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Sustainable Technologies for Fashion and Textiles

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Part One

Introduction
Sustainability is a main objective in most of the manufacturing sectors and sustainable practices means commitment beyond the company and customers while the community and environment are important. In recent years, sustainable practices have been gaining impetus in garment manufacturing due to increased consumer awareness and stricter global legislations (Fletcher, 2012; De Brito et al., 2008; Marcuccio and Steccolini, 2005). The term sustainability was coined in 1987 in Brundtland report, which means “satisfying the current needs without compromising the future generations’ needs” (Keeble et al., 2003). The sustainable practices are viewed from three perspectives, which are environmental, economic, and social, also known as the “Triple Bottom Line (TBL)” of sustainability (Hacking and Guthrie, 2008). Almost all the three TBL of sustainability are neglected during the production and supply chain activities in the garment manufacturing sector. However, this chapter will only focus on the environmental aspects of sustainability, which is the major concern among the TBL of sustainability.

The fashion and textile manufacturing industries around the world are struggling with varying degrees of environmental problems (Roberts, 2003). The inherent nature of the production processes required for garments largely impacts the environment due to a large amount of energy usage and water consumption; greenhouse gas (GHG) emission; hazardous waste generation; and discharge of toxic effluent containing dyes, finishes, and auxiliaries to the ecosystem (Gardetti and Torres, 2013; Niinimäki and Hassi, 2011). It has been shown that about 20% of all water pollution is caused by the textile treatments such as dyeing, which greatly impacts the environment. Although the carbon emission intensity in garment production (between 1990 and 2005) has been decreased for gray cloth, jute goods, and polyester goods by 1.90%, 2.07%, and 0.72%, respectively, it has not achieved the desired results to save the planet earth (Reddy and Ray, 2014). Cotton yarn production has shown the highest increase in the emission intensity by 7.37%, which indicates that cotton yarn continued to be produced without caring for the environment, due to the consumption of harmful pesticides and fertilizers, which releases hazardous wastes into the nearby land and...
water systems. Hence, there is a need for green practices in the production of sustainable fashion and textiles.

As the term “green production” is becoming important in many of the manufacturing segments, garment producers and retailers are increasingly preparing to adapt this term in order to save the environment and present ethical practices. Vachon and Klassen (Vachon and Klassen, 2008) mentioned that the green production practices can help garment industries to achieve economic benefits of having a higher number of target customers, and to achieve “the edge” over their competitors. Several approaches can be taken to achieve sustainability in fashion and textile manufacturing starting from the selection of raw materials to the end-of-life (EOL) of a product. In fact the first stage of garment manufacturing, the “conceptualisation stage” lays the foundation for the degree of environmental impact (Nayak and Padhye, 2018). This stage can alter the selection of raw materials, which are sustainable and need sustainable process routes for conversion into final product. Sustainable fashion and textile production involves ecofriendly and nondepleting material selection; environmentally friendly manufacturing processes; green supply chain, distribution, and retailing; and ethical consumers (Shen et al., 2014; Choudhury, 2014).

Emerging technologies (e.g., nanotechnology, enzyme processing, laser processing, digital printing, and plasma technology), advanced materials (i.e., renewable and biodegradable materials), and ecofriendly production methods are paving their way for sustainable fashion and textile production (Xing et al., 2007; Mahltig et al., 2004; Dubas et al., 2006; Gomes et al., 2013). The combined actions of manufacturers, government and nongovernment organizations, and finally the consumers can help the objective of zero-emission by 2050 as mentioned in the Kyoto protocol (Huang et al., 2008). Fabric chemical processing, with the greatest environmental impact among other garment production processes, can be made greener by adopting newer technologies such as the use of enzymatic processing; plasma applications; natural dyes; microwave and ultrasound applications; and use of advanced colorants.

In this chapter, a brief introduction has been given on the sustainability of fashion and textiles. Various environmental aspects of “sustainable fashion and textile production” in relation to raw material selection, spinning, weaving, chemical processing, and garment manufacturing have been briefly discussed in this chapter, which are discussed in detail in the corresponding chapters. The importance of ecolabeling, product life cycle (PLC) management and recycling are also included in this chapter. The views expressed by the manufactures of fashion and textiles in Vietnam, the forth largest clothing exporter, have also been included.

### 1.2 Chapter design and preparation

This chapter was prepared using the information gathered from various review and research articles available in different databases, such as Google Scholar, Web of Science, Scopus, EBSCOhost, and Sci-founder. The database search was based on the keywords used in the context of sustainable garment production. Major keywords

The timeframe of the collected literature was primarily based on the last 15 years of academic and research work, but in some cases earlier papers were also included, as they were relevant to the review. The type of papers (>15 years) included mainly published articles in various journals, conference proceedings, and research (Masters and PhD thesis). In some instances, creative sustainable works produced by fashion institutes and research organisations were also included. In the beginning all the possible articles were collected using the above-mentioned keywords. Subsequently, these articles were closely inspected for their abstract and research outcomes as per their relevance in the context of the chapter designed. The articles focusing on the environmental sustainability in garment production were included in the review.

Initially the papers were classified into three groups based on the three sustainability pillars they were covering, such as (i) environmental, (ii) social, and (iii) economic. Subsequently, based on their content, they were classified into subgroups, as shown in Table 1.1.

**Table 1.1** Grouping of articles based on the area of research relating to sustainable fashion.

<table>
<thead>
<tr>
<th>Category</th>
<th>Subgroups</th>
<th>Number of papers</th>
<th>Percentage of papers (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental</td>
<td>Green and sustainable approaches practiced in garment production</td>
<td>23</td>
<td>12.8</td>
</tr>
<tr>
<td></td>
<td>Green and sustainable approaches practiced in textile production</td>
<td>46</td>
<td>25.6</td>
</tr>
<tr>
<td></td>
<td>Sustainable approaches for treating and evaluating effluents</td>
<td>52</td>
<td>28.9</td>
</tr>
<tr>
<td>Social</td>
<td>Workplace related, such as work practice, facilities, light, amenities, tools, and working aids</td>
<td>17</td>
<td>9.4</td>
</tr>
<tr>
<td></td>
<td>Workforce related such as incentives and rewards</td>
<td>13</td>
<td>7.2</td>
</tr>
<tr>
<td></td>
<td>Development of the society</td>
<td>8</td>
<td>4.4</td>
</tr>
<tr>
<td>Economic</td>
<td>Related to business strategies and profitability</td>
<td>9</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>Economic development</td>
<td>5</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>Resource consumption and environmental impact</td>
<td>7</td>
<td>3.9</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>180</td>
<td>100</td>
</tr>
</tbody>
</table>
It can be seen from Table 1.1 that the majority of research works on sustainable fashion and textiles addressed environmental aspects. In this category, the maximum number of publications was targeting the effluent production and treatment, followed by the alternative techniques used to produce sustainable fashion. Social accountability recorded the second highest number of publications, whereas economic development was the lowest, with only 2.8% of the papers.

In addition to the above three groups, which were based on sustainability, the papers were grouped in terms of their type of publication, such as journal articles, conference proceedings, research theses (Masters and PhD), creative works, and newspaper blogs, as shown in Fig. 1.1. As indicated, journal publications accounted for the highest number, at 76% of the total publications collected. The research thesis (Masters) and creative works were the lowest in the group (3% of the total). Although several bachelor’s and PhD theses were available, this review only selected the relevant works addressing the three aspects of sustainability (environmental, social, and economic). It is important to mention that the data collected and the findings of this chapter are based on the number of outcomes, while the specific keywords were used in the selected databases.

1.3 Sustainable fashion and textile

One of the key challenges faced by the fashion and textile industries is adopting sustainability in product manufacturing. Sustainability focuses on the “triple bottom line”: environmental, social, and economic impacts of a product or service (Henriques and Richardson, 2013). From a sustainability perspective, fashion and textile products are inherently at odds with the production process, as designers and product developers face several challenges to streamline a style. This section focuses on the requirements,
fashion consumption, and consumer attitude relating to sustainability in fashion and textiles.

### 1.3.1 Requirements of sustainability

The increasing pressure from international organizations and nongovernmental organizations (NGOs) has created the impetus in the fashion enterprises to adopt the concept sustainability (Hall et al., 2010). Fashion entrepreneurs have realized that environmental sustainability is quintessential to reduce the impacts of fashion manufacturing; and corporate socially responsible practices are the key in gaining competitive advantages to ensure that any negative impact of the industry on society is reduced. Due to the inherent nature and fast-pace of the fashion industry, several fashion manufacturers in the past have used unsustainable practices to meet the demand and gain increased profitability. As there is an increased global trend toward sustainable fashion, many of the current fashion brands are now adopting sustainable practices in the three pillars of sustainability (Choi et al., 2012a). The most important sustainability factor is the environmental impact created during the production of fashion and textiles, which has been discussed in detail. However, the other two factors, economic and social, not discussed in this chapter, are briefly discussed below:

*Economic sustainability is defined as “the ability of an economy to support a defined level of economic production indefinitely” (Thwink, 2014). Economic sustainability focuses on seeking alternative sources of materials, which are natural, biodegradable and recyclable; and energy from renewable resources such as wind and solar energy.*

*The third aspect of sustainability is the corporate social responsibility (CSR), which ensures that the corporations follow the approaches that create minimal harm to the society and contribute towards social improvement while generating profit. Existence of a range of definitions of CSR makes it difficult for the corporations to thoroughly understand the CSR concepts and implement during the business operation. One of the widely used definitions provided by Bowd, Harris and Cornelisen stated CSR as: CSR is corporations being held accountable by explicit or inferred social contract with internal and external stakeholders, obeying the laws and regulations of government and operating in an ethical manner, which exceeds statutory requirements (Bowd et al., 2003).*

Furthermore, the social accountability and economic aspects of fashion and textile production are neglected in many countries, which are a global concern. It is believed that the fashion and textiles produced by sustainable practices can alleviate the ecological and social strains in addition to providing an ethical choice for sustainable-conscious consumers to buy sustainable product (Choi et al., 2012b).

### 1.3.2 Fashion consumption and consumer attitude

Consumers in developed countries discard fashion items more often, even though the items are still useful (Morgan and Birtwistle, 2009). The “throwaway culture” has been
developed as a result of easy availability of low-priced high street clothing and the success of the major brand retailers. The reusability of these garments is reduced if they are out of fashion, poor in aesthetics, and poor in dimensional stability and durability (Steinhart et al., 2013). If not reused, these garments meet with landfill or generation of bonda-waste, depending on the degree of wear, physical condition, type of garment, and fiber composition. The economic viability of recycle and reuse depends on the infrastructure and technology available for recycling.

Birtwistle and Moore (2006) explained that early fashion innovators or early adopters, which account for about 16% of the total consumers, are highly influenced by fashion trends. They buy new fashion items more quickly and use them for socializing only a few times and then discard them leading to “throwaway fashion” (Birtwistle and Moore, 2006). The concept of “throwaway fashion” plays a major role in global sustainability.

Over the last decade, the concept of fast fashion has revolutionized the fashion industry, where new fashion styles are available every week (Joy et al., 2012; Bhardwaj and Fairhurst, 2010). Easy access to the fast fashion stores online and at a competitive price has especially helped young female consumers to fulfill their demand for new fashion styles (Morgan and Birtwistle, 2009). In addition, fast fashion retailers such as Zara, Benetton, H&M, and Topshop are now selling fashion items at competitive prices that are designed to be used less than 10 times then becomes a “throwaway fashion” (McAfee et al., 2007).

To address the “throwaway culture”, consumer ethics has played a significant role in recent years (Barnes et al., 2006). Ethical consumers consider the impact of consumption of a product on the environment, humans, and animals (Barnett et al., 2005). Although ethical consumers are focusing on sustainable products and practices, research evidence shows that many consumers are yet to adopt these practices for certain products (Carrigan and Attalla, 2001; Harrison et al., 2005). Indeed, when fast fashion is considered, consumer awareness on sustainable techniques is found to be low. For example, it is often difficult for consumers to use ethical practices in their fast fashion consumption, as information is hard to find. Hence, the concept of sustainable fashion becomes “unfashionable” which can increase the disposal of fashion products after only limited use (Morgan and Birtwistle, 2009).

The concept of slow fashion, on the other hand, helps consumers to consider the economic models and sustainable practices related to fashion production, distribution, and use (Fletcher, 2010). It helps consumers to pay attention to “valuing and knowing the object” (Clark, 2008a) and integrates experience with self-enhancement values (Manchiraju and Sadachar, 2014). The slow fashion approach avoids several negative factors related to fast fashion, in particular, large volumes of waste and environmental pollution (Clark, 2008b). Clark (2008b) mentions that the approach of slow fashion is just the opposite of fast fashion. Slow fashion offers better sustainable solutions that have a direct and positive impact on design, production, consumption, and use (Fletcher, 2010). The slow fashion approach is based on the practices of food production and consumption for a sustainable living (Parkins and Craig, 2006).

Successful consumer adoption of sustainable fashion model depends on consumer awareness through education on reducing waste and environmental impact.
Furthermore, understanding the consumer’s ethical values and the complex driving factors can provide key guidelines for sustainability in fashion products (Connolly and Shaw, 2006). Recent research demonstrates that barriers such as lack of consumer awareness, inappropriate retail environment, and social norms impact on the movement toward “eco-conscious fashion acquisition” (Connell, 2010).

1.4 Environmental sustainability

The global consumption of fashion and textiles is ever-growing, which creates challenges to the environment (Chen and Burns, 2006). In order to achieve low-cost production, the fashion manufacturers in developing countries take advantage of lack of strict regulations and lower environmental awareness, which hinders environmental sustainability (Nagurney and Yu, 2012). For achieving sustainable fashion and textile production, the fashion manufacturers should focus on the sustainability aspects of production and follow the sustainability guidelines outlined in the ISO 14000 and other environmental management standards (also see Table 1.2). The following section describes the approaches such as selection of raw materials, ecofriendly processes, product life cycle assessment (LCA), and recyclability to achieve environmental sustainability in fashion and textiles.

1.4.1 Raw material selection

While selecting raw materials for fashion and textile production, the objective should focus on renewable (natural fibers such as cotton, flax, wool, and silk) and recyclable materials (fibers such as recyclable polyester and nylon). As the synthetic fibers are not biodegradable, recyclable fibers must be selected so that they are recyclable at the EOL to minimize accumulation of waste. The use of blends such as synthetics and natural fibers should be avoided as it is rather difficult to recycle a blend compared to a single fiber.

Table 1.2 Various categories of ecolabels (Roy Choudhury, 2013).

<table>
<thead>
<tr>
<th>Category</th>
<th>Name of the ecolabel</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>Governmental</td>
<td>Blue Angel</td>
<td>Germany</td>
</tr>
<tr>
<td></td>
<td>Green seal</td>
<td>USA</td>
</tr>
<tr>
<td></td>
<td>Ecomark</td>
<td>Japan, India</td>
</tr>
<tr>
<td></td>
<td>European Flower</td>
<td>EU</td>
</tr>
<tr>
<td></td>
<td>NF environment</td>
<td>France</td>
</tr>
<tr>
<td></td>
<td>Oeko-Tex standard 100</td>
<td>Austria/Germany</td>
</tr>
<tr>
<td></td>
<td>GuT</td>
<td>Germany (carpet)</td>
</tr>
<tr>
<td></td>
<td>GuW</td>
<td>Germany (furnishing)</td>
</tr>
<tr>
<td></td>
<td>GOTS</td>
<td>Global organic textile standard</td>
</tr>
</tbody>
</table>
The natural fibers are not inherently green. For example, the widely used natural fiber cotton, although biodegradable, its production requires a substantial amount of fresh water. The water consumption for the production of synthetic fibers is significantly lower (about 1/10) compared with cotton. For example, acrylic fiber needs 0.3–15 L/kg of water (Cupit, 1996), whereas cotton fiber needs 2000 L/kg. However, the production of synthetic fiber consumes a higher amount of energy. For example, the polymerisation, spinning, and finishing of polyester fiber consume 369–432 MJ/kg of energy, whereas the production of cotton requires much lower energy, in the range of 38–46 MJ/kg of cotton (Cupit, 1996).

Production of cotton fiber consumes substantial amount of synthetic fertilizer. The seeds are treated with insecticides, herbicides are applied to control weed growth and pesticides are applied for pest control. Approximately 26% of world’s insecticides are used in conventional cotton production (Roy Choudhury, 2013). Many of the synthetic chemicals used for cotton fiber cultivation contribute to acute toxicity, which can deteriorate soil quality and potentially drift into neighboring environment. On the other hand, organic cotton reduces soil and water pollution in addition to its superior properties such as free from allergic reaction and soft feel. Organic cotton heals the planet, supports a true economy, and protects our health.

In the last two decades the technological developments in polymer science have resulted in the commercial production of fibers such as soya, bamboo, and polylactic acid (PLA), which are prepared from renewable biological sources and are biodegraded (Mohanty et al., 2000). These fibers provide a solution to the recycling problems involved with synthetic fibers (Gross and Kalra, 2002). The clothing prepared from soya fibers has softness similar to cashmere and elastic handle, but it is less durable than cotton. Similarly, bamboo is a resilient and durable fiber, with a high breaking tenacity, better moisture-wicking properties, and better moisture absorption, compared to cotton (Majumdar et al., 2010). The advantage of bamboo fiber compared to cotton is free from pesticides and fertilizers when growing bamboo. In addition, the EOL bamboo clothing can be disposed in an ecofriendly manner. PLA is a thermoplastic aliphatic polyester fiber prepared from corn starch or sugarcane. PLA fiber can be used as compost and it degrades rapidly at EOL.

### 1.4.2 Ecofriendly processes

The conventional fashion and textile manufacturing practices are based on non-renewable energy sources (gas, coal, or petroleum), which are limited and create environmental burden. As the term “green production” is becoming important in many of the manufacturing segments, fashion and textile producers and retailers are adopting the terms “green production”. Vachon and Klassen (2008) mentioned that the green production practices can help industries to achieve the economic benefits of having a higher number of target customers, and to achieve “the edge” over their competitors. Emerging technologies (sol-gel, layer-by-layer deposition, enzyme processing, and plasma deposition) and materials (nanomaterials) are paving their way for sustainable fashion and textile production (Xing et al., 2007; Mahltig et al., 2004; Dubas et al., 2006; Gomes et al., 2013). Sustainable practices in yarn, fabric, and garment manufacturing are discussed in the following section.
1.4.2.1 **Yarn and fabric manufacturing**

Yarn and fabric manufacturing are mechanical processes that need large amount of energy and generate waste, dust, and noise (Gardetti and Muthu, 2015). The total energy consumption in a textile industry can be split as 34% in spinning, 23% in weaving, 38% in chemical processing and 5% in other miscellaneous processes. But the more interesting fact is that the energy consumed during the care and maintenance of a cloth is almost four times (75–80%) compared to the energy consumed for its production (20–25%) (Nayak and Padhye, 2014a). The global emphasis on sustainability has led to the development of yarn and fabric manufacturing machines that use less energy, work with higher efficiency, and generate less dust and noise. As a result, several new techniques have evolved in spinning (such as open-end rotor and air jet spinning), weaving (rapier, projectile, air jet, multiphase, and water jet looms), and knitting (high-speed circular knitting, computerized flatbed machine, and seamless knitting). The details of sustainable developments have been discussed in Chapters 3 and 7.

Similar to yarn manufacturing, fabric production is also an energy-intensive process. The total electrical energy consumed per linear meter of fabric (including production and consumer use) is 0.45–0.55 kWh, whereas the thermal energy per linear meter of fabric (production and consumer use) is 18.8–23 MJ (Fletcher, 2013). From the above discussions, it is evident that energy is one of the prime factors influencing the cost; hence, energy-efficient technologies can help in sustainable production. Newer weaving technologies such as projectile, rapier, air jet, water jet, and multiphase looms consume lower energy, give better efficiency, and generate less waste compared to the conventional weaving machineries.

Between the two major processes of fabric production, weaving and knitting, the former has the higher environmental impact. This can be attributed to the additional process of sizing, desizing, and warp preparation for weaving, which is not needed for knitting. The application of sizing and subsequent desizing consumes large amount of water in addition to energy. The effluent of traditional sizing is highly polluting, which is being replaced with new sizing materials such as polyvinyl alcohol (PVA) to achieve sustainability (De Smet et al., 2015).

The use of seamless garment manufacturing can help to reduce the environmental impact (Nawaz et al., 2015). In seamless technology the 3-dimensional (3D) garment is produced by avoiding the steps of fabric manufacturing (weaving/knitting), cutting, and sewing operations. Hence, this process consumes 30%–40% less time and saves energy compared to the conventional process. Furthermore, seamless technology reduces labor cost and lead time and eliminates waste involved in cutting of pattern pieces.

