assessments directed through determining the penetration of sodium chloride aerosol particles with a 260-nm mass median diameter designated that fibers with a high surface roughness, large specific surface area, and large nano-pore volume significantly enhanced the particle detention effectiveness and simplified the penetration of airflow. Moreover, the introduction of TiO_2 nanoparticles gives the significant fibrous membrane with antibacterial properties. The PLA/TiO_2 fibrous membrane loaded with 1.75 wt% TiO_2 nanoparticles designed at a relative humidity of 45% demonstrated high filtration efficacy (99.996%) and a relatively low pressure drop (128.7 Pa), besides a high antibacterial activity of 99.5% [92]. In another work, PLA and poly(vinylpyrrolidone) (PVP) nanofibers loaded with copaiba (*Copaifera* sp.) oil were created using solution blow-spinning. Copaiba oil is extracted from *Copaifera* L., a tree natural to steamy areas of Latin America and West Africa. Some of the vigorous substances in copaiba oil are β-bisabolol, an anti-inflammatory agent, and β-caryophyllene, a bactericidal and anti-inflammatory composite. The copaiba oil was described by means of gas chromatography (GC). PLA and four PLA/PVP blends holding 20% (wt%) oil were spun. GC analysis proved that the chief component of the copaiba oil was β-caryophyllene, a recognized antimicrobial agent. In vitro release examinations of copaiba oil volatiles exhibited a higher release rate in nanofibers having PVP. Nanofibers prepared from blends holding higher quantities of PVP had superior antimicrobial act against *Staphylococcus aureus* [93].

Biosensors

Nootsuwan et al. [94] formulated nanosilver-coated carbon black through benzoxazine oxidation as a filler for PLA to create new hybrid materials with enhanced electrical properties. The optimum structure of the hybrid materials was found to be 15 phr of nanosilver-coated carbon black in PLA (15AgCB-PLA) [94]. Biotin surface-functionalized PLA nanofibers are produced as biosensors. Variable concentrations of biotin (up to 18 weight total percent (wt%) were combined to PLA fibers together with poly(lactic acid)-block-poly(ethylene glycol) (PLA-b-PEG) block polymers. The incorporation of PLA-b-PEG block copolymers not only reduced fiber diameters but also affectedly improved the quantity of biotin accessible at the fiber surface capable to bind. Fiber water stability examinations exposed that both biotin and PLA-b-PEG migrated to the aqueous phase after comparatively extended times of water exposure. These nanofibers display a possible application as a biosensor for point-of-care diagnostics [95].

PLA Nanoparticles as Gene-Delivery Systems

Polymer nanoparticles (NPs) signify one of the most advanced non-aggressive methods for drug-delivery uses. One of the usage types of NPs is to carry the therapeutic molecules such as drugs, proteins, or nucleic acids straight into the targeted organ or tissue. PLA NPs are made of simple monomers which are naturally present in the body and consequently simply defecated without being toxic [96]. Tri-block PLA/poly(ethylene glycol)/PLA (PLA/PEG/PLA) copolymers are among the most active nano-carriers for gene delivery into mammalian cells, because of their biocompatibility and biodegradability properties. In a novel effort in 2019, researchers examined the nanoparticles formulated with the polyethylenimine (PEI) associated with PLA–PEG–PLA copolymer for effective DNA encapsulation and delivery. PLA–PEG–PLA/DNA and PLA–PEG–PLA/PEI/DNA nanoparticles with various concentrations of PEI were organized by the double emulsion-solvent evaporation system. The flow cytometry examination exposed that through increasing the mass ratio of PEI:(PLA–PEG–PLA) (w/w%) in PLA–PEG–PLA/PEI/DNA nanoparticles, the proficiency of the gene delivery into MCF-7 cells was enhanced. The consequences also confirmed that PLA–PEG–PLA/PEI/DNA nanoparticles in the serum medium enhanced the efficiency of gene delivery more than twofold, compared to PEI/DNA complex [97].