1.4.2.2 **Chemical processing**

Fabric chemical processing or wet processing is the most environmentally harmful process among all the textile and garment processes as it uses a large amount of water, energy, and toxic chemicals (Robinson et al., 2001; Correia et al., 1994; Karn and Harada, 2001). Marcucci et al. (2001) noted that the production of 1 kg of processed fabric consumes about 200–400 L of water, which generates substantial amount of effluent. Water pollution produced by the textile industries is a major concern in
many developing countries (Wu et al., 1999; Wang et al., 2008). In addition to water pollution, the demand for water usage is ever-increasing due to increased volume of textile and clothing production. In many countries such as China, there is acute shortage of clean water. Hence, the direct discharge of the effluents into the water systems is aggravating the scarcity of clean water.

Conventional wet processes such as scouring, bleaching, dyeing, and printing consume large amount of water and result in a substantial amount of effluent. About 2000 different chemicals are used in textile wet processes, which are about 27% of the global chemical consumption (Dirty Laundry-Unravelling, 2011). Many of these chemicals are harmful to the environment as well as to human health. Textile effluents contain contaminants such as dyes, surfactants, solvents, heavy metals, inorganic salts, enzymes, and oxidizing and reducing agents, as listed in Table 1.3.

Several chemicals listed in Table 1.3 are banned in many countries, based on the global legislation governing the use of toxic chemicals in fashion production. Approaches such as use of safe chemicals, reduced chemical usage, use of ecofriendly processes, use of enzymes, and biotechnology can help in sustainable fashion production, which are highlighted in the following section.

### 1.4.2.2.1 Ecofriendly chemical processing

The effluent created in wet processing contains toxic organic materials as discussed in Table 1.3, which are nonbiodegradable and difficult to separate during effluent treatment. Therefore, newer technologies and nontoxic chemicals (dyes, auxiliaries, and surfactants) should be used to reduce the environmental load. These newer approaches should focus on the use of alternative advanced techniques or combined processes, new chemical formulations, reuse of dye-bath, waste reduction, and effluent treatment. Several research works have been done to save energy and reduce consumption of water and hence, the effluent by adapting alternative greener technologies (Mohsin et al., 2013; Ali et al., 2014).

Khatri et al. (2015) reviewed developments in the dyeing of cotton fabrics with reactive dyes to reduce effluent pollution. It was suggested that focusing on the use
of alternative dyeing techniques can substantially reduce the effluent. As effluent treatment requires additional capital investment in addition to high cost of effluent treatment and maintenance, textile plants should focus on adapting newer technologies. Approaches such as use of advanced processes with recent dyestuffs and modern dyeing machinery can help to reduce environmental concern. Some of the approaches include: dyeing with low liquor-to-material ratio, low padding trough volumes, pad dyeing technology, urea and salt-free continuous dyeing, modified washing-off techniques, micelle dyeing, polymerisation techniques for dye fixation, use of biodegradable organic compounds as dye liquor, and use of chemically modified cotton materials prior to dyeing. Khatri et al. (Ali et al., 2014) also showed that the integrated approach of desizing, bleaching, and reactive dyeing can result in reduced cost due to reduced use of chemicals and energy.

As mentioned earlier, fabric chemical processing consumes large amount of water, which necessitates drying at the end of the process using thermal energy. Hence, alternative water-free techniques can reduce the consumption of water and thermal energy. For example, plasma treatment is a dry and ecofriendly technology that can help to achieve new functionalities, such as hydrophilicity, water repellency, anti-static effect, increased dyeability, and antibacterial properties, without altering bulk properties and aesthetics of fabrics (Shishoo, 2007; Samanta et al., 2009, 2010; Yaman et al., 2009; Nayak and Padhye, 2014b). Plasma treatment is performed by exciting partially ionized gas with the consumption of low amount of water and energy. Although plasma technology is an ecofriendly process that avoids generation of effluents, the economic aspects of textile application need to be assessed before adopting the technology.

Thermal processes such as extrusion coating (Singha, 2012) can be applied to textiles for achieving various functionalities such as flame retardancy, hydrophobicity, and antibacterial properties. Radiation curing process that uses light-emitting diode (LED) or ultraviolet (UV) or electron-beam can be used to reduce the energy consumption to achieve flame retardancy, improved abrasion resistance, and hydrophobicity (Goethals et al., 2014). Digital printing can be used for the coloration or printing of textiles with minimal or no use of water and solvents (Nayak et al., 2007; Bal et al., 2014).

Research interest is increasing on Layered Double Hydroxide (LDH) to achieve various functionalities in textiles for developing nanohybrids (Barik et al., 2016). LDHs are environmentally benign that can be applied to textiles, biotechnology, pharmaceuticals, filtration, and scavenging electroactive and photoactive materials. In a recent publication Barik et al. (2016) showed that the application of Mg-Al nano-LDH with reactive remazol dye helped to improve UV protection and enhanced flame retardancy, with significantly increased tensile strength of cotton fabric.

The application of enzymes in chemical processing is ever-increasing, due to their ability to replace harsh chemicals and reduce the use of water, energy, and chemicals (Araujo et al., 2008; Cavaco-Paulo and Gubitz, 2003). Chemical processes using enzymes operate at lower temperature and neutral pH, which can help in reducing energy consumption and effluent in several applications. For example, in cotton garment production, enzymes can be used in desizing, scouring, bleaching, and stone-washing of denim to create a fashionable appearance. Furthermore, enzymes can also be used in bio-finishing, to remove pills and fuzz (to improve surface appearance), laundering of
garments, and stain removal applications. Enzymes such as cellulases, amylases, pectinases, proteases, glucose oxidase, catalases, laccases, peroxidases, and tyrosinases are used in various chemical processing (Soares et al., 2011).

Other greener processes for textile coloration include the use of ionic liquids, supercritical carbon dioxide (CO₂), mass coloration, and natural dyeing. Applications such as nanofinishing, sol-gel coating, and bio-finishing are also getting increased attention in textile industries. Technologies such as DyeCoo (incorporating powder dye into polyester fabric using CO₂, which is water-free process and reduces energy and chemical consumption by 50% compared with conventional methods) and AirDye (direct transfer of dye into polyester fabric from paper using printing machines, which uses reduced water and energy and has lower greenhouse gas emissions) can be applied to reduce water and energy consumption, and reduce the generation of effluents.

1.4.2.2 Effluent treatment
Generally, the effluent generated during chemical processing is treated by different techniques before discharged to the water systems. Conventional effluent treatment techniques such as UV treatment (Arslan et al., 1999), ozonisation (Gaehr et al., 1994), hydrogen peroxide treatment (Lin and Chen, 1997; Georgiou et al., 2002), TiO₂ photocatalysis (Pekakis et al., 2006), Fenton’s reagent (Parsons, 2004), and electrochemical processes (Naumczyk et al., 1996) are found to be inadequate in effluent treatment, as the new classes of dyestuffs and auxiliaries can resist these processes (Marmagne and Coste, 1996; Ciardelli et al., 2000; Baig and Liechti, 2001). Hence, advanced techniques such as chemical precipitation (Sahinkaya et al., 2008), biological treatment (Willmott et al., 1998; Raghu and Basha, 2007; Paprowicz and Słodczyk, 1988), activated carbon adsorption (Banat and Al-Bastaki, 2004), membrane technology (Fersi et al., 2005), ultrafiltration (Marcucci et al., 2001; Aouni et al., 2012), microfiltration (Fersi et al., 2005), nanofiltration (Tang and Chen, 2002; Lau and Ismail, 2009; Akbari et al., 2002), reverse osmosis (Treffry-Goatley et al., 1983; Suksaroj et al., 2005), coagulation-membrane separation (Harrelkas et al., 2009), and evaporation (Kim, 2011) are being widely adopted by textile manufacturers.

The application of membrane-based processes (filtration) for effluent treatment is becoming popular due to their high removal efficiency, as well as reusability of water and other constituents (Marcucci et al., 2002). For recycling of insoluble dyes (such as disperse or Indigo), auxiliary chemicals (polyvinyl alcohol), and water, the ultrafiltration process is becoming popular (Aouni et al., 2012; Fersi and Dhaibi, 2008). Filtration processes may need high initial outlay, but the process can be economical due to high efficiency of extracting reusable salt, permeate, and water. The drawbacks of filtration process is the disposal of concentrate stream, which is done by incineration, evaporation, or discharging into the ocean. These processes are not environmentally friendly. The combination of a biological reactor and a membrane separation device, commonly known as membrane bioreactor (MBR), is a new innovative concept for effluent treatment (Salazar Gámez et al., 2009; Badani et al., 2005).

1.4.2.3 Garment manufacturing
Garment manufacturing process is energy intensive and there are a wide range of areas garment manufacturers can focus to reduce the energy usage (Nayak and Padhye,
The use of energy efficient tools, equipment, and machinery for cutting, sewing, pressing, and packaging, and the use of ecofriendly processes are the key factors requiring improvement to produce sustainable fashion (Aakko and Koskenurmi-Sivonen, 2013). The waste generated during garment production such as paper, plastic, fabric remnants, cardboards used for packaging, and wire coat hangers should be recycled and reused. Several other strategies for saving energy and water, such as installing water efficient fixtures, training the staffs on energy efficiency skillsets, energy-efficient heating/cooling devices, sensor-enabled lighting systems, and rain-water harvesting for non-drinking purposes, can also help in achieving sustainable fashion.

The production process of a garment industry follows the steps as shown in Fig. 1.2 (Nayak and Padhye, 2015b). The dotted and solid lines show the material and process flows, respectively. The selection of appropriate raw materials with a lower ecological footprint (renewable, biodegradable, and nondepleting) and energy-efficient processes can help to reduce the environmental impact. The factors related to sustainability in fashion products are marked inside the red rectangle. Use of renewable energy, energy saving, reducing air pollution, and recycling hard waste can help in achieving sustainability in fashion.

The operational costs in garment production can be reduced by adopting the concept of “Lean manufacturing”, which focuses on eliminating the process waste, improving productivity, empowering people with greater communication, and converting the organisation into a leaning organisation (Bruce and Daly, 2004). The process waste can be reduced by avoiding overproduction, unnecessary motion, improper inventory management, and overprocessing. Continual improvement (generally known as the Japanese word “Kaizen”) is the major principle of lean manufacturing. “Kaizen” promotes continuous and necessary changes (big or small) toward the achievement of a desired goal.

The fundamental thrust of lean manufacturing is to produce a high-quality product at lower cost by reducing or eliminating the seven cardinal wastes such as waiting, inventory, over-production, repair, inappropriate processing, excess motion, and transportation from the value stream through continuous improvement and to deliver the
value to the customer (Benders and Van Bijsterveld, 2000). The goal of the lean manufacturing is to create an integrated system using multidimensional approach that includes adoption of management practices such as pull strategy, just in time (JIT) philosophy, total quality management (TQM), cellular manufacturing, electronic data interchange (EDI), Kanban, and co-design. Lean production techniques create a sustainable and positive work environment by empowering the workers and adopting the tools, which enhance the operational efficiency by cycle reduction, cellular manufacturing, working in teams, and stabilizing workflow. Yang et al. (2010) added that when different forms of wastes in lean culture are reduced, it will in turn be useful in managing the environmental waste by enhancing environmental performance.

Herva et al. (2008) developed a useful tool to evaluate the influence of a garment manufacturing plant’s environmental impact. They analyzed the ecological footprint (EF) and compared the data to examine the environmental impact of different processes in a garment manufacturing plant. The authors collected data and divided the data into three categories: energy, resources, and waste. The major contributor to the final EF was obtained from the resources category (91.33%), as materials constitute the primary factors in garment manufacturing. Energy consumption was the second contributor accounting for 5.32%, while the waste category was the lowest at 3.35%.

1.4.2.4 Eco-labelling

The Global Eco-labelling Network defines an eco-label as “a label which identifies overall environmental impact of a product within a product category based on life cycle consideration” (Members, 2007). Ecolabels provide information on ecofriendly products to consumers, which can help in reducing the environmental impacts on their daily activities. Consumers can compare various products manufactured using ecofriendly processes from the ecolabel and they are informed about the adverse consequences of the product during use and disposal. Ecolabelling has an important role in the development of sustainable fashion products globally and it differentiates retail markets for “go green” customers. Neutral third parties are involved in awarding the ecolabel to the products that fulfill the established environmental criteria. The major goals of ecolabelling are (Fletcher, 2009):

- Creating awareness on ecofriendly products,
- Improving environmental protection,
- Assuring enterprises contribute toward improved environmental safety and social impacts,
- Performing an educational role with a seal of ecological approval,
- Increasing transparency within the international market, and
- Promoting “green innovation” and “entrepreneurship” resulting in higher future value.

The ecolabels may be categorized into governmental and commercial, which can vary in different countries. Various categories of ecolabels are listed in Table 1.2 (Roy Choudhury, 2013).

1.4.2.5 Product life cycle assessment

Global environmental challenges and climatic changes have necessitated the integration of environmental considerations into individuals, businesses, policymakers, and
public administrations (Eckerberg and Nilsson, 2013). Tools and indices are being developed for assessing and benchmarking the impact of various systems on the environment, which include Life Cycle Assessment (LCA), Environmental Impact Assessment (EIA), Strategic Environmental Assessment (SEA), Cost-Benefit Analysis (CBA), Environmental Risk Assessment (ERA), Material Flow Analysis (MFA), and Ecological Footprint (Finnveden and Nilsson, 2005; Ness et al., 2007). Among these, LCA is widely used for fashion and textile products.

LCA is a systematic approach used to estimate the total environmental impact of a product from cradle to grave (from raw material procurement, production, and use phase, to the waste management stage) (ISO, 2006). The design and development phase of the product is not involved in LCA, although these stages can greatly influence the other stages of LCA (Rebitzer et al., 2004). In the LCA process, the impact of the product on human health, the natural environment, and resources is measured during each stage of product manufacture (ISO, 2006).

A schematic of the fashion and textile production from cradle to grave is shown in Fig. 1.3. The major participants in fashion production include fiber producers, yarn and fabric manufacturers, fashion manufacturers, retailers, and finally the consumers. For an accurate LCA, environmental data and process inputs and outputs need to be collected from each of these participants. However, the complexities involved in getting information lead to lack of transparency in manufacturing and potential negative environmental impacts.

Fashion products should be manufactured with the objective that they are serviceable for a sufficient amount of time and recyclable so that they are not ending up in landfill at the EOL. Extending the overall service life of apparels can reduce the environmental load. Approaches such as (i) manufacturing products with extended durability or reconfigurable garments so that their durability is extended in the first life, (ii) manufacturing reusable garments, (iii) making garments reusable after their first life, and (iv) selecting fibers with easy recyclability for manufacturing the garment can help to address sustainability issues.

1.5 Reduce, recycle, and reuse

As discussed previously, fast fashion items are disposed of more frequently, and this has become a relatively new area of research (De Coverly et al., 2008). Consumers
should be aware of the concepts of reuse or recycle while discarding fast fashion items. Producers and retailers should encourage consumers to purchase environmentally sustainable products and recycle waste. Three major factors such as intrinsic factors (related to the product style, age, condition, value, cost, and durability); psychological factors (related to decision-making, which involves attitude, personality, and social conscience); and situational factors (extrinsically related to the product such as fashion changes, finances, and storage space) explain the “disposal” behavior of the consumers and place them as “redistributors” in the fashion chain, as opposed to “end-users” (Jacoby et al., 1977). Burke et al. (Burke et al., 1978) surveyed consumer’s responses toward discarding a product and observed that young consumers pay little attention to reuse or recycle while disposing.

Fashion items become unusable after certain time-frame, resulting in an EOL product. In the past, EOL products were disposed to landfill, or they were used for second-hand clothing, wiping cloths, or fiber reclamation. As the importance of sustainability is increasing, sustainable solutions such as recycle or reuse are needed to reduce the negative environmental impacts and reduce the resource consumption. This will also help in the reduction of pollution levels and energy consumption. Various sustainability factors associated with a fashion production are shown in Fig. 1.4.

Energy is consumed from the fiber to the finished garment stage, waste is generated, and the product then needs to be transported to the point of sale, which should be addressed by sustainable approaches. Furthermore, at the EOL, the fashion and textile products can be dumped as landfill, reused as secondhand clothing, or recycled. The option of reusing or recycling seems to be more sustainable compared to landfill as shown in Fig. 1.4.

Fig. 1.4 Various sustainability factors associated with a fashion production.
As the world is becoming more environmentally conscious, it is appropriate that all fashion items are recyclable. The recent legislative regulations in many countries do not allow landfilling of EOL fashion products. Associations such as United Nation (in UN’s Environment Program (UNEP)), the European Commission (in the European Platform for LCA), the Society of Environmental Toxicology and Chemistry (SETAC), and the Recycling Consortium (TRC) are facilitating research to use recyclable materials and to design for ease of disassembly. Table 1.4 shows the recycling possibilities of EOL fashion products.

Fashion wastes can be classified as consumer waste and industrial waste. The recycling of consumer waste (EOL apparels) is rather difficult as it consists of materials of unknown fiber mixture, and nonfibrous materials such as zippers, buttons, and other metal parts. However, the recycling of industrial waste is easier. Hence, the option of “reuse” of consumer waste is the appropriate method; this involves inspection, cleaning, ironing, and packing. The EOL fashion items that cannot be reused can be used as wiping or cleaning cloths, flocks for nonwovens, bonda-waste, and fiber extraction.

Table 1.4 Various recycling possibilities for EOL fashion products.

<table>
<thead>
<tr>
<th>Sustainability practices</th>
<th>Process</th>
<th>Areas of application</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reuse</td>
<td>Sorting, laundering, ironing, packaging, and display</td>
<td>Secondhand apparels</td>
<td>Reduced/no waste, Low energy consumption</td>
</tr>
<tr>
<td>Upcycle (to reusable product)</td>
<td>Sorting, rework, laundering, ironing, packaging, and display</td>
<td>Secondhand apparels</td>
<td>Reduced/no waste, Low energy consumption</td>
</tr>
<tr>
<td>Recycle (to new product)</td>
<td>The fibers/yarns are extracted from the fabric and used to make different products</td>
<td>Complete new outfits, Cleaning or wiping cloths, filling materials in some low-cost mattresses</td>
<td>Reduced/no waste, Low energy consumption</td>
</tr>
<tr>
<td>Fiber extraction (thermoplastics)</td>
<td>Depolymerization of fibers to obtain raw polymer</td>
<td>Can be used to produce textiles with low-quality requirements</td>
<td>High waste generated, Highest energy consumption</td>
</tr>
<tr>
<td>Landfill</td>
<td>Dumping into the landfill sites</td>
<td>Landfilling</td>
<td>Highest waste generated</td>
</tr>
</tbody>
</table>

As the world is becoming more environmentally conscious, it is appropriate that all fashion items are recyclable. The recent legislative regulations in many countries do not allow landfilling of EOL fashion products. Associations such as United Nation (in UN’s Environment Program (UNEP)), the European Commission (in the European Platform for LCA), the Society of Environmental Toxicology and Chemistry (SETAC), and the Recycling Consortium (TRC) are facilitating research to use recyclable materials and to design for ease of disassembly. Table 1.4 shows the recycling possibilities of EOL fashion products.

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1.6 Research findings from survey

Since the Vietnamese war was over, the economy of Vietnam has progressed rapidly, and the large-scale poverty has been reduced significantly. Today, Vietnam is one of the fastest growing developing countries, which attracts many foreign direct investors in manufacturing sector. Among all the manufacturing sectors, the most notable is the fashion industry, which comprises of textile, garment, and trim manufacturers. As manufacturing of fashion primarily involves the textile and garment industries, this chapter has focused on these two sectors. In the last two decades or so, the textile and garment industries in Vietnam have witnessed rapid growth. Competitive labor prices and favorable government policies in Vietnam have helped to boost the export of textile and garment and position the country among the top five global exporters. With about 6000 garment industries, this sector provides employment to about 2.5 million people, which is about 2.7% of the country’s population.

Vietnam is involved in the production and distribution of both the natural and synthetic fibers. Among the natural fibers, Vietnam is mainly involved in the production of cotton. Vietnam’s cotton export in 2016 was the fifth highest in value accounting for $2.1 billion (4.1%) of the world total, with China as the major importer. To increase cotton export, the “cotton plant development program” will focus on the increase in the production of cotton fiber as discussed in Table 1.5. Vietnam is also among the top 10 exporters of synthetic yarn in the global market with $0.84 billion (market share of 3.52%). The synthetic yarn (filament) industries have maintained a compound annual growth rate (CAGR) of 30.3%, which is the highest in the global market.

About 70% of the textile and garment manufacturers in Vietnam use imported raw materials such as yarns, fabrics, and trims especially from China via the processing trade (Anonymous, 2014). There is a continuous increase in the import values of the raw materials. Over the period from 2009 to 2013, the import value of raw materials was increased at a CAGR of 20.5% per year (CAGR for export for the same period was 18.4% per year) (Vachon and Klassen, 2008). Out of the total import value, about 48.1% of the raw materials were used in the products for export destinations. This indicates that the self-reliance of Vietnam on raw materials is very low for export market, which needs to be improved.