Food Packaging

An innovative method to improve the antimicrobial properties of PLA packaging films through holding their thermo-mechanical properties was tested. ZnO nanoparticles were deposited on the outer and inner sides of halloysite nanotubes (Hal) with a new solvothermal technique, and these ZnO deposited Hal (ZnO-Hal) were combined into the PLA matrix as reinforcing filler. PLA composite films were made up by means of the solution casting process with different filler loadings (0–10 mass%). PLA films with ZnO had inferior mechanical properties while PLA films with ZnO-Hal presented noteworthy developments, where tensile strength and modulus improved by 30% and 65% with the adding of 5 mass%, correspondingly [98]. In a different research in 2017, carboxymethyl chitosan was processed to nanopowder (NCMC) form with a diameter of 483 nm over ball-milling. Four hundred milligrams of NCMC was effectively electrospun to nanofibers with the assistant of 4-g PLA to formulate NCMC/PLA nanofibrous composite mats. NCMC/PLA mats with different morphology could be organized through changing the electrospinning voltage at 12–30 kV and the distance at 10–22 cm. X-ray photoelectron spectroscopy and Fourier transform infrared spectroscopy confirmed the presence of NCMC in the composites [33]. Another packaging material was gained via combining cinnamon essential oil/bcyclodextrin inclusion complex (CEO/b-CD-IC) to PLA nanofibers via electrospinning method. The CEO/b-CD-IC was organized through the co-precipitation system, and scanning electron microscopy (SEM) and Fourier transform infrared (FTIR) spectroscopy analysis specified the effective creation of CEO/b-CD-IC, which developed the thermal stability of CEO. The CEO/b-CD-IC was then incorporated into PLA nanofibers via electrospinning, and the PLA/CEO/b-CD nanofilm presented improved antimicrobial activity compared to PLA/CEO nanofilm [99].

PLA Fiber Wet Processing

To attain the best use of the PLA fiber fabrics in respect of their physical features (strength, hand, drape, etc.), the serious attention is needed to determine the correct wet-processing procedure types (pretreatment such as scouring, bleaching process, surface modification using UV/ozone treatment, plasma treatment, and dyeing) and their related process conditions. The recent improvements in wet processing of PLA with modern procedures were discussed in the coming sections.

PLA fiber has emerged as an eco-friendly substitute to conventional poly(ethylene terephthalate) (PET) polyester fiber in many textile and clothing goods. Though it is alike to PET in many features, this fiber requires to some extent altered pretreatment and dyeing settings and conditions from PET to maintain its strength and other necessary features during production and daily usage [42, 100]. The mechanical possessions of PLA fibers are deliberated to be approximately alike to those of conventional PET fibers [101]. The specific gravity of PLA fibers is lesser than that of PET fibers. The melting point of PLA fibers is between 130 °C and 170 °C, while that of PET fibers is in the variety of 254–260 °C [102]. Elastic recovery of PLA fibers at 5% strain is greater than that of PET fibers [103]. PLA fibers display higher sensitivity to alkali than do PET fibers. Some loss of fiber strength throughout following wet treating is perceived if care is not occupied in the dyeing and finishing of the PLA fiber owing to these mentioned sensitivities [63, 104]. It necessitates lower-temperature conditions and some procedure alterations in pre-heat setting, scouring dyeing, finishing, and posttreatments [105].

Scouring Process

PLA was not damaged throughout the scouring process with a non-ionic detergent and sodium carbonate up to 5 g/L. A treating temperature up to 60 °C (T_g) should be used for PLA and the pH must not surpass 11. The SEM investigation specified that scouring above T_g produced the creation of pin holes in the structure of fibers; the surface deformation was higher at 100 °C [106].

Bleaching Process

Bleaching with sodium hypochlorite at 40 °C for 30 min did not affect negatively in respect of the tensile strength. Sodium chlorite concentration as high as 10% weight of fabric (owf) at 85 °C was found to be suitable. Bleaching with hydrogen peroxide up to 50 mL/L at ambient settings did not affect negatively the PLA tensile strength. Alkaline-oxidative conditions were more harmful to PLA polymer than acidic-oxidative conditions; the lower the application temperature, the lower the fiber damage. ATR-FTIR spectroscopy of scoured and bleached PLA designated that few or no new functionalities were introduced into the PLA polymer. The XPS of pretreated PLA exposed that through scouring and bleaching newer surfaces were unprotected and that bleaching with sodium hypochlorite and sodium chlorite was less damaging than hydrogen peroxide. It was stated that the polar groups for example hydroxyl and carboxyl produced in the pretreatment process might increase the adhesion of textiles to several coatings and decrease the static charge buildup [106].