Table 1.5 Cotton plant development program in Vietnam for the period of 2015–20.

<table>
<thead>
<tr>
<th>Indicators</th>
<th>Unit</th>
<th>Year 2015</th>
<th>Year 2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crop area</td>
<td>Ha</td>
<td>30,000</td>
<td>76,000</td>
</tr>
<tr>
<td>Irrigated area</td>
<td>Ha</td>
<td>9,000</td>
<td>40,000</td>
</tr>
<tr>
<td>Average yield</td>
<td>Tons/ha</td>
<td>1.5</td>
<td>2</td>
</tr>
<tr>
<td>Average yield of irrigated cotton</td>
<td>Tons/ha</td>
<td>2</td>
<td>2.5</td>
</tr>
<tr>
<td>Production of cotton fiber</td>
<td>Tons</td>
<td>20,000</td>
<td>60,000</td>
</tr>
<tr>
<td>Quantity</td>
<td>1,000 packs</td>
<td>91.86</td>
<td>257.57</td>
</tr>
</tbody>
</table>

Source: Department of Trade Promotion, Vietnam.
Vietnam has showed tremendous growth in the raw material production; however, the quality of the products has not achieved the requirements of the international fashion brands. This has been shown by the rise in the amount of fiber, yarn, and fabric imports in 2015. For example, the fiber, yarn, and fabric imports were increased in volume by 39%, 22.5%, and 19.3%, respectively, in 2015. The growing export market for textile and garment demands Vietnam to become self-reliant in the raw material manufacturing.

Although Vietnam exports a large amount of cotton, it also imports some varieties or better quality that are not available locally. The major import destinations of cotton fiber are the United States, India, and Australia. Cultivation of hybrid cotton and the use of advanced technologies in cultivation can improve the quality of Vietnamese cotton. As the world demand for high-quality cotton fiber is increasing so as the price, being self-reliant can help Vietnam to maintain the low cost of production. Vietnam also imports natural and synthetic yarns mainly from China, Hong Kong, Taiwan, and Thailand. Modernization of spinning industries can help to improve the yarn qualities and self-reliance of Vietnam.

Vietnam is also dependant on other countries for good quality fabric. The major fabric import countries are China, South Korea, and Taiwan. The major reason of poor quality fabrics in Vietnam can be attributed to the use of traditional looms for fabric production. Many industries are upgrading to modern looms such as projectile, rapier, and air jet, which can produce better quality fabric at higher productivity. For example, Vinatex (Vietnam National Textile and Garment group) in 2013 has invested $2.8 billion in 42 projects to increase the quality and productivity of yarn and fabric. This will help to improve the ratio of local production to imports and the self-reliance of Vietnam on raw materials. Due to significant role of Vietnam, we conducted a survey in Vietnamese fashion enterprises which involved four small, and medium-sized enterprises (SMEs) and four large enterprises (LEs). The findings are discussed in the following section.

1.6.1 SWOT analysis based on the survey

We completed a SWOT analysis for the Vietnamese fashion and textile industries based on the interview and the survey findings, which are discussed in Table 1.6.

1.6.2 Survey findings

Based on the survey from the LEs, we found that the LEs are forerunners in the sustainability race due to exposures to global market, larger access to skill, availability of funding, and management policy. To meet the global demand of the international brands, the large fashion enterprises are targeting to achieve certifications such as ISO 9001 (for quality management systems), ISO 14001 (for environmental management), and Okeo Tex 100 (for product free from harmful substances). They are installing effluent treatment facilities in many of their chemical processing units. They always comply with the specifications set by the local authorities in terms of biological oxygen demand (BOD), chemical oxygen demand (COD), and total dissolved salt (TDS) present in the effluents.
Table 1.6 SWOT analysis of Vietnam’s textile and garment industries based on the survey and research.

<table>
<thead>
<tr>
<th>Opportunities</th>
<th>Threats</th>
</tr>
</thead>
<tbody>
<tr>
<td>The major strengths of Vietnamese fashion industries include:</td>
<td>Claire et al. (Xing et al., 2007) in their recent book have described two major challenges or weaknesses for Vietnamese textile and garment industries which are:</td>
</tr>
<tr>
<td>• Cheap labor,</td>
<td>• the lack of good quality raw materials (i.e., fabrics) for export, and</td>
</tr>
<tr>
<td>• Supportive government policies for local manufacturers,</td>
<td>• manufacturing and selling of goods at lower cost.</td>
</tr>
<tr>
<td>• Duty-free import of raw materials,</td>
<td>The other weaknesses are:</td>
</tr>
<tr>
<td>• A good source of raw materials such as cotton fiber,</td>
<td>• lack of technology and skilled labor,</td>
</tr>
<tr>
<td>• Proximity to ports and other countries for raw materials, and</td>
<td>• lack of training and skill development programs by the manufacturers, and</td>
</tr>
<tr>
<td>• Promotional schemes for foreign direct investment (FDI).</td>
<td>• the inclusion of Vietnam into the World Trade Organisation (WTO), which will create</td>
</tr>
<tr>
<td></td>
<td>more challenges for the industries to compete with other countries within the WTO. In</td>
</tr>
<tr>
<td></td>
<td>addition, the manufacturers must meet the stringent WTO specifications.</td>
</tr>
<tr>
<td></td>
<td>The textile and garment industries in Vietnam face several threats as discussed below:</td>
</tr>
<tr>
<td></td>
<td>• many of the industries are small- and medium-sized enterprises (SMEs) with low capital investment, limited access to technology, and innovation capabilities,</td>
</tr>
<tr>
<td></td>
<td>• manufacturers in Vietnam always face stiff competition from the manufactures in Bangladesh, China, and India to stay competitive in the global market,</td>
</tr>
<tr>
<td></td>
<td>• the increasing labor and logistics cost in comparison to Cambodia, Bangladesh, and Myanmar is putting extra pressure on Vietnamese textile and garment manufacturers,</td>
</tr>
<tr>
<td></td>
<td>• Vietnam has to transform majority of its old industries for fulfilment of international requirements, especially in terms of improving the competitiveness of the firms and products,</td>
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<thead>
<tr>
<th>Opportunities</th>
<th>Threats</th>
</tr>
</thead>
<tbody>
<tr>
<td>The major opportunity for Vietnam’s textile and garment industries that will promote future export are:</td>
<td></td>
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<tr>
<td>• Highly supportive government,</td>
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<tr>
<td>• Strong incentives for FDI that attracts many foreign investors,</td>
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<tr>
<td>• The free trade agreement (FTA) between Vietnam and other ASEAN (Association of SouthEast Asian Nations) countries,</td>
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<tr>
<td>• The FTA with many non-ASEAN countries such as Korea, India, Australia, and New Zealand,</td>
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<tr>
<td>• Joining of Vietnam with Trans-Pacific Partnership (TPP) will open doors for new FDI to produce raw materials and other allied industries,</td>
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</tbody>
</table>
On the other hand, the SMEs are struggling to survive in the global market due to limited access to funding, lack of skilled people, and lack of consumer awareness. The fashion SMEs are unable to adopt newer technologies as they lack funding. Hence, many of the traditional technologies that they are following are not sustainable. Furthermore, the lack of skilled people makes it difficult to develop their concept of sustainability. They are not sure about whom to approach to get organic cotton or BCI cotton certification (SME 3). Although they can produce organic fabrics, the consumers are not willing to pay higher prices for the garment made from organic cotton (SME 1). Hence, for SMEs, the approach to achieve sustainability is rather difficult.

Based on the survey, we also found the following information as expressed by the participants. Vietnam has suffered a great loss in the 21st century, which will continue beyond if necessary steps are not taken to reduce the impact of rapid industrialisation as expressed by one of the LEs. The climate change caused by rapid industrialisation has led to the rise of the sea level. Many models have shown that Vietnam will be impacted the most in the world due to the rise of the sea level. This can be attributed to the natural geography of Vietnam with its 3200 km long coastline facing South China Sea or Vietnamese East Sea, which erodes 30 cm per year as of today. The two major river deltas (i.e., Mekong and Red River Delta), which are the economic hub of Vietnam, will be greatly impacted by the rise of the sea level (LE2).

One of the major ports, Hai Phong and even the capital Hanoi will also be impacted. As the findings indicate, 40% of the Mekong Delta will be submerged toward the end of the 21st century, or even earlier, many parts of the southern Mekong Delta will sink. This sink is a threat to the world’s food security as Vietnam is one of the rice producing hub in the world. The chance of rising of sea level by 6–7 m can not be neglected due to the melting of the Greenland ice glacier. This rise would cause problem to Ho Chi Minh City as well and even many countries will be submerged in water. The impacts of climate change have already been felt in the form of severe floods in major cities and recent droughts in the Mekong Delta.

Table 1.6 Continued

<table>
<thead>
<tr>
<th>Opportunities</th>
<th>Threats</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Joining of Vietnam with TPP has reduced the tax to 0%, which can boost the profitability of the manufacturers,</td>
<td>• Vietnam must meet the challenging commitments of accession to become a member of the WTO,</td>
</tr>
<tr>
<td>• Joining of Vietnam with WTO will boost the export, and</td>
<td>• rapid industrialisation in Vietnam is polluting the ecosystem (land, water, and air), which affects people’s health and can lead to the death of aquatic and marine animals, and even extinction of local flora and fauna, and</td>
</tr>
<tr>
<td>• The FTA further opens the export opportunity of textile and garment.</td>
<td>• rising labor cost coupled with the stricter government policies in some areas can lead to the shifting of manufacturing to countries such as Bangladesh, Cambodia, and Laos.</td>
</tr>
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1.7 Conclusions

This chapter has systematically discussed the ecofriendly practices followed for sustainable garment manufacturing. This chapter has focused on the sustainable approaches in raw material selection, yarn and fabric manufacturing, chemical processing, and finally sewing in brief. The significant findings, limitations, and future direction in the sustainable fashion and textile manufacturing are discussed in the conclusion.

1.7.1 Significant findings

Globalisation has led to the shifting of the garment manufacturing to the developing countries such as Vietnam and Bangladesh, which are neglected in all the three aspects of sustainability: environmental, social, and economic. This chapter has focused on the environmental aspects of sustainability related to fashion and textile manufacturing, which is the most important factor among the three. To keep the product cost low and survive in the global competitive market, the garment manufacturers around the globe are facing several challenges. One of the key challenges is reducing the environmental pollution during fashion and textile manufacturing and achieving sustainability. From a sustainability perspective, the processes involved in fashion and textile manufacturing are inherently at odds as designers and product developers face several challenges to streamline a garment style.

Selection of ecofriendly and biodegradable fibers such as organic cotton, organic wool, flax, hemp, polylactic acid, and Lyocell is the next stage of sustainable fashion and textile manufacturing. Technologies such as air jet and rotor spinning for yarn manufacturing; rapier, Sulzer, air jet, and water jet weaving looms for fabric manufacturing; and knitting and seamless garment manufacturing can be adopted depending on the product type to reduce the environmental impact. Similarly, in chemical processing, ecofriendly processes such as the application of ultrasound, microwave, plasma technology, enzymes, and digital printing including the natural dyes can help to reduce the amount of effluent discharge. The combined approaches from selection of raw materials till sewing can help to achieve environmental substantially.

The survey finding indicated that the large fashion enterprises are adopting fashion sustainability due to global competition, consumer awareness, and management policy, whereas the SMEs are struggling to survive in the global market due to limited access to funding, lack of skilled people, and lack of consumer awareness.

1.7.2 Limitations and future directions

This chapter has only focused on the ecofriendly approaches followed for sustainable garment manufacturing from raw materials selection to the final stage of garment manufacturing, i.e., sewing. Future studies can focus on the other two approaches (social and economic) in fashion and textile manufacturing. There are several approaches that can be adopted during the transportation and retail operations to achieve
environmental sustainability. The consumer practices for care of the garments during use and various approaches to deal with the end-of-life clothing also greatly influence the environmental impacts. The future studies can focus in these aspects. The concept of reduce, reuse, and recycle is the key term emphasized by many leading global fashion brands to heal the planet earth, which can also be included in the future studies.

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Part Two

Sustainable technologies in yarn and fabric manufacturing
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2.1 Introduction

Yarn manufacturing or spinning is the second process following fiber production in the whole process of textile supply chain. Yarn manufacturing is the process of converting fibers into yarns, where different types of fibers such as cotton, wool, flax, hemp, nylon, and polyester are spun as single fibers or as blends of multiple fibers in different spinning systems such as ring, rotor, and air-jet to produce yarn.

The spinning process can be of two types: staple and continuous filament yarns. The staple yarn production can be applied to both natural and synthetic fibers, whereas the filament yarns are produced only for the synthetic fibers. Production of staple yarns needs different machineries compared with the filament yarns. Staple yarn spinning needs blow room, carding, and draw frame (for open-end spinning); roving frame; and ring spinning for producing ring yarns. Filament yarn production requires fiber/filament extrusion machines and texturing machines. However, both the processes are energy-intensive, require air conditioning and lighting, and generate waste.

The ring spinning system is the most widely used due to superior yarn qualities and its versatility to spin a wide range of yarn counts. However, the problem of ring spinning is low productivity and higher number of machineries in the process route that use substantially higher electricity. Hence, the new spinning systems such as rotor and air-jet come into play where the high strength is not a prime factor. The new spinning systems reduce the carbon footprint to a significant amount (van der Velden et al., 2014). The sequence of spinning operations for different spinning systems is shown in Fig. 2.1.

In the spinning industry, there are several types of raw materials such as fibers that vary in their compositions, color, fineness, strength, and uniformity. In addition, the spinning industries must deal with a range of materials used for the maintenance of the machines starting from the blow room to winding. Almost all the materials in the spinning industries are dealt manually, which is a time-consuming process and inaccurate. Hence, there is a good scope of the Radio Frequency Identification (RFID) technology to be implemented in the identification of materials, keeping record of the production, quality management, real-time information availability, and process control (Nayak, 2019; Nayak et al., 2015a).
The spinning processes for staple spinning involves ring spinning, rotor spinning, and air-jet spinning. Among these, ring spinning is the traditional process of yarn manufacturing that existed since 1779s. Ring spinning is the most versatile process as it can produce a wide range of yarns with the highest strength. Hence, it is the most widely used spinning system to produce yarns. The energy consumption by ring spinning changes according to the fiber type, twist level (i.e. higher twist needs more energy), and yarn count produced (with finer yarns needing more energy). Furthermore, combed yarn production uses more energy than carded yarn due to increased number of machines.

This chapter discusses various environmental impacts created by spinning industries producing yarn for the weaving industries. Various impacts such as solid waste generation, excessive power consumption, greenhouse gas emission, and noise pollution are discussed in this chapter. This chapter also discusses various approaches taken in the major spinning systems such as ring spinning, rotor spinning, and air-jet spinning to achieve sustainability. Waste management in spinning industries are also discussed in this chapter. The approaches of spinning industries to use renewable energy such as solar energy, wind energy, and recycled water have been covered.

### 2.2 Environmental impact of yarn manufacturing

The spinning industries around the globe are facing many problems due to increased energy cost, increased raw material, and labor cost. Unlike the 1990s, many of the industries struggle to get a net profit of 5%. In addition, many of the industries are also struggling to implement new technology to save energy, increase productivity, and reduce process waste. Low profitability and declining sales are the main pediments for many spinning industries to implement new technologies in their manufacturing facilities. Hence, they have to operate with the traditional machineries making it hard to achieve environmental sustainability.
Yarn manufacturing or spinning involves mechanical processes that consume large amount of energy and generate waste, dust, and noise in addition to polluting air (Gardetti and Muthu, 2015). The total energy consumption in a textile industry can be split as 34% in spinning, 23% in weaving, 38% in chemical processing, and 5% in other miscellaneous processes, which is shown graphically in Fig. 2.2.

It can be seen from Fig. 2.2 that energy consumption is the second highest in spinning industries after chemical processing. Courtiers such as Bangladesh, India, Vietnam, Cambodia, China, and Laos are the major yarn manufacturers in the world. Many of the industries rely on electricity produced from thermal energy by burning coal or electricity generators run by gas and diesel. The thermal power generates large amount of carbon dioxide (CO2) in the atmosphere, and releases greenhouse gases to the environment.

Spinning wastes can be divided into two main groups: solid wastes with dust as the major component and fiber wastes taken out during carding and combing processes. During the processes in blow room and carding, a large amount of dust and particle matters are collected as hard waste. Assuming a yarn realization of 75%–80%, there will be about 20–25 kg of waste generated during the manufacturing process including some invisible losses. These hard wastes are thrown as landfill by many spinning industries. The other wastes are basically raw material (fiber waste) of each production step, which cannot be put into the product due to inferior quality. In yarn manufacturing, these wastes are generated during cleaning of the fibers or combing out short staple fibers from the long ones in combing process. This unclean fiber waste has the potential to be reused.

The noise level in spinning industry ranges between 8 and 90 dBA, where the blow room is the lowest noise generator and ring frame is the highest. Sound levels exceeding 85 dBA have many negative health impacts such as hearing loss, ear diseases, ear pain, and otitis (Talukdar, 2001). In addition, high noise levels reduce performance, ability to concentrate, lack of sleep, and annoyance to the workers.

![Fig. 2.2 Energy consumption in various processes in textile manufacturing.](image)
2.3 Sustainable practises in yarn manufacturing

The global emphasis on sustainability has led to the adoption of new technologies, which is helping in sustainable manufacturing that conserve energy and the natural resources, and is nonpolluting and economically sound and safe for employees, communities, and consumers. It means the new system should use less energy, work with higher efficiency, and generate less dust and noise. As a result, several new machineries have evolved in spinning (such as open-end rotor and air-jet spinning), weaving (rapier, projectile, air-jet, multiphase, and water-jet looms), and knitting (high-speed circular knitting, computerized flatbed machine, and seamless knitting) (Nayak and Padhye, 2015b).

Power consumption is a critical factor in spinning industries affecting sustainability. Generally, the most influencing factor when the energy consumption is considered is the energy usage per kilogram of yarn production. With the rise of electricity charges, the spinning industries are trying various ways of increasing the productivity and reduce wastage. The productivity in yarn manufacturing can be improved by considering various factors such as fiber type, operating speeds, energy consumption, yarn count, yarn twist, and yarn package type. Yarn manufacturing processes such as ring, rotor, and air-jet spinning are energy-intensive (Fletcher, 2013). The energy consumption in the spinning machineries depends on the yarn count, twist, and fiber type. It is worth to mention that finer yarn counts need more energy; the electricity consumption is linearly related with the twist level; and cotton spinning needs more energy compared with the polyester or other synthetic fiber spinning.

2.3.1 Material and process management

The cost of yarn comprises of 50% of the raw material or fiber cost. The approach of selection of right type of raw materials especially in the case of natural fibers can help to improve the productivity. As natural fibers largely vary in their properties compared with the synthetic fibers, the yarn quality also changes. Hence, the use of modern testing and evaluation tools while purchasing fibers and right mixing formulations in the blow room can help to achieve sustainability in spinning.

Modern spinning mills are trying to reduce the energy loss and the use the concept of 3R (reduce, reuse, and recycle) in the materials wherever possible. The appropriate control of the humidity and temperature of the spinning plants can help to achieve increased productivity and reduce cost. Many of the spinning machineries used in the developing countries are still based on the traditional technology that consume a large amount of electricity. These machineries need to be replaced with the modern high-speed and energy efficient machineries. Moving towards automation such as autodoffing and autosplicing can increase the productivity and efficiency, which can save electricity.

The adaptation of new management tools such as strategic planning and balanced score card can help to achieve sustainability in spinning. In addition, the use of modern tools such as lean manufacturing (Kaizen, Kanban, and Muda) can help to reduce waste and increase productivity. A careful consideration of the target market, types
of product, technological advancements, material, quality, finance, skill enhancement, and training can help to achieve sustainability in spinning.

The use of recycled fiber and yarn is gaining popularity in spinning industries. The use of polyester bottles to make the fibers followed by the yarn will be the new trend in sustainable fashion. The cutting waste collected from the garment manufacturing process can also be converted into fibers by specialty machines such as Bonda machines. These fibers can be used for making yarn, which will lead to the concept of circular economy.

Cotton and polyester are the most widely used fibers in this modern age. The increase of cotton cultivation areas may seem possible above of the 36 million hectares geographically, but it is not possible economically. The demand of food plants are increasing rapidly. The usage of fertile cotton land for food production is dominant idea nowadays. Synthetic fibers are the most popular fibers in the world to overcome the problem of farming land. It is estimated that synthetic fiber production accounts for about 65% of world total fiber production versus 35% for natural fibers (Tarakcioğlu, 2008).