Surface Modification

Surface modification of the fabrics by means of various systems such as plasma treatment, alkaline hydrolysis, and treatment with enzyme is a dynamic region of the investigation in the textile industry [5, 107]. For using a PLA fabric in the textile industry, appropriate pretreatment surface modification procedures can be designated to improve the usability of PLA in different applications. For instance, researchers evaluated the hydrolytic action of a proteolytic enzyme (*Alcalase* from *Bacillus licheniformis*) on PLA fibers. The special effects of an additive on the enzymatic hydrolysis were also investigated. The consequences exposed that the optimum enzymatic-hydrolysis situations for this Alcalase are: pH 9.5, temperature 60 °C, enzyme concentration 50% on weight of fabric (owf), and L-cysteine concentration of 3 mM. PLA fabrics were hydrolyzed efficiently, but there was no damage to these fabrics judging by tensile strength and surface observations. X-ray diffractometry recognized a new peak (at $2\theta = 18.5°$), implying a morphological change produced with the treatment. Besides, hydrophilic properties such as moisture regain and dyeing properties were improved via this proteolytic enzymatic hydrolysis. So, enzymatic hydrolysis can be chosen as an appropriate technique for improvement of hydrophilicity of PLA fabrics [108].

Plasma Treatment

To attain bifunctional PLA fibers from the opinion of hydrophilicity/hydrophobicity, both sides of a PLA fabric were exposed to a plasma treatment [109]. The plasma treatment was accomplished at 100 W, 1.8 mbar, throughout 30 min. By means of scanning electron microscopy (SEM) morphological investigation, it became apparent that the fabric side facing the oxygen inlet presented micropittings, whereas the opposite side had flat surfaces. Analysis by X-ray photoelectron spectroscopy (XPS) exposed an increase in the quantity of oxygen in the surface of the PLA on both sides of the fabric. The surface function was considered using measurements of water absorption rate, where it was controlled that one fabric side was more hydrophilic than the other side. The consequences designated a success of a bifunctional fabric through orientation of employed gases via a plasma treatment [110]. Physical assets of pre-electrospinning polymer solutions play an important character in electrospinning as they powerfully control the morphology of the gained electrospun nanofibers. In a novel research in 2018 by Rezaei et al. [111], an atmospheric-pressure argon plasma straight immersed in the liquid phase was used to alter the physical characteristics of PLA spinning solutions for advancing their electrospinnability. The electrical features of the plasma were explored by means of two systems—V–I waveforms and Q–V Lissajous plots—while the optical emission appearances of the plasma were also controlled via optical emission spectroscopy (OES). Furthermore, a fast intensified charge-couple device (ICCD) camera was utilized to image the bubble dynamics during the plasma treatments. The results demonstrated the plasma treatment persuade important modifications to the chief physical characteristics of the PLA solutions leading to an improvement of electrospinnability and development of PLA nanofiber construction [111]. It is known that it is difficult to create deep dyeing effects on PLA fibers. In a different research Wang et al. [112] used chitosan, *succine anhydride*, *siloxane*, and *polyethylene glycol* to create a series of chitosan/siloxane polyesters that have a hydrophilic part (chitosan) and a hydrophobic part (siloxane), and this chitosan/siloxane polyester can be covered on PLA fiber, which they had exposed to argon plasma treatment for developing their antimicrobial properties and increasing the fibers dyeing efficacy. The results demonstrate that, after the surface plasma treatment, longer PEG chain lengths caused greater color yield (K/S) values leading to higher color strength. So, the surface plasma pretreatment and chitosan/siloxane polyesters coating presented that lower DE values cause more leveling dyeing of PLA fiber [112]. The effect of oxygen plasma treatment on PLA fabric and the effect on its wetting features were also studied. A different analytical structure, based on image analysis, was established for assessing the rate of spreading and dynamic movement of liquid over the fabrics. The techniques of X-ray photoelectron spectroscopy (XPS) and scanning electron microscopy (SEM) were used to test the nature of the surface modifications after the plasma treatment. The tests displayed that the oxygen plasma treatment abraded the surface of the PLA fibers; nevertheless, it did not change their chemical nature. The improved surface abrasion made alteration to the wetting or wicking rates of water on PLA fibers [113].