Most synthetic fibers (approximately 70%) are made from polyester, and the polyester most often used in textiles is polyethylene terephthalate (PET). Polyester fibers that are a petroleum derivative are obtained from fossil fuels. The majority of the released CO$_2$ emissions in the world are caused by fossil fuels. Furthermore, world fiber consumption is expected to reach to 150–160 million tons from 89.5 million tons in 2050. Therefore, this fiber demand must be met with recycled fibers from textile wastes (Carmichael, 2015; Telli and Babaarslan, 2017).

Recycling wastes into new products is essential in an ecological approach. PET bottle wastes are valuable for environment if they are used as PET bottles again. But because of the contamination and low intrinsic viscosity values of PET flakes, PET bottle wastes are not used for PET bottle production again. These restrictions do not prevent the usage of PET flakes as a raw material for fiber production; therefore, PET flakes are generally utilized in textile industry.

In 2007, PET bottle consumption in the world was 15 million tons, and it is only 8% of the whole plastics consumption. Besides, 4.5 million tons of PET bottles were collected and 3.6 million tons of them were broken into PET flakes. In textiles, about 8% of the whole PET fiber production was obtained from PET flakes (Shen et al., 2010). Recycled PET or rPET fibers are produced by melt spinning process of the PET flakes, which is obtained from recycled PET wastes. These fibers have economic advantages due to the lower raw material cost. They also have lower energy consumption in production stage and low carbon emission. Because of these factors, it can be said that rPET fibers are environmentally friendly (Telli and Özdíl, 2015).

The idea of using recycled bottles from landfills or diverting waste from landfills and turning it into fibers has gained increased attention. The reason recycled polyester is considered as a green option in textiles today is because the energy needed to make the rPET is less than what was needed to make the virgin polyester, so it saves energy. If the total amount of energy needed to make virgin polyester is 125 MJ per kg, the amount of energy needed to produce recycled polyester is 66 MJ per kg. Further, the CO$_2$ emission is also 54.6% lower for rPET fiber as compared with virgin polyester fiber (https://oecotextiles.wordpress.com/2009/07/14/why-is-recycled-polyester-considered-a-sustainable-textile/).
2.3.2 **Sustainability in ring spinning**

Ring spinning is the key system of yarn manufacturing in the textile industry. The principle of ring spinning is depicted in Fig. 2.3, and Fig. 2.4 shows a commercial ring spinning frame. The roving is fed to the drafting unit through a condenser. The difference in surface velocity of the front and back drafting rollers will draft the roving to a thinner strand of parallel fibers, with the help of the double aprons.

The twisted thin strand of fibers, i.e., yarn, is threaded through a traveler and a yarn guide and balloons out between these two elements during normal spinning. Each revolution of the traveler inserts one turn of twist to the fiber strand. The traveler, a tiny C-shaped metal piece, slides on the inside flange of a ring encircling the spindle. It is carried along the ring by the yarn it is threaded with. Because of the friction between the traveler and the ring, and air drag on the yarn, balloon generated between the thread guide and the traveler, the speed of the traveler is less than that of spindle, and this speed difference enables winding of the yarn onto the package (Klein, 1987; McCreight et al., 1997).

Because of the careful fiber control during the spinning process, ring-spun yarns have a very high quality. The quality of ring-spun yarns has been used as a benchmark against which the quality of yarns produced on other spinning systems is judged. However, because twist is inserted into the tiny strand of fibers by the rotation of the relatively bigger yarn package, the power consumption in ring spinning is much higher than that in other spinning systems.

![Fig. 2.3 Process sequence in ring spinning.](image-url)
Among all the spinning systems, ring spinning uses the maximum amount of energy, hence imparts the highest amount of environmental pollution. This can be attributed to the higher number of machineries needed for the process. It can be observed that the ring spinning needs the additional process of drawing and roving frame. In the case of rotor and air-jet spinning, the carded slivers can be used as the input material to make the yarn; however, ring spinning needs the extra processes. Hence, the highest amount of energy has been consumed in ring spinning. A comparative assessment of different spinning system has been tabulated in Table 2.1.

In ring spinning, the combed yarn needs higher energy compared with the carded yarn due to additional process of combing. The spinning machine manufacturers are applying the modern technological advancements to reduce the power consumption and increase the productivity and efficiency. Approaches such as increase in the spindle speed, efficient driving systems, lightweight spindles and bobbins, and low-friction components can be helpful to reduce the environmental impact of ring spinning.

Tang et al. (2004) has given a model for predicting the ratio of energy consumption in yarn production for a full package during yarn winding in ring spinning. They also discussed the effects on energy consumption of key parameters such as spindle speed, yarn count, and package diameter during yarn winding in bobbin at ring spinning. The results indicated that the ratio of energy consumption to yarn production is proportional to yarn package diameter but is inversely proportional to spindle speed and yarn count (Tex). Overall, the effect of yarn count is greater than that of spindle speed and package diameter during yarn winding in ring spinning.

There are many methods or mechanisms for spinning such as ring spinning, rotor spinning, air-jet spinning, friction spinning, and air vortex spinning. Each method has unique energy needs and its own dedicated process flow.
Table 2.1 Comparison of ring, rotor, and air-jet yarn spinning systems (Rieter, 2013).

<table>
<thead>
<tr>
<th>Spinning machine</th>
<th>Positive points</th>
<th>Quantitative data</th>
<th>Sustainability issues</th>
</tr>
</thead>
</table>
| Ring spinning    | • Versatility in producing a wide range of yarn counts.  
                   • Uniform helical yarn structure.  
                   • The strongest yarns are produced in this system. | • The highest energy cost/kg of yarn irrespective of yarn count.  
         • Only the ring frame itself consumes 58% of the total energy of ring yarn production system. Winding and roving making processes consume significant energy, which is absent in rotor and air-jet spinning.  
         • Very low delivery speed in the range of 25—30 m/min. | • The highest amount of electricity is consumed.  
                   • Significant waste generated during yarn production. |
| Rotor            | • Suitable for producing coarse to medium yarn count range.  
                   • Bipartite structure comprising a helical core of fibers with outer zone of wrapper fibers, which occur irregularly along the core length.  
                   • Lower yarn strength than ring and air-jet yarns but regular, bulkier, and fewer imperfections than ring yarn. | • Lowest energy cost/kg of yarn for coarser count like 30s but higher than air-jet for finer counts (40—50s) and always lower than ring yarns irrespective of count.  
         • Only rotor spinning machine consumes 80% of the total energy, which is lower than the ring spinning.  
         • Delivery speed is in the range of 200—250 m/min.  
         • Production rate is 5—8 times higher than ring-spun yarn. | • Low energy requirement and hence, more sustainable particularly for coarser yarn count.  
                   • Low waste generation and also consumes waste from ring spinning process. |
| Air-jet          | • Suitable for medium to finer count range.  
                   • Fasciated yarn structure comprising of parallel core fibers wrapped by helical sheath fibers.  
                   • The yarn strength is higher than rotor yarn but lower than ring yarn. Yarn is stiffness is the highest. | • The lowest energy cost/kg of yarn for finer counts (40—50s) but higher than rotor yarn for coarser count (30s) and always lower than ring yarns irrespective of yarn count.  
         • Only air-jet spinning machine consumes 68% of the total energy.  
         • Very high delivery speed in the range of 400—500 m/min.  
         • Production rate is 10—15 times higher than ring-spun yarn. | • Low energy requirement and hence, more sustainable particularly for medium and fine yarn count.  
                   • Low waste generation. |
Ring spinning and rotor (open-end) spinning are quite popular for spinning cotton and cotton blends. The energy requirement per one kilogram of ring-spun yarn varies between 3.49 and 3.62 kWh/kg, whereas in the case of open-end spinning, energy requirements vary between 2.44 and 2.58 kWh/kg of yarn. It should also be noted that energy consumption to produce a unit of yarn will vary significantly between various countries. For instance, ring- and rotor-spun yarns produced in China consume 3.49 and 2.58 kWh/kg, respectively, whereas in India and the United States, the energy consumption is 3.57—2.5 kWh/kg and 3.56—2.44 kWh/kg, respectively (Koç and Kaplan, 2007).

Finer yarns require more energy than coarser ones, and this is applicable to all types of fiber. Further for the same count, yarns for weaving consume more energy than those used for knitting. Knitting yarn of 20 Tex consumes 3.06 kWh/kg, whereas the same amount of yarn consumes 3.64 kWh/kg if it is to be used for weaving. A spinning plant utilizes 78% of energy in its machines, 16% for humidification plant, 3% for lighting, and 3% for compressors.

In a study for life-cycle assessment of a 100% Australian cotton T-shirts (http://www.insidecotton.com/xmlui/bitstream/handle/1/4025/QUT2%20Final%20Report%20pt.2.pdf?sequence=2&isAllowed=y), it is calculated that for a 30 Tex carded cotton yarn, MVS (Murata Vortex Spinner) yarn consumes the lowest energy (2.11 kWh/kg) followed by open-end (2.44 kWh/kg) and ring-spun yarn (3.41 kWh/kg).

Power consumption for 20s yarn is nearly double for combed ring yarn as compared to carded rotor yarn in India, China, and the United States. Only in Turkey, the difference in power consumption is lower. Rieter (2013) reports power consumption of 0.18 CHF/Kg (Swiss franc/kg) in rotor spinning, 0.25 CHF/kg in ring spinning, and 0.20 in air-jet spinning in 30s count. Thus, power consumption is the lowest in rotor spinning among the three spinning systems for coarser counts. Krause and Soliman (1982) have reported that in counts coarser than 10s, rotor spinning consumes less power than ring spinning. However, in counts finer than 20s, rotor spinning consumes more power, which is contradictory to Rieter’s results. Hence, rotor and air-jet spinning are more sustainable compared to ring spinning.

Power consumption in rotor spinning inclusive of air conditioning works out as 2.95 kWh/kg in 20s as per Kaplan and Koç (2010). Further, while machine’s share of power is 73.4%, the share of compressors is 3.5%, lighting is 3.6%, and air conditioning is 19.7%.

Measures to reduce power consumption are mentioned as below:

- Rieter suction tube ECOriized reduces suction power at the spinning position by up to 67% and results in significant cost savings. Each spinning position features a suction opening for extracting ends down and hard ends. The suction tube ECOriized features a flap that only opens fully when necessary. As a consequence, between 3 and 4 Watt power per flap is saved. Considerable energy savings are achieved in conjunction with adjustable inverter control (https://www.rieter.com/fileadmin/user_upload/products/documents/after-sales/Modernization/ECOrized_G_30_RAS_leaflet_2673-v4_87133_Original__English.pdf).
- Energy saving spindle LENA has been designed for the highest speeds with the main goal of achieving lower energy consumption. LENA stands for low energy noise absorption. It is recommended for speeds up to 30,000 RPM (revolutions per minute). The energy saving is in the average of 4%—6% because of reduced wharve diameter of 17.5 mm and lesser

- Ring frame machines that are running with lesser efficiency (91.5%) should be replaced with higher efficiency motor (94.5%), which gives good energy saving on ring frame machine.

- **PSM drafting motor**: The PSM drafting motor upgrade is an economical alternative to the standard drafting motors of the Rieter G/K ring frame machines. The technology of the permanent-magnet synchronous motor allows a higher output power of the motor by less energy consumption. Further, it gives 29% improved efficiency and 25% higher output power compared with the original motor. Also, the energy consumption is reduced up to 3% regarding total machine consumption with increased lifetime due to lower motor temperature (https://www.rieter.com/products/after-sales/modernization-solutions/).

- In ring frame machine, the speed of the machine can be set (spindle speed) with respect to length of the yarn produced from the machine. By optimizing the speed curve, peak load of the motor power can be decreased, and utilization of the motor can be enhanced. By doing so, there is a considerable power saving in the machine (Dhayaneswaran and Ashokkumar, 2013).

- For every ring frame and speed frame machines, there is an over head travel cleaning device installed to blow and suck the cotton flies sediment throughout the machine, which travels from one end to the other end of the machine. Instead of continuous running from one end to the other end of the ring frame and speed frame machine, every reversal at end of the machine, over head cleaner is stopped for 1–5 min. This has given good energy saving without any investment.

- The ring frame machine has fan motor, which is used to suck the broken thread while machine is running. By installing energy-efficient excel fans (less weight) instead of conventional aluminum fans in fan motor of ring frame machine, considerable power can be saved.

- By replacing light weight spindles and empty bobbins will give the energy savings in ring frame machines.

- Wherever the air hoses are connected for machine application in particular for automatic doffer and top arm for individual spindles, air leakage is observed in the machines. By replacing the new hose and joints, air leakage inside the machines will reduce the compressor running time and saves compressor energy.

- Humidification plant is a big power-consuming area. Using inverter on a trial basis may give optimum result. In humidification plant, by servicing and optimizing the motors that are marked as over loaded, considerable power saving can also be achieved.

- Energy can also be saved after tuning compressor ON and OFF time (6 and 7 bar, respectively) by correcting the air leakage inside the plant and machines in compressor. The inverter may be installed in compressor also.

- In the speed frame machine, to avoid over lapping of the sliver, heating lamps are used for increasing the temperature. These lamps can be avoided through circulating hot exhaust air of the compressor (https://www.textiletoday.com.bd/way-energy-efficiency-improvement-spinning-mill/).

- All main motor and suction motor of ring frame must be included in inverter drive that will reduce power up to 30%.

- Proper lubrication, good quality bearing, and driving belt can reduce power.

- Replacement of low efficiency rewounded motors with high efficiency motors.

- The normal light should be replaced immediately with LED (light emitting diode) light.

- The solar panel may be used for room light and security light. The rooftop solar panel may be easily installed over factory shed.

- Old, worn out equipment may consume more power that should be replaced immediately.

- A cogeneration system to be introduced to minimize operating cost of chiller and boiler.
2.3.3 Sustainability in rotor spinning

Open-end or rotor-spun yarns are created through a process that is fundamentally different from ring spinning. Rotor spinning is the second most widely used spinning process, which existed for the last 52 years. The number of machineries needed for rotor yarn is lower than that of ring yarn. A draw frame fiber can be used for the rotor spinning, eliminating the process of roving frame. Furthermore, the productivity of rotor spinning is about 6—8 times than the ring spinning. An illustration of this process is shown in Fig. 2.5 and Fig. 2.6 shows a commercial rotor spinning machine.

The sliver is completely disassembled into individual fibers, which are fed into a rotating chamber. The fibers are fed by means of a feed roller to a rapidly rotating opening roller that is covered with wire points. This opening roller open fibers individually from the sliver and projects them into the airstream flowing down the delivery duct. The fibers are deposited in a V-shaped groove along the sides of a rotor, and further, these fibers are peeled off to join the “open end” of a previously formed yarn. As the fibers join the yarn, twist is conveyed to the fibers from the movement of the rotor chamber. A percentage of these fibers become trapped in the yarn as it is pulled from the chamber. Because these fibers are added to the yarn after it has been partially twisted, fibers on the surface of the yarn contain less twist than those in the center of the yarn. The result is a highly twisted yarn core covered with fibers of widely varying twist angles that are partially covered by tightly bound “wrapper” fibers (Hatch, 1993).

Many of the modern spinning industries are adopting the rotor spinning method as it is considered to be more sustainable compared with the ring spinning. This is because of higher productivity and reduced electricity usage per kg of yarn. In rotor spinning, the twist is introduced into the yarn without the rotation of the package, which allows higher speeds and a relatively low power cost.

Like ring spinning, finer yarn count and higher twist level needs higher amount of energy. Majority of the research activities on rotor spinning have focused in reducing the energy consumption by suitably designing of rotor assembly, which has led to the

Fig. 2.5 Principle of rotor spinning.
energy saving of about 15%. Rotor spinning has lower environmental impact compared with ring spinning; however, it can only produce coarse yarn counts. The uses of advanced spinning technology and rotor design helps in achieving higher productivity and improved yarn quality. Approaches such as increase in the rotor speed (a challenging task), efficient driving system, improved design of rotor surface, opening roller, navel, and other spinning elements can help to have the minimal impact on the environment.

The addition of higher number of spinning heads and optimization of the space of rotor spinning frame can help to save 10%—15% of electricity. A spinning plant consisting of both ring and rotor spinning machines uses 11% energy for blow room, 12% for carding, 5% for drawing, 1% for combing, 7% for roving, 37% for ring spinning machines, 20% for open-end machines, and 7% for winding machines (Koç and Kaplan, 2007). Compared with ring spinning, open-end spinning has the following advantages:

- Elimination of some processes, such as roving and winding,
- Lower yarn fault content,
- Cheap raw material is available and there is less waste,
- Larger delivery package size,
- Reduced labor requirements and open to automation,
- Higher speed of twist insertion and delivery speed up to 200 m/min,
- Lower power consumption per kg of yarn produced for short staple yarns thicker than approximately 20–30 Tex (Nield, 1975; Oxtoby, 1987; Koç et al., 2005; Koç and Lawrence, 2006).

**Measures to reduce power consumption**

In rotor spinning, power is consumed mostly by opening action by opening roller, rotor, suction system, and winding. Balasubramanian (2013) has discussed the measures to reduce the energy consumption in rotor spinning:

- **Rotor speed and diameter**: Power consumption increases with increase of rotor speed for different rotor diameters. Power consumption increases more rapidly with rotor speed at 56 mm diameter than at 30 mm diameter. As a result, power consumption at 130,000 rotor
speed with 30 mm rotor diameter is nearly the same as at 62,000 rotor speed with 56 mm rotor diameter. So rotor diameter has to be reduced with increase in rotor speed to keep down power consumption.

- **Rotor shape and weight** have been optimized by computer-aided design to reduce air friction in Corobox SE 12 by Schlafhorst. This reduces frictional resistance and brings about significant reduction in power.

- **Type of machine:** Self-pumping rotors that do not use a separate suction system consume 50%—60% lower power compared with automatic machines with outside suction system. But speeds are much lower with former machines.

- **Rotor bearing:** Aero bearing that provides air cushion and axial support to rotor in place of steel ball can be used nowadays to reduce power consumption. The air film is produced by compressed air of 6 bars, which is continuously monitored. This reduces friction, power consumption, and wear and tear. Also, thrust bearing by Suessen is claimed to save power.

- **Magnetic rotor positioning system** by Schlafhorst contributes to power saving as it dispenses energy consuming steel balls, staggered twin discs, or air nozzles. The end of rotor shaft is fixed in position by two permanent magnets without contact of rotor shaft. This is claimed to be more energy efficient than air bearing as it avoids the energy required to produce compressed air.

- **Suction system:** Suction system for vacuum generation consumes significant power. Vacuum level decreases due to deposition of waste on filter and so higher rating motor or higher setting is used to minimize fall in suction. Autocoro 312 and later models offer an electronically controlled vacuum system with the help of a frequency inverter drive to suction fan to maintain constant suction throughout spinning. This even permits in some cases reduction in suction levels without affecting performance.

- **Drive to rotor:** Diameter of twin discs driving rotor has been increased to 78 mm and width of tangential belt reduced to 20 mm by Suessen in their new Spinbox to reduce power consumption. Oerlikon Schlafhorst claims reduction in manufacturing costs by use of plastic bushings. The replacement of belt drives with deflection pulleys through modern individual drives fundamentally saves energy in R70 rotor spinning machine (https://www.rieter.com/fileadmin/user_upload/products/documents/systems/end-spinning/rieter-r70-rotor-spinning-machine-brochure-93050-en.pdf). The rotor drive, which runs on contactless bearings, utilizes the latest technology.

- **Piecing by robot:** Coromat by Schlafhorst employs a shutter that allows suction air only at the time when it is needed like yarn search, suction for yarn piecing, and doffing of package. Controlled use of suction air in this manner reduces requirement of vacuum requirement thereby saving power.

- **Cooling system for inverter:** By designing better cooling systems for inverter and motor, power savings have been obtained in Rieter R40.

- **Air conditioning:** Instead of air conditioning the entire spinning room, Schlafhorst has developed a system of providing direct air conditioning to the required areas like sliver feed to spinbox. This helps to reduce air-conditioning costs substantially.

- **Online quality monitoring:** Schlafhorst uses energy-saving LEDs and optimized electrically controlled sensors to reduce power in yarn quality monitoring system.

Central drives ECOrized: Energy saving main drives have been developed in collaboration with a leading European motor manufacturer. Those motors reduce the energy consumption of the R 66 by about 5%.

Suction from both machine ends saves up to 30%: Extensive analysis of the air flow showed the little influence of the length to energy consumption due to the advantageous shape of the R 66 suction channel for short machines. At longer machines, the losses and differences in spinning suction increase. The suction of R 66 DE from both machine ends cuts the length in half and thus saves up to 30% in suction power. This concept, which is proven also in Rieter compact spinning machines, saves in long rotor spinning machines up to 6% of energy consumption. In the R 66 DE, both effects are combined, resulting in a saving of up to 10% of energy consumption.

Intelligent filter cleaning saves energy: The suction device needs a lot of energy. An innovative measurement of differential pressure at the filter unit of the R 66 initiates the automatic cleaning cycles. Thereby, it maintains the negative pressure for spinning at a constant low level while consuming a minimal amount of energy. The R 66 version is longer than 600 positions has energy saving suction devices from both machine ends. This secures minimal losses in the suction channel by halving the length.

2.3.4 Sustainability in air-jet spinning

The air-jet spinning process is the newest technology, which is the third most widely used technology that existed more than two decades. Air-jet spinning produces yarn at approximately twice the speed of rotor spinning and approximately fifteen times faster than ring spinning. At the time the MJS 801 (Murata jet spinner) was introduced, its delivery speed was 160 m/min, 10 times faster than rotor system. As a result of these advantages, the MJS 801 system captured great commercial success quickly in spinning pure synthetic fibers, blends of synthetic fibers, or rich blends of synthetic with cotton fibers. However, it is not suitable for pure cotton fibers or rich blends of cotton fibers. In the late 80’s, Murata introduced a new version of this system, the MJS 802 (Basu, 1999).

The MJS 802 contains a 4-line drafting unit and a modified nozzle that provides better fiber control, and a speed up to 210 m/min was possible. The process flow on MJS 802 is shown in Fig. 2.7(a). First, a draw frame sliver passes through the drafting unit that reduces the sliver weight of approximately 200 to 1. Then the delivered fiber is passed to twin air nozzles located directly after the drafting unit. The first nozzle imparts twist to the leading ends of the fiber while their trailing ends are still being held by the front roller. The second nozzle imparts false twist to the whole fiber bundle in opposite direction to that of the first nozzle. Because of the higher air pressure used in the second nozzle, the false twist to the fiber bundle travels back to the front rollers of the drafting unit. As the yarn comes through the second nozzle, the false twist is removed, and the core fibers no longer exhibit any twist. They are arranged in parallel form, and at that point, the surface fibers that were twisted by the first nozzle are caused to further increase their twist by the untwisting action (Klein, 1993; McCreight et al., 1997; Goyal, 2012).
Murata Machinery Ltd. and Rieter make machines that spin yarn using an air vortex principle. Murata’s device is called a vortex spinning machine and currently dominates the market (Hasanbeigi and Price, 2015). Rieter’s new device is called an air-jet spinning machine. The vortex spinning machine (Fig. 2.7(b)) is suitable for processing man-made fibers and their blends with cotton. Because the twist is created by air flow in the vortex spinning system, high-speed rotating mechanical parts are not required, so high production rates are possible (Erdumlu et al., 2012). Concerns have been expressed that there is excessive fiber loss using the vortex spinning machine. The fiber loss can be about 8%, but most of what is lost is short fiber, which does not contribute to yarn quality (Oxenham, 2003).

Murata introduced its third-generation vortex spinning machine, the Vortex III 870, at the International Textile Machinery Association (ITMA) exhibition in 2011. This machine is available for up to 96 spinning units with a maximum production speed of 500 m per minute (m/min). At ITMA 2011, Rieter also exhibited J20 air-jet spinning machine (Fig. 2.8), which is double-sided and has 120 spinning units, so it can produce more yarn in a smaller space than other spinning machines. These technologies have higher investment and labor costs than for an open-end rotor spinning system but lower costs than for a ring spinning system (Erdumlu et al., 2012; Oxenham, 2002).

Vortex and jet spinning machines have the following benefits compared with ring and rotor spinning (Erdumlu et al., 2012; Rupp, 2012; Oxenham, 2011; Hasanbeigi, 2013):

- Higher production speed, up to 500 m/min, which means approximately 2—3 times greater productivity than rotor spinning and 20—30 times greater productivity than ring spinning, depending on the yarn count.
- Lower energy costs than for both ring and open-end rotor spinning systems, despite the high-pressure air consumption in vortex spinning.
- Less hairiness in yarn, resulting in greater abrasion resistance and less pilling than fabrics made from ring-spun or open-end rotor-spun yarns.

Fig. 2.7 Principle of Murata air-jet spinning: (a) MJS and (b) Vortex.
Other advantages of air-jet spinning are the lower space needed compared with ring and rotor spinning. The reduced space needs less climatic control; hence, air-jet spinning has the lowest environmental impact among the three major spinning systems. Air-jet spinning needs fewer preparatory steps compared with the ring spinning, hence less power intensive.

Rieter claims that the air-jet spinning technology consumes less energy per kilogram of produced yarn than other spinning processes (https://www.textileworld.com/textile-world/features/2012/03/spinning-with-an-air-jet/). The facility of shutdown of individual spinning units pays off by saving energy cost. The dimensions of the J 20 were also considered, to ensure that the machine could be installed in existing spinning rooms. Space needs for the J 20 are 25% less than for ring-spinning equipment producing the same capacity, resulting in reduced building costs and less climate control and space conditioning, which in turn saves energy.

In a discussion with the manager (from GHCL, a leading Indian textile industry at Vapi in Gujarat) of a spinning industry in India, it is mentioned that power consumption in air-jet spinning is lower than that of ring spinning in case of count finer that 30s but for count in the range of 20–24s, ring spinning is slight economical in terms of power consumed/kg of yarn. In air-jet spinning, majority of power is consumed by compressed air. The power consumption in humidification plant for air-jet spinning is also lower (13%–14%) as compared with ring spinning (17%–18%) due to less conditioning space. During discussion, he mentioned the following measures to reduce power consumption:

- Optimization of first and second nozzle pressure.
- For finer count, put inverter in main suction blower to reduce the frequency and hence power saving.
Put inverter in knotter suction blower to reduce the frequency in fine count to save energy.
Put stop timer in over head blower.
Put big timing pulley in main motor to reduce frequency of inverter.
During yarn breakage, individual spindle solenoid valve may put for stoppage of air flow.

### 2.4 Waste management in spinning

With the ever-increasing price of cotton, huge investments on sophisticated machines, and increasing labor wages, it is a highly challenging task for any spinning mills to enhance the productivity. To survive the huge competition, it is absolutely essential that waste incurred during the yarn manufacturing processes should be kept under control. The waste occurring in the spinning mill can be classified normally as soft waste and hard waste. Soft waste is reusable in the spinning process, whereas hard waste is not reusable. To have a good control on the process waste, it is important to assess the waste in blow room, carding, comber, and ring frame at regular intervals.

Controlling process wastes such as blow room and card droppings, flat strips, comber noil, sweep waste, and yarn waste, equal emphasis should also be laid on the control of soft wastes such as lap bits, sliver bits, roving ends, pneumafil and roller waste. This is because, apart from loss in production, reprocessing of soft wastes involves extra handling and deteriorates yarn quality. It should be noted here that the control on waste has to be concomitant with achieving the desired level of cleaning.

Textile wastes can be divided into two main groups: production wastes and postproduction wastes. Production wastes are basically raw materials of each production step that cannot be put into end product due to different reasons. For yarn spinners, these wastes can occur during cleaning of the fibers or combing out short staple fibers from the long ones in combing machine, etc. These clean/unclean wastes in fiber form can be reused. After spinning mill, there are wastes in yarn and fabric forms, and they need recycling to be put again in production. Postproduction wastes are generally worn out cloths, which can be recycled and may be used again in textiles or utilized in other products.

Textiles include different raw material (fiber) types. Fibers used in textiles are categorized into two main groups, which are natural and man-made fibers. Most known examples for natural fibers are cotton (seed fibers), wool, silk (animal fibers), flax (bast fibers), sisal (leaf fibers), and asbestos (mineral fibers). On the other hand, polyester, nylon, acrylic (which are synthetic fibers), modal, viscose rayon, and acetate rayon (which are regenerated fibers) are some of the examples for man-made fibers. Thereby, textile wastes have a great variety of raw material sources. These wastes can be recycled or reused in different products. In 2017, global fiber production exceeded 100 million metric ton. Polyester has around 51% of total global fiber production. The second most important fiber is cotton, and it has approximately 25% of total global fiber production.

Textile wastes can be recycled/reused in textiles or other products. Other product wastes can also be utilized in textile production. One of the most known examples for this is PET bottles. PET bottles are collected, are recycled, and can be used in
textile products as “rPET fiber.” rPET fibers can be used in yarn production, as 100% or in blends, thereby in most of the textile structures. There are various studies about this topic. These studies cover spinning of the fiber, properties of the fiber, properties of yarn, and fabric produced from this fiber and all.

Some of the researches are focused on using textile wastes in different products. Mishra et al. (2014) used textile wastes to produce composites and tested the properties of these composites. Briga-Sa et al. (2013), Binici et al. (2013), and El Wazna et al. (2017) used textile wastes as insulation materials, and Briga-Sa indicated that they got results similar to polystyrene (PS) and mineral wool. Shukla et al. (2008) used PET fiber wastes to synthesize new chemicals that can be used in different fields. These examples show that textiles are generally sustainable materials. There are too many studies dedicated on this topic.

2.5 Recent trends in energy usage

Mechanization of almost every process involved in the textile industry from fiber to fabric has led to increased consumption of electricity. In today’s scenario where the power purchased from state electricity boards works out to be much higher than solar or wind energy, it is not surprising that more and more players in this energy-intensive industry are opting for cost-effective green energy. This is more so in a state such as Tamil Nadu, India, that leads the country in the textile sector and, at the same time, is the highest producer of wind energy. The state has a total installed wind capacity of 8764 MW, and its solar capacity at the end of 2018 stood at 2055 MW.

2.5.1 Wind energy

The textile industry is one of the early adopters of renewable energy in India. This has contributed significantly to the growth of renewable energy in the form mostly of wind installations in the country. The textile industry has about 2700 MW of wind generation capacity in Tamil Nadu alone (http://www.indiantextilemagazine.in/technology/textile-industries-growing-preference-for-solar-power/).

It must be noted that the coastal state witnesses wind flows for almost six months in a year; the winds peak during the southwest and northeast monsoon months and experience a moderate flow for four months. It also receives 300 days of clear sunshine. A large number of textile-related industries, especially spinning mills, are making use of this and other renewable sources of energy for captive power generation. Measures such as the bundling of wind power projects, the policy of accelerated depreciation, and the Technology Upgradation Fund attracted the power-intensive industries in the southern state to invest in captive wind power plants.

GHCL, which is one of India’s leading manufacturers of home textiles, also decided to start captive wind power generation for its spinning and textile mills almost 15 years back. The CEO of GHCL Limited has mentioned that the cost of installing 1 MW of wind power capacity is Rs 70 million. Although the investment can be recovered over
a period seven years, it is cheaper to buy wind power from other private players than to generate it (https://www.ghcl.co.in/news/big-on-captive).

During the current financial year, the cost of wind energy from private players is at the rate of Rs 6.17 (INR, which is about US$0.10) per kWh as against Rs 7.47 per kWh from the Tamil Nadu Electricity Board.

GHCL’s textile unit at Vapi in Gujarat has an annual production capacity of 45 million meters of finished fabric per annum. It has a 2.1 MW captive wind power generation facility, which was set up in March 2017 by Suzlon Energy at Jodia in Jamnagar. GHCL produces 27.2 MW of captive wind energy, which fulfills 35% of the energy requirement of the textile division. The manager mentioned the company is not planning to generate wind power on its own as of now. This is because of the latest discouraging government policies for captive wind power producers.

Further, he has mentioned that the solar power investment cost per MW has declined dramatically over the years. Today, the solar power investment cost is Rs 40 million per MW, almost half that of wind power. So, the company decided to add solar power to its portfolio in its quest to use more green energy. According to GHCL’s CEO, the company’s dependence on thermal power has reduced from 64 million units to 34 million units in respect of the total requirement of 120 million units for the year 2019–20. Thus, it is able to avoid carbon emissions of 24,300 CO₂e metric tonnes. During 2018–19, renewable energy comprised 49% of the total energy mix of GHCL’s yarn division’s captive consumption. In the current fiscal, we are planning to increase the share of renewable energy to 72%. We have set a target to use 90% of our total power requirements through green energy, be it wind or solar, and are optimistic of meeting this target in the coming years.

### 2.5.2 Solar energy

The textile sector is one of the highest energy-consuming sectors in India. Textile processing covers steps ranging from singeing (removal of protruding fiber) to finishing and printing of the fabric and manufacturing polyester, polyester filament yarn, acrylic, nylon, viscose, cotton textiles, etc. The Indian Textile Industry has always been amenable in adapting newer and more efficient technologies. Electricity is most necessary input that mill needs today, and it has always remained area of concern in this segment. Textile industry has been early adopter of renewable energy in India and has contributed largely in the growth of clean energy in the country. Many textile mills have set up captive power plants, wind mills, and now solar power plants. With the evolution of solar ecosystem in India and knowing the numerous advantages of solar energy, textile industry has embraced the solar power and started to deploying solar systems in a fairly big way. The advantages are quite obvious (http://www.indiantextilemagazine.in/technology/textile-industrys-growing-preference-for-solar-power/):

- **Cost reduction**: The electricity tariff for industrial consumers is the highest among all sectors, whereas solar power is much cheaper. The prices are going to remain almost constant
throughout the lifetime of the solar plant, whereas the rates for power from conventional sources are expected to escalate year on year basis.

- **Compliance of renewable purchase obligations (RPO):** Several industrial consumers of electricity have to meet their RPO, and setting up of a solar plant is one of the simplest ways to comply with the RPO.

- **Availability of roof space:** Unlike commercial establishments, most of the automotive factories have vast unshaded roof area and vast tracts of unused land. Setting up of solar plants in these unshaded and unused areas is a relatively easy task.

- **Energy savings:** Solar power generated in the site can offset electricity that needs to be drawn from the grid and reduce the reliance on diesel gensets. This, in turn, leads to further cost reduction.

- **Reducing carbon footprint:** Most of the companies operate with explicit carbon footprint reduction. Solar plants help in environmental protection and also reduce carbon footprint.

Textile industries in India pay a flat rate on energy charges between Rs. 5—6.35 per unit, and with applicable duty, the charge goes up to Rs. 6—7.46 per unit. Therefore, as long as solar energy cost remains lower than the utility tariff, it will continue to make a firm proposition for these industries. On an average, a textile industry in India has enough space to accommodate 1—5 MW capacity of rooftop solar plant or ground mounted solar plant. Such size provides cost advantage and therefore the cost of solar energy comes in the band of Rs. 5.45—5.64 per unit, thus this offers a scope for savings. The incredible drop of solar module prices and the growth of the solar ecosystem have created the ideal situation for more widespread adaption of solar power systems. Textile industry can benefit hugely by deploying solar projects in large scale (https://www.saurenergy.com/solar-energy-articles/tailoring-solar-power-for-textile-industry).

### 2.6 Conclusions

This chapter discussed the negative environmental impacts by spinning industries in the drive to achieve sustainability. Yarn manufacturing involves many mechanical processes that consumes large amount of energy mainly derived from thermal power plants that generate large quantities of greenhouse gases. In addition, spinning industries generate large quantities of solid waste, dust, and noise and pollute air. In many countries, the spinning industries are facing several challenges due to increased energy cost, increased raw material cost, increased labor cost, and increased sustainability drive by many global fashion brands. Because of these reasons, many of the global spinning industries are struggling to get a net profit of 5%. Low profitability and declining sales are the main hindrances for many spinning industries to implement new technologies in their manufacturing facilities.

This chapter also discussed various approaches taken by the spinning industries to achieve sustainability in the major spinning systems such as ring spinning, rotor spinning, and air-jet spinning. Waste management in spinning industries are also discussed in this chapter. In ring spinning, various approaches such as increasing the spindle speed, efficient driving systems, lightweight bobbins, low-friction components,
advanced spindle design can be helpful to reduce the environmental impact. In rotor spinning approaches such as increase in the rotor speed, efficient driving system, improved design of rotor surface, opening roller, navel, and other spinning elements can help to have the minimal impact on the environment.

Air-jet spinning produces yarns at the highest speed among the three major systems of yarn manufacturing. In addition to the speed, the other advantage of air-jet spinning is the lower space needed, compared with ring and rotor spinning, which indicates less climatic control. Hence, air-jet spinning has the lowest environmental impact among the three major spinning systems. However, the energy consumption is higher compared with rotor spinning, but lower than the ring spinning. Textile industry has been early adopter of renewable energy in India and has contributed largely in the growth of clean energy in the country. This chapter also includes expert views from GHCL, a leading Indian textile industry at Vapi in Gujarat, which highlighted that nowadays textile mills have set up renewable energy sources such as captive power plants, wind mills, and solar power plants for their power requirement, which reduce the cost and carbon emission. By adopting many of the approaches mentioned in this chapter, the textile industries in India as well as other developing countries can become more sustainable.

References


Sustainability in fabric manufacturing

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3.1 Introduction

The production of the textile goods is considered to be the oldest consumer goods industry. The manufacturing of textile products starts from the cultivation of natural fibers like cotton and production of synthetic fibers like Polyester. These fibers are further processed in a series of operations such as spinning, weaving, and chemical processing to form different types of textile products like garments, home furnishings, and technical textiles. The basic purpose of the textile fabrics/garments is to provide primary protection to humans but with development of scientific knowledge, the functionality and the aesthetic appeal of fabrics/garments become the primary objective of clothing. The fabrics produced mostly used for the traditional use like garments, home furnishings, and functional use as in the form of technical textiles. It is also reported that more than 60% share of fabrics is used for the clothing and the rest are used for home furnishings and technical textiles (AM Mindpower, 2010).

Gugnami and Mishra (2012) reported that the apparel industry consumed 400 billion square meters of fabric per annum in 2015. This amount of fabrics need to be produced from 100 million tonnes of fibers (natural and synthetic). The production of this huge quantity of fabric needs around 1 billion KWh of energy as well as huge amount of water (Ecotextiles, 2009). This huge electricity demand for the fabric production leads to 1.2 billion tonnes of green house gases (GHGs). The huge requirement of water generates a huge quantity of wastewater or effluent. For example, Chinese textile manufactures alone discharged 2.5 billion tonnes of wastewater in 2019 as per IPE, 2012. Therefore, the textile and apparel industry is considered to be the second most polluting industry in the world (Sweeny, 2015) and is a major player in global climate change (Hiller Connell, 2015). In addition, the textile and apparel industry is also the second largest polluter of freshwater resources on the planet (Conca, 2015).

The textile and apparel industry significantly contributes to global climate change, mostly because its primary energy (mostly electricity) source is fossil fuels. From the report of Intergovernmental Panel on Climate Change (IPCC, 2014), the electricity and heat production sector account for 25% of global GHG emissions, which is the largest in comparison to any other economic sector. Apart from wastewater and toxicity from fertilizer, pesticides, herbicides, and other pretreatment and finishing chemicals, converting raw fibers to finished apparel requires a great deal of energy. This energy generation emits carbon dioxide (CO$_2$), methane (CH$_4$), and other GHGs. The GHG
emissions calculator, developed by the Environmental Protection Agency (EPA, 2013), estimates that generating one kilowatt-hour (kWh) of electric energy emits 0.0007 metric tonnes of carbon dioxide equivalent.

Nonrenewable sources of energy such as coal, used to generate electricity, are becoming scarce (Robertson, 2017) and when coupled with the climate change realities linked to energy consumption, the global energy crisis is becoming a more urgent topic. From the triple bottom line (i.e., environment, economic, and social responsibility) perspective, the social responsibility aspect of sustainability has garnered much attention, and improvements have been made within the apparel manufacturing industry (Nayak et al., 2019).

However, the environmental and economic sectors have not gained much attention.

This chapter discusses various fabric manufacturing technologies such as weaving and knitting and their environmental impact. This chapter also discusses about the energy conservation approaches that can be used in fabric manufacturing process. Other problems such as noise pollution and waste generation including various approaches to control them have also been discussed.

### 3.2 Fabric manufacturing

Textile fabrics are the major component of fashion industry. Textile fabrics are special materials as they are generally lightweight, flexible (easy to bend, shear, and twist), moldable, permeable, and strong. Textile fabrics are generally two-dimensional flexible materials made by interlacing of yarns or intermeshing of loops with the exception of nonwovens and braids. Fabric manufacturing is one of the four major stages (fiber production, yarn manufacturing, fabric manufacturing, and textile chemical processing) of the textile value chain. Most of the apparel fabrics are manufactured by weaving technology though knitting is catching up fast especially in the leisure and sportswear segment. Natural fibers (like cotton, wool, silk, linen, etc.), synthetic fibers (like polyester, acrylic, nylon, etc.), and regenerated fibers from natural sources (like rayon) are the most popular raw materials for woven and knitted fabrics intended for apparel use.