UV/Ozone Treatment

One of the operative and efficient procedures of surface modification of natural polymers and synthetic polymers, such as polyethylene, polypropylene, polyacetylene, and PET, is ultraviolet/ozone (UV/O_3) irradiation [114, 115]. Excitation and dissociation of the polymeric molecules occur throughout exposing the surface to the UV/O_3 treatment, which is recognized as a photosensitized oxidation procedure. This treatment alters the surface morphology and topography of the polymer. The SEM (scanning electron microscopy) images displayed a noticeable growth in the grain size and the surface roughness of the irradiated polymer in comparison to the surface of the untreated examples [2, 116, 117]. Fattahi et al. [5] explored the influence of UV/ozone irradiation together with the pretreatments via distilled water, hydrogen peroxide, and hydrogen peroxide/sodium silicate solutions on the dyeing depth of the PLA fabrics with the use of disperse dyes, and the consequences were associated with that of the untreated fabrics. The outcomes revealed that the reflectance and the lightness ($L*$) level of the treated PLA fabrics reduced and these decreases maximized by the pretreatment of the fabrics with the *hydrogen peroxide/ sodium silicate* solution. The SEM images of the PLA fiber fabrics displayed an alteration in the surface morphology of the treated fabrics which is accredited to the extended etching influence of the UV/ozone irradiation [5].

Dyeing

The hydrolytic degradation of PLA fibers in the conservative aqueous dyeing situations limited its uses in textile industry. A novel sustainable and hydrolysis-free dyeing method was advanced for PLA fibers. A solvent dyeing procedure was established by means of *liquid paraffin* as a nonaqueous dyeing medium [118].

High-quality dyed PLA fabrics were gained without overwhelming water and auxiliaries. Nominal strength loss of dyed fibers was attained by post-heat setting treatment. The *3R principle (reduce, reuse, and recycle)* was applied to confirm the environmental friendliness of solvent dyeing procedure. The consequence of a 9-cycle reclaim system confirmed the exceptional color uniformity of dyed PLA fabrics. The sustainability of this novel dyeing procedure was calculated in the charter of *environmental/health/social* impact. The dyeing technique sustainability index designated that the solvent dyeing route was favored over the aqueous dyeing. This process qualified the useful utilization of PLA as textile fibers [118]. Researchers considered the dyeing procedure of PLA and PHBV blends and the investigational outcomes displayed that an admirable dyeing influence and bursting strength can be attained via suitably applied dyes (C.I. disperse orange 30, red 74, and blue 79) under optimum low-dyeing-temperature settings (100 °C, 10 min, pH 5, LR 30: I) [119]. Dispersant-free dyeing of PLA fabric with three temporarily solubilized azo disperse dyes which hold β-sulfatoethylsulfonyl group was carried out. The temporarily solubilized azo disperse dyes were effectively applied to PLA fabric without the usage of dispersant. The color strength on PLA fabric was reliant on dyebath pH and dyeing temperature too. The best consequences were obtained at pH 7–8 and 110 °C. The dyes exhibited significantly greater color yields on PLA fabric when compared to the commercial disperse dyes. Wash fastness was very poor but light fastness was respectable [120]. Lee et al. [121] heightened an appropriate dyeing process for PLA fabrics with disperse dyes. For this, C.I. disperse red 60 (DR 60), disperse blue 56 (DB 56), and disperse yellow 54 (DY 54) were utilized and dyed on PLA fabrics reliant on dyeing temperature and dyeing time. The color fastness of PLA fabrics dyed with three disperse dyes were assessed. Additionally, dye exhaustion, color strength (K/S value), and colorimetric properties of PLA fabrics were associated with PET fabrics. PLA fabrics exhibited good color fastness to washing, dry cleaning fastness, hot pressing fastness, rub fastness, and perspiration fastness by DR 60, DB 56, and DY 54. The dye exhaustion of PLA fabrics was inferior to PET fabrics, although color strength (K/S) values of PLA fibers were more than those of PET fabrics.