Different types of fabrics can be manufactured by weaving, knitting, nonwoven, felting, tufting, and braiding technologies. Generally, for clothing, weaving and knitting are the most widely used processes. Weaving is more time- and energy-consuming process and requires more machineries than knitting. However, the fabric properties produced by knitting and weaving are different from each other; hence, they are used for specific end use applications. The products from other fabric manufacturing processes are used for technical textile applications and can be done from fibers except braiding. As there is no need for yarn preparation, the environmental impacts of nonwoven, felting, and tufting processes are very less compared to weaving and knitting. However, the products from these processes cannot be directly used for apparel clothing.
3.2.1 Fabric manufacturing by weaving technology

Woven fabrics are the most dominant fabrics in apparels and produced by interlacing two sets of threads, commonly known as warp and weft (or filling). Warp usually runs along the length of the fabric and the weft or filling essentially at a right angle to warp across the width of the fabric (Goswami et al., 2004). The process of transformation of yarns into fabric by interlacement of warp and weft is called weaving. The interlacement pattern between the warp and weft is called weaves which affects the aesthetics, mechanical and comfort behavior of the fabric.

The woven fabrics usually consist of a number of warp yarns in the whole width. Hence, it is practically difficult to weave the woven fabric from the cones produced in winding machines. The weaving process, therefore, requires the preparation of a weaver’s beam, which is placed at the back of the loom. The weaver’s beam contains the exact number of warp yarns (ends) required to produce a fabric of the given specifications. The weaver’s beams are produced from multiple warper beams, which are typically produced from the sizing machines (Goswami et al., 2004). The sizing of the warp yarns is primarily carried to improve the weavability and reduce the end breakages. Weavability is the ability of the warp yarns to withstand the mechanical stresses and abrasion during weaving. This objective is achieved by applying a temporary coating of the size particles in the yarn surface as also penetrating few size particles into the yarn core. The sizing or slashing operation needs a lot of chemicals like adhesives (starch, polyvinyl alcohol (PVA), etc.), lubricants, and binders.

The weaver’s beam also can be prepared by sectional warping machine without sizing process for those warp yarns having sufficient weavability. A single warper’s beam is assembled by placing in the creel as many packages as required by the number of yarns in it. The packages placed in the creel of the warping machine are large wound packages in the form of cones obtained from winding machines and the cones are produced from the ring bobbins. Other packages can also be used in warping machines directly from modern spinning systems such as open end, friction, and air jet spinning. Therefore, certain preparatory processes are required to transfer the spun yarns from the spinner’s package to a weaver’s beam for weaving (Goswami et al., 2004). These sequence of processes required for weaving is called weaving preparatory processes.

The schematic diagram of the preparatory processes used for weaving is shown in Fig. 3.1. Again, the success of the weaving operation is considerably influenced by the quality of the input yarn and the care taken during the preparatory processes, such as winding, warping, and sizing. Also, careful consideration of the sizing ingredients, size add-on levels, process of slashing, and slasher-related parameters are a few of the several variables that must be controlled precisely for the success of an efficient weaving operation.

After the successful operation of weaving preparatory processes, the weaver’s beam is produced. The multiple ends from the weaver’s beam is then interlaced with the weft in the weaving machines. The weaving machine commonly known as looms is used for the formation of gray fabrics. The performance, productivity, and efficiency of the looms are greatly influenced by the weft insertion technology of the weaving machines. First-generation handlooms and then shuttle looms are the oldest among all
types of looms but the shuttle-less looms are evolved with time to overcome the drawbacks of the shuttle looms. The shuttle-less looms are popular in industry as the fabric production rate is higher and they also produce better quality fabrics.

The shuttle looms are the most versatile machine available in the market. These types of looms suffer with many problems like heavy medium (shuttle) to carry the weft, guideless weft carriage, higher power consumption per square meter of fabric production, higher noise generation, etc. The rapier weaving machines are the most flexible machines in the shuttle-less section. Their application range covers a wide variety of fabric styles. These types of looms are characterized by the minimum noise pollution due to the minimum vibrations of the reed, sley, and the heald frames (Castelli et al., 2010).

The projectile weaving machine (another kind of shuttle-less loom) is characterized by good productivity level and high operational reliability. These types of looms are useful for weaving of high width fabrics (Castelli et al., 2010). The most popular weaving machines in the shuttle-less loom section are the air jet weaving machines. These weaving machines are characterized by the highest weft insertion rate and considered as the most productive in the manufacturing of light to medium weight fabrics, preferably made of cotton and certain man-made fibers (sheets, shirting fabrics, linings, taffetas, and satins in staple yarns of man-made fibers) (Castelli et al., 2010).

The air jet looms can also be used for the production of heavy weight fabrics like denims as well as terry fabric production. These machines are preferred for the manufacturing of bulk quantities having customized fabric styles (Castelli et al., 2010). The weaving width generally ranges from 190 to 400 cm and can be used for the multicolor weft carrier, up to 8 different wefts. It has, however, to be considered that the air jet weaving machines require a high energy consumption to prepare the compressed air and that this consumption rises definitely with increasing loom width and running speed. The reduction in energy consumption by air jet looms is in fact one

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**Fig. 3.1** The flow chart of the weaving preparatory processes (Dash line (---): Optional process and solid line (—): Mandatory processes).
of the main concerns of the fabric manufacturers, which is an important selection criterion (Castelli et al., 2010).

The water jet looms are used for the manufacture of light, and medium-weight fabrics with standard characteristics and for hydrophobic fibers such as nylon and polyester. These looms are primarily used for the weaving of multi-filament synthetic yarns. These looms are characterized by high weft insertion rate and low energy consumption (Castelli et al., 2010).

The concept of multiphase weft insertion was started in 1955. These types of looms are based on the multished formation during weaving. The multished formation can be achieved by two basic techniques, namely, wave-shed and multilinear. The multiphase looms are unable to gain success due to the inherent shortcomings, such as the difficulty of repairing miss-picks, difference in weft tensions as a consequence of several weft-yarn carriers being activated at the same time and difficulty to achieve the required beat-up necessary to obtain uniform insertion across the entire weave length (Mastuo, 2008). The comparative assessment of the weft insertion rates and other characteristics of different types of looms is listed in Table 3.1.

### 3.2.2 Fabric manufacturing by knitting technology

The knitting technology is the second most widely used technique for fabric production after weaving technology. The knitted fabrics can be produced by two methods such as weft knitted method and warp knitted method. The weft knitted fabrics are formed by knitted loops, where each yarn in the width of the fabric. Warp knitted

<table>
<thead>
<tr>
<th>Weaving machines</th>
<th>Reed width (m)</th>
<th>Speed (rpm)</th>
<th>Weft insertion rate (m/min)</th>
<th>Energy consumption KWh/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shuttle loom</td>
<td>Upto 1.9</td>
<td>150–200</td>
<td>350–450</td>
<td>0.8</td>
</tr>
<tr>
<td>Projectile</td>
<td>1.9–6.55</td>
<td>300–450</td>
<td>1200–1500</td>
<td>0.26</td>
</tr>
<tr>
<td>Rapier (rigid)</td>
<td>1.4–3.6</td>
<td>350–700</td>
<td>1000–1200</td>
<td>0.52</td>
</tr>
<tr>
<td>Rapier (flexible)</td>
<td>1.2–4.0</td>
<td>350–550</td>
<td>1000–1200</td>
<td>0.52</td>
</tr>
<tr>
<td>Air jet</td>
<td>1.4–4.3</td>
<td>400–1150</td>
<td>1200–2500</td>
<td>0.65</td>
</tr>
<tr>
<td>Water jet</td>
<td>Upto 3</td>
<td>800–1000</td>
<td>1500–2000</td>
<td>0.35</td>
</tr>
<tr>
<td>Multiphase (linear)</td>
<td>1.5–2.0</td>
<td>1000–1500</td>
<td>2000–3000</td>
<td>NA*</td>
</tr>
<tr>
<td>Multiphase (circular)</td>
<td>1.5–1.8</td>
<td>2400–3200</td>
<td>4000–6000</td>
<td>NA*</td>
</tr>
</tbody>
</table>

NA*, Commercially not used.
fabric is composed of knitted loops in which warp threads forming the loops travel in warp-wise direction down the length of fabric. Weft knitted fabrics can be conventionally divided into flat knitted fabric, which is made by a machine having straight needle bed, and circular knitted fabric, which is made by a machine having the needle set in one or more circular beds.

Flat knitting machine is feasible to make fashioned parts to be linked and nonsewn seamless knitted fabrics, whereas circular knitting machine is designed to produce garment-length fabrics for inner wear and high gauge fabrics for cut-sew process. In warp knitting machine, threads are delivered from warper’s beam and therefore, this process is less flexible. But it can produce fabric having more stable structure with higher productivity and can also be applicable to produce axially structured fabrics. Its fabric is mainly used for household, technical textiles, and composite reinforcement (Mastuo, 2008).

The knitting fabric manufacturing process is a simpler method as compared to weaving as knitting process eliminates many of the preparatory processes such as warping, sizing, drawing-in, and desizing. Hence, the knitting technology is more eco-friendly as it consumes less energy and water. In addition knitting has lower effluent generation and subsequent effluent treatment. Hence, the knitted fabric production needs lower electrical energy. The electrical energy consumption during knitting will depend on the factors like yarn linear density, yarn tension, machine speed, gauge, garment style and size, and method of garment production.

The efficiency of circular knitting machines depends on the rpm (revolutions per minute) of the knitting machine, which is dependent on yarn structure and type, machine gauge and size of the dial (diameter of machine). Alternatively, flat-bed knitting machinery expresses efficiency as the linear speed in meters per minute, again which will change depending of yarn structure and type, and bed-width among other factors.

The industry has seen a recent trend for ultra fine gauge knitwear for which the main markets being sportswear and underwear (Steele, 2008). By definition fine gauge knitwear is less eco-friendly than the coarse gauge alternatives, since more energy and yarn will be required to produce a garment of similar dimensions. The productivity declines by around 14% when using finer gauges (Lau and Yu, 2016), gauges of 60 needles per diametric inch are now attainable in circular machines (Steele, 2008) and up to 18 needles per inch in flat-bed technologies including complete garment machinery.

The use of seamless garment manufacturing can help to reduce the environmental impact (Nayak and Padhye, 2015b). In seamless technology the 3-dimensional garment is produced by avoiding the steps of fabric manufacturing (weaving/knitting), cutting and sewing operations. Hence, this process consumes 30–40% less time and saves energy compared to the conventional processes of weaving and knitting. Furthermore, seamless technology reduces labor cost and lead time and eliminates waste involved in cutting of pattern pieces for sewn garments. However, seamless technology is only limited to only few knitted garments and interior clothing. The cost of production can be high if the number of garments produced is low in this technology. Therefore, the seamless technology has not widely used for garment manufacturing.
3.3 Energy consumption in fabric manufacturing

3.3.1 Energy consumption pattern in fabric manufacturing

Electricity is the major source of energy for the production of textile goods. This energy is used for machinery operation, illumination, humidification, and temperature control. The percentage share of the energy consumption of a composite textile industry is shown in Fig. 3.2.

Electrical energy is also used for the operation of the compressors, which supplies compressed air for winding, warping, sizing and looms. Apart from the electrical energy, thermal energy is also utilized for the sizing operation, which is produced from the steam. The steam is generally used for the heating of the size liquor in the size box as well as for the heating of multiple drying rollers. This thermal energy is produced at the boilers for the production of steam and transported to the sizing department by the insulated pipes. Mostly fossil fuels (petrol, diesel, and gas) are used for the boiler operation. Apart from the energy consumption for different manufacturing processes, energy is also utilized for the material handling, office work, and temperature control.

There are several units used for the expression of the energy consumed like megawatt hour per ton (MWh/ton), kilowatt hour per kilogram (kWh/kg), Gigacalorie per ton (Gcal/ton), Gigajoule per kilogram (GJ/kg), Gigacalorie per kilogram (Gcal/kg), Gigajoule per ton (GJ/ton), and Gigawatt hour per ton (GWh/ton) (International Energy Agency, 2013). The International Energy Agency (2013) defined energy intensity as total primary energy consumption per dollar ($) of Gross Domestic Product (GDP). Hasanbeigi et al. (2012) used energy intensity as the ratio of the total “Energy consumption (kWh or GJ)/Production quantity (unit of output)”.

![Fig. 3.2 The percentage share of the energy consumption of a composite textile industry.](image-url)
In addition to the above terms “specific energy consumption (SEC)” is also used to indicate how much energy is consumed for the unit quantity of production like energy units per kg of yarn produced (kWh/kg) or units per kg or meter of fabric processed (kWh/m) or units per 1000 m of fabric garmented (kWh/1,000 m).

Koç and Çinçik (2010) have reported the tentative energy requirement (in SEC) for winding, warping, and sizing machines and the values are shown in Table 3.2. The typical energy consumption value for the winding process varies between 0.1 and 0.4 kWh/kg, while the warping process requires around 0.1—0.3 kWh/kg and sizing process requires 0.05—0.08 kWh/kg of energy (Koç and Çinçik, 2010). The amount of energy consumption during weaving preparation changes with the type of raw material used (natural, or synthetic fiber), linear density of the yarn, number of ends, and type of machine used (direct or indirect warping machine).

Similar to yarn manufacturing, fabric production is also an energy-intensive process. The total electrical energy consumed per linear meter of fabric (including preparation and production) is 0.45—0.55 kWh, whereas the thermal energy consumed per linear meter of fabric (including preparation and production) is 18.8—23 MJ (Fletcher, 2014). Koç and Çinçik (2010) also estimated the total energy consumption for the production of 1 kg of fabric, which typically varies between 1.7 and 4.2 kWh.

The breakdown of the specific energy consumption of different types of weaving machine is listed in Table 3.1. But the energy consumption of weaving process is dependent on many factors like type of loom, weft insertion rate (WIR), weave designs, and ends and picks per centimeter (Castelli et al., 2010).

Various motions in a loom also consume different portions of the energy. Shedding, picking (weft insertion) and beating are the three primary motions, whereas Let-off and Take-up are the secondary motions. Furthermore, auxiliary motions like stop motions, weft mixing motion, feeler motion, and break motion are useful to control the quality of the fabric. Koç and Çinçik (2010) reported that a majority part of the energy is utilized for the functioning of primary motions and the rest percentage of the energy is utilized for performing other operations. The details of energy consumption pattern for different types of motions in a rapier loom are shown in Fig. 3.3.

Among the shuttle-less weaving machines, air jet, rapier, and water jet looms are the most widely used for fabric manufacturing. Air jet looms are considered to be more

<table>
<thead>
<tr>
<th>Name of process</th>
<th>Specific energy consumption (SEC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winding (autconers)</td>
<td>Electrical (kWh/kg) 0.1—0.4</td>
</tr>
<tr>
<td></td>
<td>Thermal (MJ/kg) None</td>
</tr>
<tr>
<td>Direct warping</td>
<td>Electrical (kWh/kg) 0.1—0.2</td>
</tr>
<tr>
<td></td>
<td>Thermal (MJ/kg) None</td>
</tr>
<tr>
<td>Indirect warping</td>
<td>Electrical (kWh/kg) 0.2—0.3</td>
</tr>
<tr>
<td></td>
<td>Thermal (MJ/kg) None</td>
</tr>
<tr>
<td>Sizing</td>
<td>Electrical (kWh/kg) 0.05—0.08</td>
</tr>
<tr>
<td></td>
<td>Thermal (MJ/kg) 5</td>
</tr>
</tbody>
</table>

sustainable than others due to their high weft insertion rate (WIR) and low cost of production. However, due to the highest speed, the warp should be carefully prepared for air jet looms. Furthermore, the use of compressed air in the air jet looms is an energy-intensive process. Hence, the countries where the energy cost is rising may be a problem for air jet looms. The rapier looms can be selected for delicate weft yarns and for intricate weaving. Although the projectile looms can give high WIR similar to the rapier looms, they have some limitations in number of weft colors and weft yarn tension. Multiphase looms can weave the fabric at the highest WIR; however, the limitations in the design of the looms have not made them commercially successful.

As discussed earlier, knitting technology consumes less energy as compared to weaving technology (Nayak and Padhye, 2015a). Allwood et al. (2006) estimated that the total energy consumption for a T-shirt manufacturing with circular knitting is of 109 MJ and the energy required for production alone is 24 MJ. The energy required for the manufacturing with flat-bed knitting machine is varied from 3 to 10 MJ. The efficiency and productivity of knitting machines can be increased by the use of energy-efficient driving systems, regular care, and use of electronic devices in place of the mechanical ones, which can help in achieving sustainability.

### 3.4 Energy conservation techniques in fabric manufacturing

In a textile industry, energy is used in different processes for different purposes. Hasanbeigi (2010) categorized the final energy used for the different processes of US-based textile industry. The energy used for the production of textile goods by the US textile industry are: steam and motor-driven systems, pumps, fans, compressed...
air, material handling, and material processing. The percentage share of each of the above actions is shown in Figs. 3.4 and 3.5.

According to an illustration of US textile industry by Hasanbeigi and Price (2012), “around 36% of the energy input to the US textile industry is lost onsite”. It was also pointed out that “motor driven systems have the highest share of onsite energy waste (13%) followed by distribution and boiler losses (8% and 7% respectively)”. This is shown in Fig. 3.6. The share of losses could vary for the textile industry in other countries depending on the structure of the industry in those countries.

The energy consumption in weaving can be reduced by making the processes more efficient with regular care and maintenance, cleaning, and efficient driving systems. Reducing the waste yarn generated during weaving process can help to improve the
sustainability. Weaving process can also be made more sustainable by effecting driving systems and increased productivity. Any steps during the weaving process to reduce the energy consumption increase the process efficiency and productivity, which can help to achieve sustainability.

From the above discussions, it is evident that the energy is one of the prime factors influencing the cost; hence, energy efficient technologies in fabric manufacturing can help in sustainable production. Newer weaving technologies such as projectile, rapier, air jet, water jet, and multiphase looms consume lower energy and give better efficiency compared to the conventional weaving machineries and also generate less waste. Hence, switching to newer weaving technologies is a major step to achieve sustainability.

The rationale of focusing on energy consumption in the textile industry was supported by the findings of several researchers. For instance, Palanichamy and Babu (2005) determined that a 1% reduction in energy consumption could substantially reduce the annual production costs in the spinning mill and sewing thread industry in India. They have shown that changing the equipment operational steps, building structural modifications, changes in machinery accessories and steam heating in place of electrical heating could result in a reduction of 171.10 kWh (of energy) for every ton of textile product.

Price et al. (2010) found that the Chinese government’s goal regarding reducing energy consumption in top 1000 energy-intensive enterprises, including the textile and apparel supply chain, could contribute to somewhere between 10% and 25% of the savings required to achieve a 20% reduction in energy use per unit of GDP by 2020. Steinberger et al. (2009) have found that a T-shirt accounts for over 70% of the energy used and CO₂ emissions in the consuming country, whereas for a jacket, more than 70% of energy consumption and CO₂ emissions occur in the producing country.
Reddy and Ray (2011) stated that between 1991 and 2005, cotton yarn had the highest increase in emission compared to gray cloth, jute goods, and polyester chips production. This increase was due to a transformation from manual to intensive mechanization process of production where fuel use is very high. They have found substantial improvements in energy consumption in production of textiles (cloth and gray cloth) by changes in energy intensities and specific energy consumption.

### 3.5 Noise pollution and its control in fabric manufacturing

In addition to high energy consumption, the other major environmental problem of weaving machines is the noise pollution. In fact, weaving process is the step in whole garment production, which generates the highest level of noise pollution. The vibration of the mechanical parts of the machine is the major source of noise. The rotating and reciprocating moving elements of the machines have kinetic energy (Khurmi and Gupta, 2004) and share it to the other machine elements through bearings. The machine elements like shafts, gears, and pulleys are mostly rotating in nature, whereas reed, sley, and heald frames are mostly reciprocating in nature. These moving parts of the machines are usually the main source of vibrations, which are then transmitted to the other parts of the machine (Castelli et al., 2010).

The beat-up action of the looms is the major contributor of the noise pollution than the other basic loom functions like shedding, weft insertion, let-off, and take-up. These basic loom motions are cyclic in nature and hence cause repeated vibrations and noise at a particular interval. The frequency and amplitude of the vibrations increase with the increase of the machine speed as well as with the machine composition. The reciprocating machine elements are the prime cause of severe vibrations as compared with the rotating elements as the balancing of the machines for reciprocating masses is very difficult to achieve.