3D Printing

3D printers establish a fast-growing universal market. These printers are frequently employed in research and advance cases associated with engineering or architecture, mainly for structural components or rapid prototyping. PLA filaments are very popular as a thermoplastic material used in the 3D printing process via “fused deposition modeling” technique in the last decade. On the other hand, 3D printing is a growing technology that has a large financial potential in many industries where PLA is one of the chief elections as the source polymer owing to its ease of printing, environmentally friendly nature, glossiness, and multicolor appearance properties [122]. In this class, PLA filament is fed to the 3D printing mechanism via a clamping cylinder and is melted at the wanted temperature extrusion head and the solid portion of the filament drives the melt into the nozzle and the nozzle could be moved horizontally along the *xy* plane. Throughout this drive, the molten material is deposited on the table, which can be motivated in the vertical *z*-direction. "Fused deposition modeling" (FDM), "fused filament fabrication" (FFF), and "melt extrusion production" (MEM) terms are extensively used for this kind to designate the machineries based on the material extrusion. These methods are essentially similar and only their trade titles are unalike. Wholly the supplied thermoplastic material solidifies rapidly after accumulation. This permits the production of complex 3D substances. PLA plays a significant character in FDM. This printing technology is an inexpensive utensil for the progress of efficient components or cases for electronics. The conductivity of PLA can be improved by means of mixing it with the ionic liquid "*trihexyl tetradecyl phosphonium decanoate*." This offers a method to modify PLA for multifaceted useful goods formed via an efficient fused filament fabrication [123]. Antoniac et al. [124] in 2019 demonstrated the viability of obtaining magnesium (Mg) filled PLA biocomposites as filament feedstock for material extrusion-based additive manufacturing (AM). Filaments were formed from two PLA/magnesium/vitamin E compositions and then used for experiment testers and anterior cruciate ligament (ACL) screws on a low-cost 3D printer. Although the filament built-up procedure could not confirm an even distribution of Mg particles in the PLA matrix, a good integration was observed, possibly owing to the use of vitamin E as a forerunner [124]. Cheng et al. [125] in 2017 examined the capability of the *chemical vapor deposition (iCVD) procedure* to construct 3D printed matters made with PLA and acrylonitrile butadiene styrene (ABS). The thermally insulating possessions of the 3D printed plastics are a challenge for the iCVD method owing to the wide thermal gradients along the constructions throughout processing. The processing parameters, such as substrate and filament temperatures, have been analytically varied to control how these factors mark the equality of coatings during the 3D printed substances. 3D printed items were later covered by both hydrophobic and hydrophilic polymers. Contact angle goniometry and X-ray photoelectron spectroscopy were recycled to describe functionalized surfaces [125].

Conclusions

PLA is a sustainable, renewable, biodegradable, bioabsorbable, biocompatible linear aliphatic thermoplastic polyester fiber produced from 100% renewable resources like corn, starch, and rice. PLA's melt processing simplicity, sustainable and renewable source origin, exceptional property spectrum, and composting easiness and recyclable nature at the end of its lifetime have resulted in PLA fibers finding an enhancing interest and acceptance over a wide range of commercial textile sectors. PLA can find many different application types from medical and pharmaceutical applications to environmentally benign film and fibers for packaging, houseware, and apparel. In this chapter, the latest (especially in the last decade) technological developments on PLA fiber, their recent end-use application types such as different biomedical application types (tissue engineering, wound dressing, drug-delivery systems, antibacterial mats, etc.), the recent improvements in wet processing of PLA (such as pretreatment, scouring, bleaching, surface modification, and dyeing) with modern sustainable processing techniques and 3D printing with PLA were reviewed in detail.

As one can realize, researchers and scientists were aimed to create advance applications for the unique property set obtained from PLA fibers. Many more innovative and futuristic applications will be possible in the near future to increase the usability of PLA for many different purposes and end-use application types. With the future detections and improvements in polymer and fiber and its different processing setups along with future expansions in suitable applications for the fibers, it can be expected that the usage of PLA fibers will develop and enhance speedily in the next numerous years.

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Angela Liliana Dotor Robayo

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