The noise level generated by various looms is given in Table 3.3. It can be observed from this table that the water jet looms generate the lowest amount of noise, whereas the traditional shuttle looms produce the highest amount of noise. The weft insertion and beating in the shuttle looms create the high noise level. The use of shuttle-less

<table>
<thead>
<tr>
<th>Weaving machines</th>
<th>Noise level (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shuttle loom</td>
<td>90—115</td>
</tr>
<tr>
<td>Projectile (sulzer)</td>
<td>85—100</td>
</tr>
<tr>
<td>Rapier</td>
<td>80—100</td>
</tr>
<tr>
<td>Air jet</td>
<td>90—100</td>
</tr>
<tr>
<td>Water jet</td>
<td>80—95</td>
</tr>
</tbody>
</table>

Table 3.3 Noise level produced by different weaving machines.
looms is the solution for reducing the noise level in weaving industries. However, the type of looms should be selected depending on the fabric type, cost of production and productivity. For example, water jet looms, although produce the lowest amount of noise, are only suitable for filament or synthetic fabric, but not for fabric from natural fibers.

Furthermore, the walls and ceilings of the weaving shed can be fitted with appropriate sound absorbing materials to reduce the noise level. It is always better to keep the weaving section isolated from other departments and keep the doors closed. The employees should be provided with proper ear protecting devices to reduce the environmental impact. Although reducing the operational speed can help in reducing the noise level, the productivity will be reduced. The use of electronic devices and mechanism instead of mechanical devices also can help in reducing the noise level.

3.6 Solid waste problem

Solid waste generation is becoming a serious issue with increase in fabric demand. The major source of the solid waste is caused after the end of life cycle of the apparels. Goworek (2011) cited that these abandoned apparels are mostly end up in landfills. The other source of solid waste is the process waste or pre-consumer waste generated at every stage of fabric production. These solid wastes can be reused as low-quality textile product after recycling. There is an ever-increasing effort to reduce the process waste in order to reduce the cost of production. The waste minimization can be achieved with a systematic approach. The thrust area of waste minimization is to use fewer amounts of water, chemicals, and energy which will lead to lower emission of green house gases. The other area of waste minimization is the use of modern technology, software, and lean manufacturing concepts in the production floor.

3.6.1 Process waste in fabric manufacturing

The average waste related to warp in a weaving industry lies in the range of 2.5—4%. The warp waste is mostly formed at the auxiliary selvedge at shuttle-less looms, warping machines (left over yarns in cones after warping), in the sizing zone, knotting, gaiting/tying-in, and as weaver’s beam residues. It was observed that the warping waste accounts for about 85% of total warp waste and all other warp wastes account for only 15%. The knitting technology produces less waste as compared to the weaving technology. The typical process waste generation for knitting technology is 1.5—2%.

3.7 Wastewater generation and its control in fabric manufacturing

The warp for weaving requires sufficient weavability, which can be achieved by sizing of warp yarns. The sizing process is the only process in weaving which consumes lots
of water and chemicals. The sizing materials used primarily in the cotton manufacturing industry are natural starches derived from corn, wheat, tapioca, etc., but they have a tendency to form very stiff films. The starches need to be cooked and applied at a relatively high temperature (about 95 °C), which consume lots of energy.

The desizing (i.e., removal of starch from fabrics) of starch can be carried out by enzymatic treatment and making the degraded product water soluble. The starch is mostly not suitable for sizing of the synthetic fibers; hence, new types of synthetic sizing materials are introduced like carboxymethyl cellulose (CMC), polyvinyl alcohol (PVA), copolymers of acrylic acids, and other chemicals such as water-soluble materials. These synthetic adhesives do not require cooking before use, hence, consumes lower energy than starch. The chemistry of these materials made the desizing simpler and easier. By controlling the degree of polymerization of these synthetic compounds, sizes with considerably different physical and solubility properties have been made.

Another class of materials called “binders” has also been developed to improve adhesion and properties of size films formed by synthetic materials. A range of synthetic chemical sizing materials available in the market offer a greater flexibility to the textile technologists to engineer sizing ingredients to meet the processing requirements of various types of fibers for high-speed weaving.

The application of sizing and subsequent desizing consumes large amount of water in addition to energy. Reduction in the use of heat energy and eco-friendly chemicals can reduce the environmental impact of the sizing process. Cold sizing agents and reducing the steam temperature during sizing can help to reduce the energy consumption. The use of superior yarn quality (yarns with higher uniformity and less hairiness) in the warp can eliminate the sizing process and its impacts.

The desizing process also requires a large amount of water, which can be up to 50% of the total wastewater released from a textile industry. The effluent of traditional sizing is highly polluting; therefore, the traditional sizing materials have to be replaced with new sizing materials such as polyvinyl alcohol (PVA) (De Smet; Weydts and Vanneste, 2015) to make the sizing process more sustainable.

### 3.8 Conclusions

The fashion and apparel industry is an essential sector for the humas, but also a severe polluting industry. The fabric manufacturing industry prepares base fabric for fashion and apparel sector after using a lot of energy, chemicals, water, and fibers from natural and petroleum sources. Sustainability is defined as the “Design of human and industrial systems to ensure that humankind’s use of natural resources and cycles do not lead to diminished quality of life due to either losses in future economic opportunities or adverse impacts on social conditions, human health and the environment”. Hence, the textile fabrics should be produced from eco-friendly raw materials, renewable energy sources, and natural and biodegradable chemicals so that the textile fabrics can be considered as a sustainable material in the journey of sustainable fashion.
Approaches like consumer awareness, improvement of product and process design, frequent energy audits, and stricter statutory guidelines can help the textile industries to achieve sustainability in fabric manufacturing.

References


Part Three

Sustainable technologies in chemical processing
4.1 Introduction

Enzymes are globular proteins, and like the other proteins, they contain long linear chains of amino acids. Every individual amino acid sequence creates a unique structure, with properties specific to it. Enzymes are collected from several primary sources such as plants, microbes, and animal tissues (Mojsov, 2011). Enzymes are a sustainable alternative to the toxic chemicals used in the fashion and textile manufacturing. Enzymes are rapidly becoming very important, especially in the spheres of sustainable technology and green chemistry. Enzymes carry out thousands of the metabolic processes that sustain life.

It has been estimated that by 2020, the global market for industrial enzymes will surpass the USD $7.5 billion marks and its five-year compound annual growth rate (CAGR) will be around 8.2%. The market for food enzymes alone is projected to reach USD $2.94 billion by 2021, at a CAGR of 7.4% between 2016 and 2021. Moreover, it is expected that the maximum growth rate will be observed in the detergent enzyme segment (CAGR of 11.3% in the 2016–21 period). Proteases were the prominent product segment in 2015, accounting for 27.4% of the global enzyme market; now, they are expected to show even more profitable growth in light of their increasing application in pharmaceutical, detergent, and chemical sectors (Rigoldi et al., 2018). Approximately 10% of the total industrial enzymes find their application in textile processing (Silva et al., 2010). On the basis of types of enzymes, the market is fragmented into protease, carbohydrate, lipase, polymerase, nuclease, and other types. Carbohydrase accounted for the largest market share in 2017 and is expected to continue this trend. The impact of biotechnology in the textile industry is mainly observed at three levels: (i) the use of enzymes in wet preparatory processes and laundry detergent, (ii) the use of enzymes in the design of new biodegradable fibers, and (iii) the use of enzymes in the treatment of textile effluent.

For the production of a desired enzyme, fermentation is carried out under controlled pH, oxygen level, feed additives, carbon dioxide, nutrients, minerals, and other substances which induce the production of enzyme. Fermentation is carried out for 5–9 days when the maximum production level is reached. The fermentation broth is then filtered, concentrated, and transformed into a storage stable product for the commercial application. The products can either be a liquid, which has to be formulated to guarantee a shelf life, or supplied in powder form.
Wilhelm Kühne was the first to use the term “enzyme” and years later Emil Fisher proposed “Lock and key model” to visualize the substrate and enzyme interaction (Matama and Cavaco-Paulo, 2010). Enzymes are produced by all living organisms in the fermentation industry by molds or bacteria, but they themselves are not living organisms.

There are different types of enzymes used in textile and garment manufacturing. For example, the enzymatic desizing of cotton with α-amylases is in practice for many decades. Various other enzymes are also being used since long in different cotton pre-treatment and finishing processes (Meyer-Stork, 2002). The enzymes are also used for the processing of other natural fibers, e.g., enzymatic degumming of silk with sericinase (Gulrajani, 1992), felt-free finishing of wool with proteases (Fornelli, 1994) and softening of jute with cellulases and xylanases (Kundu et al., 1991). The surface treatment of synthetic fibers such as polyester (Yoon et al., 2002) or polyacrylonitrile (Tauber et al., 2001) with enzymes has also been studied extensively.

Till date, more than 3000 different enzymes have been isolated and classified. However, only a limited number of enzymes are commercially available and even a smaller number of enzymes are used in large quantities. More than 75% of industrial enzymes are hydrolytic in action. Out of all the commercial enzymes, 40% are protein-degrading enzymes. Detergents (37%), textiles (12%), starch (11%), baking (8%), and animal feed (6%) are the main industries, which use about 75% of industrially produced enzymes (Shrinivas, 2007). Major companies involved in the preparation and marketing of enzymes are Novozymes (formerly Novo Nordisk), Genencor, DSM, Röhm and Haas, and Clariant (formerly Sandoz).

The enzymes are different from each other due to the following features:

- Differences in amino acids present,
- The difference in the sequence of amino acids in the structure,
- The presence or absence of metal ions, and
- The confirmation of the structure as a whole.

One of the recent studies (Chen et al., 2006) showed that biotechnology in textile industry reduces water usage and energy demand for bleaching (bio-cleanup) by about 9%—14% and 17%—18%, respectively. Enzyme usage could also reduce water consumption by as much as 30%—50% (bio-scouring) and cost associated with water usage and air emission by about 50%—60% (bio-stone washing). Evidently, the application of textile biotechnology can result in cleaner processes that produce less waste and use less energy and water. The application of enzymes is one of the most promising approaches to pollution prevention, resource conservation, and cost reduction.

### 4.2 Enzymes: Definition and types

Enzymes are biological catalysts. The term “enzyme” has been taken from the Greek word “enzumé” meaning “in (en) yeast (zumé),” The term was first used by Kühne in 1878. Chemically, enzymes are proteins of high molecular weight. They consist of complex three-dimensional proteins that are composed of polypeptide chains.
They range from individual proteins with a relative molecular mass (RMM) of around 13,000 catalyzing a single reaction, $\alpha$-amylase enzyme of about 1,00,000 to multienzyme complexes of RMM of several million catalyzing several distinct reactions. For catalytic function, some enzymes additionally require some specific small non-protein molecules, known as cofactors (De Bolster, 1997). Cofactors can be either inorganic (e.g., metal ions and iron-sulfur clusters) or organic compounds (e.g., flavin and heme). These cofactors serve many purposes; for instance, metal ions can help in stabilizing nucleophilic species within the active site (Voet et al., 2016). Organic cofactors can be either co-enzymes, which are released from the enzyme’s active site during the reaction, or prosthetic groups (a non-protein group forming part of a protein or combined with it), which are tightly bound to an enzyme. Organic prosthetic groups can be covalently bound (e.g., biotin in enzymes such as pyruvate carboxylase) (Chapman-Smith and Cronan, 1999).

Coenzymes of small organic molecules are loosely or tightly bound to an enzyme. Coenzymes transport chemical groups from one enzyme to another (Suzuki, 2015). Since coenzymes are chemically changed as a consequence of enzyme action, it is useful to consider coenzymes to be a special class of substrates, or second substrates, which are common to many different enzymes. Enzymes are relatively delicate substances; they get easily denatured and thereby become inactive by high temperature, ionizing radiation, light, acids, alkalis, and biological factors. Enzymes are obtained from three primary sources:

1. Animal tissue
2. Plants, and
3. Microbes.

Enzymes are not readily available in nature in sufficient quantities for industrial use. The most important manufacturing process is the well-known fermentation process, which has been used by the humans for more than 3000 years. Various microorganisms used for the production of enzymes important for the textile industry are listed in Table 4.1 (Shaikh, 2009).

### 4.2.1 Advantages and disadvantages of enzyme applications

The following benefits can be achieved when the enzymes are used in textile processing (Cavaco-Paulo and Gübitz, 2003):

- Enzymes lower the activation energy of reaction thereby accelerating the rate of a chemical reaction. The enzymes are not destroyed at the end of the reaction.
- Enzymes are very specific in their actions thereby maintaining the chemical precision remarkably. Enzyme engineering can further improve their stability and specific activity.
- The activity of an enzyme depends upon operating conditions. Therefore, it is easier to control enzyme-assisted processes.
- Enzymes are biodegradable and eco-friendly.
- Enzyme-assisted processes require milder conditions of temperature (below 100°C), pressure (atmospheric), and pH (around neutral). However, for faster chemical reactions, high-temperature and stable enzymes are developed in recent years.
Lower energy requirements due to enzyme applications lead to lower manufacturing cost and lower emission of greenhouse gases to the environment.

Enzyme application saves energy and water with combined processing—processes can be combined in the production of denim products such as jeans. For combined desizing and stone washing processes, the energy savings for the production of 1 ton denim products amounts to 3000 MJ in the form of process heat and 20 m³ of water. In towel and T-shirt production, the combined one bath bleaching, cleaning up, dyeing, and biopolishing with catalase enzyme entail savings up to 4000 MJ of heat and 30 m³ of water, as well as a reduction of costs related to wastewater treatment (Novozymes, 2013).

Enzymatic reactions are several orders of magnitude faster.

In enzyme-assisted processes by-products are rarely generated.

The waste generation is minimized with enzyme application, thereby minimizing waste disposal problems.

Enzymes are safe to handle as they are non-corrosive.

The high biodegradability of enzymes reduces pollution load.

Enzymes after use can be inactivated by changing pH or temperature and discharged safely.

The use of enzymes results in a reduction in global warming, saving in acidification and nutrient enrichment (Nielsen et al., 2009).

### Table 4.1 The microorganisms used for the production of various enzymes.

<table>
<thead>
<tr>
<th>Microorganisms</th>
<th>Enzymes produced</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bacteria</strong></td>
<td></td>
</tr>
<tr>
<td><em>Bacillus subtilis</em></td>
<td>Amylase</td>
</tr>
<tr>
<td><em>B. coagulans</em></td>
<td>α-Amylase</td>
</tr>
<tr>
<td><em>B. licheniformis</em></td>
<td>α-Amylase, protease</td>
</tr>
<tr>
<td><strong>Fungi</strong></td>
<td></td>
</tr>
<tr>
<td><em>A. niger</em></td>
<td>Amylases, protease, pectinase, glucose oxidase</td>
</tr>
<tr>
<td><em>A. oryzae</em></td>
<td>Amylases, lipase, protease</td>
</tr>
<tr>
<td><em>Candela lipolytica</em></td>
<td>Lipase</td>
</tr>
<tr>
<td><em>P. notatum</em></td>
<td>Glucose oxidase</td>
</tr>
<tr>
<td><em>Rhizopus sp.</em></td>
<td>Lipase</td>
</tr>
<tr>
<td><em>Trichoderma reesei</em></td>
<td>Cellulase</td>
</tr>
<tr>
<td><em>T. viride</em></td>
<td>Cellulase</td>
</tr>
<tr>
<td>Ascomycetes</td>
<td>α-Amylase</td>
</tr>
<tr>
<td>Basidiomycetes</td>
<td>α--Amylase</td>
</tr>
<tr>
<td><em>Aspergillus sp.</em></td>
<td>Pectinase, lipase</td>
</tr>
</tbody>
</table>
The problems and challenges of enzyme application in textile processing are listed below (Leitat, 2013):

- It is difficult to recover and reuse enzymes after their application.
- It is not easy to scale up enzymes in an industrial environment.
- The reaction times are more in some enzyme-assisted processes.
- The use of some enzymes is not economically feasible.

Enzyme-assisted processes need a stricter monitoring of process parameters during their application. The following precautions should be strictly followed during enzyme-assisted processes:

- Live steam should not be used during processing.
- Chemicals should be diluted before addition to enzymes.
- Compatible ionic surfactants should be used.
- Nonionic wetting agents with appropriate cloud points are preferred (Saravanan et al., 2008).
- Temperature, pH, and the contamination with heavy metal should be monitored closely.
- Enzymes are delicate and hence, they should be stored carefully under prescribed conditions.

### 4.2.2 Adverse effects of enzymes

According to the American Soap and Detergent Association (SDA), exposure to enzymes may cause irritation and/or respiratory allergies. Skin and eye contact with proteolytic enzymes may cause irritation. Other classes of enzymes are less irritating or pose no risk of irritation. However, some of the formulation ingredients may be irritating. Exposed areas should be protected by using hand and eye protection and other protective gears (ETA, 2000).

### 4.2.3 Enzyme nomenclature

The International Commission of Enzymes (EC) in collaboration with International Union of Pure and Applied Chemistry (IUPAC) classified the enzymes and developed a nomenclature system, the EC numbers, by which each enzyme is identified by a 4-digit number preceded by “EC”. The first number broadly classifies the enzyme on the basis of its mechanism of action.

Enzymes can be classified into six broad groups (top-level classification) according to the type of catalyzed reactions as shown in Table 4.2. The enzyme with the nomenclature of EC 4.2.1.20 belongs to the fourth main class, second subclass, first sub-subclass having a serial number of 20 (NC-IUBMB, 2018).

Hydrolase (class 3) enzymes are the most popular in textile industry. The second number in the enzyme code, such as hydrolase, describes the type of bond present in the enzyme hydrolyses and the third number further defines the reaction catalyzed. An enzyme code starting with the number “3.2.” is a hydrolase enzyme that catalyzes the hydrolysis of glycosidic bonds—bonds between carbohydrate residues in polymers such as starch and cellulose (Athalye, 2018).
4.2.4 Blue enzymes

Paul Anastas (1991) described Green Chemistry as the design of sustainable chemical products and processes that reduce or eliminate the use or generation of hazardous substances (Anastas and Warner, 1998).

Among the different existing oxidant enzymes, laccases (benzenediol: oxygen oxidoreductases; EC 1.10.3.2) have been subject of intensive research in the last two decades due to their low substrate specificity (Couto and Toca-Herrera, 2006). Laccases are a group of oxidative enzymes whose exploitation as biocatalysts in organic synthesis has been neglected in the past, probably because they were not commercially available. The use of laccases in the textile industry is growing very fast; besides the decolorization of textile effluents, laccases are used to bleach textiles (Vinod, 2001), to modify the surface of the fabrics (Zille, 2005) and to synthesize dyes (Setti et al., 1999). Therefore, laccase-based processes might replace the traditional high chemical energy and water-consuming textile operations. The enzyme can be applied at a temperature range of 30–50 °C and at a pH of 3–5.

Laccases (EC 1.10.3.2, p-diphenol: dioxygen oxidoreductase) belong to the so-called blue-copper family of oxidases (Barreca et al., 2003). Laccases are multi-copper oxidases expressed under ligninolytic conditions by white-rot fungi. They are glycoproteins, which are ever-present in nature—they have been reported in higher plants and virtually every fungus that has been examined for them (Bourbonnais et al., 1997).

Laccases have relatively lower redox potential (450–800 mV) compared to those of ligninolytic peroxidases (>1 V), so it was initially thought that laccases would only be able to oxidize phenolic substrates (Kersten et al., 1990). A mediator-involved reaction mechanism can increase the range of substrates oxidized by laccases. Mediators are low molecular weight compounds, which are easily oxidized by laccases mostly producing very unstable and reactive cationic radicals. These radicals can oxidize more complex substrates before coming back to their original state. The electrons taken by laccases are finally transferred back to oxygen to form water (Wong and Yu, 1999). In view of the low redox potential, native laccases can oxidize

---

**Table 4.2 Six types of enzyme-catalyzed reactions.**

<table>
<thead>
<tr>
<th>Class</th>
<th>Name of the enzyme</th>
<th>Types of reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>EC 1</td>
<td>Oxidoreductases</td>
<td>Catalyze oxidation/reduction reactions</td>
</tr>
<tr>
<td>EC 2</td>
<td>Transferases</td>
<td>Transfer a functional group (e.g., a methyl or phosphate group)</td>
</tr>
<tr>
<td>EC 3</td>
<td>Hydrolases</td>
<td>Catalyze the hydrolysis of various bonds</td>
</tr>
<tr>
<td>EC 4</td>
<td>Lyases</td>
<td>Cleave various bonds by means other than hydrolysis and oxidation</td>
</tr>
<tr>
<td>EC 5</td>
<td>Isomerases</td>
<td>Catalyze isomerization changes within a single molecule</td>
</tr>
<tr>
<td>EC 6</td>
<td>Ligases</td>
<td>Join two molecules with covalent bonds, usually at the expense of an energy source (usually ATP)</td>
</tr>
</tbody>
</table>
only phenolic fragments of lignin, with the concomitant reduction of oxygen (O2). However, the oxidation of non-phenolic substrates can also take place on mediation by appropriate substances. One such mediator is 2,2',6,6'-tetramethylpiperidine-N-oxyl (TEMPO) (Fabbrini et al., 2001).

The laccase-mediator system (LMS) has yet to be applied on large scale due to the high cost of mediators and the lack of studies that guarantee the absence of toxic effects of these compounds or their derivatives. The use of naturally occurring laccase mediators would present environmental and economic advantages.

At present, the main technological applications of laccases are in textile dyeing and printing industries, and in processes related to decolorization of dyes (Li et al., 1999). In addition, laccases are used in the pulp and paper industries for the de-lignification of woody fibers, particularly during the bleaching process (Galante and Formantici, 2003). In most of these applications, the laccases are used together with a chemical mediator.

It is known that white-rot fungi are able to perform lignin degradation using a cocktail of oxidative enzymes, including laccases, despite the fact that the bulkiness of this polymer prevents direct interaction with these enzymes. Indeed, it has been shown that the treatment of pulp with laccase alone does not catalyze the degradation of lignin but instead leads to only minor structural changes and depolymerization (Potthast et al., 1996). To explain this puzzling situation, it has been hypothesized that small molecules might act as redox shuttles between the enzyme’s active site and the lignin core, which cause polymer debranching and degradation (Fritz-Langhals and Kunath, 1998). Nowadays, this is regarded as more than just a hypothesis as the effect of chemical mediators, such as 3-hydroxy-anthranilic acid, on laccase-catalyzed lignin degradation has been evaluated extensively (Fabbrini et al., 2001).

### 4.3 Functioning of enzymes

Chemical reactions proceed when the free energy of the products is less than that of the reactants. The speed of the chemical reactions depends on the energy barrier between the substrate and the product. This barrier is known as the “activation energy” and for molecules to react, they must possess the energy to overcome the barrier. However, enzymes do not increase the energy levels of substrate molecules but provide an alternative low-energy route for the reaction to proceed. They achieve this by forming an intermediate enzyme-substrate complex, which alters the energy of the substrate such that it can be quite readily converted to the product. The enzyme itself is released unaltered at the end of the reaction, thus acting as a catalyst. It can be schematically represented by Eq. (4.1):

\[
\text{Enzyme} + \text{substrate (Initial stage)} \rightarrow \text{Enzyme} - \text{substrate complex (Intermediate stage)} \\
\rightarrow \text{Enzyme} + \text{product (Final stage)}
\]

(4.1)
The formation of the enzyme-substrate complex requires very little energy. Consequently, enzymes are very effective catalysts, enhancing reactions up to several thousandfold more than the most effective chemical catalysts (Athalye, 2018).

Enzymes being highly specific catalysts, the substrate must fit precisely into the active site of the enzyme just like a key fitting into a lock. The substrate reaction specificity of enzymes is determined by the structure of the enzyme. The primary structure is determined by the amino acid sequence, the secondary structure by the specific conformation of the protein chain and the tertiary structure by the arrangement of the chain segments.

Most enzymes have a maximum activity at an optimum temperature and pH. The reaction rate increases with increasing temperature until the optimum temperature is reached and activity decreases sharply on both sides of the optimum pH range.

Enzymes work mostly on renewable materials. Fruit, cereals, milk, fats, cotton, leather, and wood are some typical renewable materials, which are degraded by the enzymes. Quite recently it has been observed that some enzymes are able to modify the surfaces of synthetic textile materials such as polyester and polyamide.

Enzymes are usually much larger than their substrates. Sizes range from just 62 amino acid residues, for the monomer of 4-oxalocrotonate tautomerase (Chen et al., 1992), to over 2500 residues in the animal fatty acid synthase (Smith, 1994). Only a small portion of their structure (around 2–4 amino acids) is directly involved in catalysis: the catalytic site. This catalytic site is located next to one or more binding sites where residues orient the substrates. The catalytic site and binding site together comprise the enzyme’s active site. The remaining majority of the enzyme structure serves to maintain the precise orientation and dynamics of the active site (Suzuki, 2015). In some enzymes, no amino acids are directly involved in catalysis; instead, the enzyme contains sites to bind and orient catalytic cofactors.

The “active site” of an enzyme is directly involved in the catalytic reactions. The substrate is bound at the active site and then the reaction proceeds. Enzymes can also contain sites that bind cofactors, which are needed for catalysis. Like all proteins, enzymes are long, linear chains of amino acids that fold to produce a three-dimensional product. Each unique amino acid sequence produces a specific structure, which has unique properties. Individual protein chains may sometimes group together to form a protein complex. Most enzymes get unfolded and inactivated (called denatured) on heating, change of pH or by treatment with chemical denaturants due to the changes in the three-dimensional structure of the protein. Depending on the enzyme, the denaturation may be reversible or irreversible.

Enzymes are very specific in action. Nobel laureate organic chemist Emil Fischer (1894) suggested simplistic “the lock and key” model for enzymatic action. Both the enzyme and the substrate possess specific complementary geometric shapes that fit exactly into one another. The high substrate specificity of enzymes is due to the individual architecture of the active site where only certain molecules can “stereo-fit in.” The enzymes have a true activity center in the form of fissures, holes, pockets, cavities or hollows. The active site is a perfect fit for a specific substrate and that once the substrate binds to the enzyme no further modification is necessary. The enzyme catalysis operates first to form an enzyme-substrate complex as shown in Fig. 4.1.
At the active site on the enzyme, hydrolysis of the substrate is accelerated. The decomposition products of the substrate thus formed are usually unstable in the active site due to steric hindrances that force them to be released and return the enzyme to its initial unbound state so that further substrate is reabsorbed on the active site of the enzyme. The process continues until the enzyme is deactivated by conditions in the processing bath. Deactivation may occur through competitive or noncompetitive chemicals called “bogies” in the processing bath. The competitive bogies compete with the substrate for the enzyme, while noncompetitive bogies are adsorbed on the enzyme causing the shape of the enzyme to change — both prevent enzymatic catalysis from occurring. All enzymatic systems function best within a narrow range of pH and temperature; hence, far outside the range, the enzymes become deactivated by changes in the three-dimensional structure. As the enzyme twists and coils into a shape that prevents sorption between enzyme and substrate, catalysis no longer occurs.

Although the lock and key model explains enzyme specificity, it fails to explain the stabilization of the transition state that enzymes achieve. Daniel Koshland (1958) suggested a modification to the lock and key model called “Induced fit model,” i.e., the substrate induces a change in the shape of the active site to the correct fit. Since enzymes have rather flexible structures, the active site is continually reshaped by interactions with the substrate (Vasella, Davies and Bohm, 2002). As a result, the substrate does not simply bind to a rigid active site; the amino acid side chains which make up the active site are molded into the precise positions that enable the enzyme to perform its catalytic function.

In some cases, as in the case of glycosidases, the substrate molecule also changes shape slightly as it enters the active site. The active site continues to change until the substrate is completely bound, at which point the final shape and charge are determined (Boyer, 2002).

Most of the enzymes are inactivated or destroyed by temperatures over 75°C. Once destroyed, they cannot be revived or reactivated. Currently thermo-stable enzymes (such as \( \alpha\)-Bacillus subtilis, \( \alpha\)-Bacillus licheniformis, etc.) are available which can withstand temperature up to 90°C. Certain enzymes require some specific bivalent metallic ions (e.g., \( \text{Ca}^{2+} \), \( \text{Mg}^{2+} \), \( \text{Fe}^{2+} \), \( \text{Mn}^{2+} \), etc.) as activators which act probably
by stabilizing enzyme-substrate complex or sensitizing substrate to the attack of enzymes. Certain chemicals like alkalis, antiseptics, and acid-liberating agents tend to inhibit the enzyme activity.

Enzymes are classified and named according to the chemical reaction they catalyze, as this is the specific property that distinguishes one enzyme from another. In other words, they are named by the substrate on which they act. An enzyme name is assigned not to a single enzyme protein, but to a group of proteins with the same catalytic property, even if they are obtained from different sources.

4.3.1 Enzyme immobilization

For an immobilized molecule, the movement in space has been restricted either completely or to a small limited region by attachment to a solid structure. By enzyme immobilization, the enzyme can be easily separated from the reaction mixture (substrates and products) and its reusability for tens of time, which reduces the enzyme and the enzymatic products cost tremendously (Elnashar, 2010). Other advantages are:

(1) Quick start and stop of the reaction by moving enzyme into and away from the reaction solution, by monitoring reaction conditions thereby enhancing enzyme stability.
(2) The product is not contaminated with the enzyme.
(3) Easy separation of the enzyme from the product.

In the industrial biotechnology, the skill to stabilize and reuse an enzyme catalyst through immobilization has proven one of the key steps in rendering an enzymatic process that is economically viable (Zhou, 2009). The expense of products may be reduced if highly active and highly stable immobilized enzyme catalyst is available (Parmar et al., 2000). Several new types of carriers and technologies have been implemented to improve traditional enzyme immobilization, which aimed to enhance enzyme loading, activity, and stability to decrease the enzyme biocatalyst cost in industrial biotechnology. These include cross-linked enzyme aggregates (CLEAs), microwave-assistant immobilization, mesoporous support, and single enzyme nanoparticle.

In the early stages of enzyme immobilization, support was used to insolubilize the enzyme and thus to facilitate its separation and reuse, which provides easy control over the noncatalytic properties of the obtained immobilized enzyme. Thus, with the increased understanding of the correlation of enzyme property with structure and microenvironment a great number of synthetic or natural carriers of tailor-made chemical and physical properties, with different shapes/sizes, porous/nonporous structures, different aquaphilicities and binding functionalities, have been specifically designed for various bio-immobilization and bio-separation procedures (Xie et al., 2009).

Epoxy resin carrier shows maximum immobilization and extreme stability in successive cycles comparatively. The immobilized conditions and parameters may influence the activity of immobilized cellulose (Kumar et al., 2008).

Among various kinds of substrates for attaching enzyme, cellulose and its derivatives are one of the ideal matrixes because they are cheap, nontoxic, renewable, biodegradable and biocompatible. Liu and Chen (2016) summarized the recent progress in the research of enzyme immobilization on cellulose matrixes.
Low-cost textile fabrics, made of polyester or polyamide, are alternative carrier materials for the immobilization of enzymes. Low-cost fabrics with a high enzyme load, a high relative reactivity, and good permanence can be produced by photo-induced cross-linking and grafting processes using monochromatic excimer-UV-lamps. Depending on the support and the used reactive agent, 20–70 mg enzyme per gram carrier could be fixed. The activity of the catalase after the immobilization was 5%–20% relative to that of the free unfixed catalase. The immobilized enzyme showed a distinct and integral activity even after 20 overall reuses, 3.5 times higher than the activity of the free catalase (Wiseman, 1985).

Immobilization of various industrial enzymes onto or within the textile matrix can be achieved via adsorption, covalent bonding, and entrapment, to get increased activity and stability in various applications as well as to build new functionalized textile products (Wiseman, 1985). \(\alpha\)-Amylase, alkaline pectinase, and laccase enzymes were immobilized onto ester-crosslinked as well as on Cu-chelated cotton fabrics followed by an assessment of the degree of antimicrobial activity against gram-negative and gram-positive bacteria and fungi. Cu-chelated cotton fabric showed higher activity. Among immobilized enzymes, alkaline pectinase showed the highest, \(\alpha\)-amylase showed intermediate and laccase showed the lowest activity irrespective of the used microorganism. Antimicrobial activity of the treated fabric lasted for more than 10 washing cycles (Ibrahim et al., 2007).

Antimicrobial functionalization for textile goods may be an effective way to prevent disease transmission in consumer textiles, military, and healthcare markets. For example, the enzyme, lysozyme was successfully immobilized onto the surface of wool fabric support by using glutaraldehyde as a crosslinking agent in order to impart wool fabric better antibacterial effect. The maximum activity of immobilized lysozyme was obtained through the optimization of several immobilization parameters (Wang, 2009). Lysozyme can also be covalently attached to cotton fabrics, which are activated via esterification with glycine and glycine dipeptide. For applications in the food industry, lysozyme can be incorporated into chitosan films for controlled release of the enzyme. Besides lysozyme, oxygen-consuming enzymes may be immobilized in food-packaging materials to prevent microbial growth.

Smart materials are expected to detect changes in the environment and respond with specific actions. The high specificity of enzymes can be exploited for the design of smart materials in two ways. On the one hand, enzymes can impart novel sophisticated functionalities to materials ranging from antimicrobial effects to self-cleaning or self-detoxifying properties. On the other hand, enzymes can be used as triggers to impart bioreponsive properties to materials containing specific elements susceptible to modification by these biocatalysts. In several areas, smart materials are constructed such that they respond to triggers (e.g., enzymes) allowing a controlled release of active agents (such as drugs and perfumes). Many active agents in pharmaceuticals, food, and agriculture require temporal stabilization and protection against degradation or oxidation. In addition, the efficacy of such agents may be improved by increasing their solubility or by masking unwanted properties, such as toxicity or bad taste, at least before the target environment is reached. Finally, a sustained or triggered release may be required. A natural or synthetic polymer may be judiciously combined with
a drug or other active agent in such a way that the active agent is released from the material in a predesigned manner. Enzyme immobilization onto textiles was used to create smart materials with novel properties such as self-detoxifying or anti-microbial activity. For military purposes, organophosphorus hydrolase was covalently immobilized on cotton for detoxification of organophosphorus warfare agents.

Textiles with antimicrobial properties have been produced by immobilization of a variety of enzymes. Attachment of alkaline pectinase, alpha-amylase or laccase leads to antimicrobial fabrics retaining full activity for at least 10 consecutive wash cycles (Ibrahim et al., 2007).

Fabrics are increasingly gaining importance as supports for enzyme immobilization. Various strategies have been developed for the incorporation of enzymes into polymers including entrapment, covalent attachment, and adsorptive binding. Polydimethylsiloxanes have been used for covalent attachment of enzymes including lipases and proteases. Plasma treatment has been used for activation of polyethylene, whereas polyester and polyamide are activated photochemically. Polypropylene can also be activated with polyaniline using ammonium persulphate as the oxidizer. This pre-treatment greatly facilitated both adsorptive and covalent immobilization of proteins such as HRP (Horseradish peroxidase).

Wehrschütz-Sigl et al. (2010) summarized strategies followed by various researchers for immobilization of enzymes (Table 4.3) using a variety of fabrics.

It has been found that HRP immobilized on non-woven polyester fabrics in the presence of glutaraldehyde as a crosslinking agent retained 85% of its activity after 4 weeks of storage at 4°C while free enzymes lost 90% of its activity under the same condition. Catalase is widely used for textile bleaching and sterilization of liquid food products by conversion of residual peroxide to oxygen and water. Apart from various inorganic carrier materials, fabrics have been used for catalase immobilization. Catalase was photochemically immobilized on polyester and polyamide 6,6 using diallylphalate or cyclohexane-1,4-dimethanoldivinyl ether as a cross-linking agent. The immobilized enzyme was highly stable with a 3.5 higher activity after 20 cycles when compared to free enzyme (Opwis et al., 2005).

For effluent treatment and other applications, laccase has been immobilized on inorganic carrier materials such as alumina pellets. Recently laccase has been bound to organic polymers (i.e., polyethylene glycol) to obtain water-soluble immobilized proteins with enlarged molecular weight and modified sorption properties. Such constructs have been used in detergents to prevent dye transfer. A novel method of laccase immobilization on polyamide 6,6 involved limited surface hydrolysis of polyamide 6,6 by a protease to introduce functional groups. Thereafter, the spacer 1,6-hexanediocamine followed by laccase was attached by glutaraldehyde.

In the traditional methods, the control of release and the stabilization of the agent are based on encapsulation. There are three primary mechanisms by which active agents can be released from this kind of delivery system: diffusion, swelling followed by diffusion and degradation. Diffusion occurs when a drug or other active agent passes from the polymer matrix into the external environment through the polymer that forms the controlled release system. Since polymer coating is essentially uniform and of a nonchanging thickness, the diffusion rate of the active agent can be kept fairly
stable throughout the lifetime of the delivery system. The active agent diffuses on a macroscopic scale, through the pores in the polymer matrix, or on a molecular level, by passing between the polymer chains. The kinetics of release of the active agent is controlled in a site- and time-dependent manner in mot systems. The release of the active agent can be triggered by the local conditions in the target environment. Much effort is focused on creating biodegradable polymers for enzymatic drug delivery systems that permit release of the entrapped drug only during degradation of the polymer matrix. Another possibility is the preparation of films of different enzymatically degradable polymer such as chitosan.

### 4.4 Conclusions

There are several types of enzymes used in textile and garment manufacturing in the place of traditional methods. The application of enzymes is making the manufacturing
process used for fashion and textiles more sustainable. These enzymes are being used mainly in chemical processing of cotton and its blends since long. The enzymes are also used for the processing of other natural fibers, e.g., the enzymatic degumming of silk with sericinase, the felt-free finishing of wool with proteases or the softening of jute with cellulases and xylanases. The surface treatment of synthetic fibers such as polyester or polyacrylonitrile with enzymes has also been studied extensively by many recent researchers. Although more than 3000 different enzymes have been isolated and classified until now, only a limited number of enzymes are commercially available and even a smaller number of enzymes are used in textile industries. More than 75% of industrial enzymes are hydrolytic in action. Many of the fashion brands are adopting the enzyme application for various finishes. In future, many traditional processes will be replaced with enzyme applications.

References


Enzyme applications in textile chemical processing

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5.1 Introduction

The use of enzymes in textile industry is one of the most rapidly growing fields in industry. The most popular enzymes used in the textile field are amylases, catalase, and laccase, which are used to remove starch, degrade excess hydrogen peroxide (H₂O₂) after bleaching, bleach textile materials, and dissolve lignin. The use of enzymes in the textile chemical processing is rapidly gaining global recognition because of their nontoxic and eco-friendly characteristics. Enzymes are nowadays used to reduce pollution in textile production, which includes solid waste and effluent. The application of cellulases for denim finishing and lactases for decolorization of textile effluents and textile bleaching are the most recent commercial advances. The use of enzyme technology is attractive as enzymes are highly specific, efficient, and work under mild conditions. Furthermore, the use of enzymes results in reduced process time, energy and water savings, improved product quality, and potential process integration.

In Chapter 4, the definition and types of enzymes; enzyme nomenclature; advantages and disadvantages of enzyme applications; functioning of enzymes; and enzyme immobilization have been discussed. This chapter will discuss on various applications of enzymes in textile and garment manufacturing process including the mechanism of enzyme application. Enzyme applications in important textile preparatory processes such as desizing, scouring, and bleaching, finishing, and denim-wash have been discussed in detail. In addition, the process of peroxide removal from fabrics, shrinkage control of wool, degumming of silk, and degumming of ramie have also been discussed in this chapter. Ornamentation processes such as surface modification of synthetic fibers, textile dyeing, and printing are discussed. Finally the application of enzymes in laundering and effluent treatment is also discussed.

5.2 Textile applications of enzymes

Textile processing has benefited greatly in both environmental impact and product quality through the use of enzymes. From the 7000 known enzymes, only about 75 are commonly used in textile manufacturing processes (Quandt and Kuhl,
Some of the common types of enzymes and their specific fields of application are listed in Table 5.1 (Shenai, 1984; Shaikh, 2009).

Table 5.1 Enzymes used in textile processing.

<table>
<thead>
<tr>
<th>Name</th>
<th>Nomenclature</th>
<th>Textile application</th>
<th>Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxido-reductase</td>
<td>EC 1</td>
<td>Dyeing</td>
<td>Catalyzes the transfer of electrons from one molecule, also called the hydrogen or electron acceptor</td>
</tr>
<tr>
<td>Laccases</td>
<td>EC 1.10.3.2</td>
<td>• Discoloration of textile effluent</td>
<td>Degrade a wide range of recalcitrant (unruly) organic compounds including lignin</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Bleaching of lignin-contained fibers and indigo in denim fabric</td>
<td></td>
</tr>
<tr>
<td>Catalases</td>
<td>EC 1.11.1.6</td>
<td>Removal of hydrogen peroxide after bleaching</td>
<td>In situ peroxide decomposition</td>
</tr>
<tr>
<td>Lipases</td>
<td>EC 3.1.1.3</td>
<td>• Make polyester hydrophilic, a substitute for alkaline hydrolysis</td>
<td>• Split fats and oils into glycerol and fatty acids</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Detergent additive</td>
<td>• Remove most difficult lipid stains during washing</td>
</tr>
<tr>
<td>Amylase</td>
<td>EC 3.2.1</td>
<td>Starch desizing</td>
<td>Split starch (amylase) into dextrin and sugars</td>
</tr>
<tr>
<td>Cellulase</td>
<td>EC 3.2.1.4</td>
<td>• Stone washing</td>
<td>Degrade cellulose into soluble products</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Biofinishing for handle modification</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Carbonization of wool</td>
<td></td>
</tr>
<tr>
<td>Xylanase</td>
<td>EC 3.2.1.8</td>
<td>Bleaching</td>
<td>Degrade hemicellulose by breaking linear polysaccharide beta-1,4-xylan into xylose</td>
</tr>
<tr>
<td>Pectinases</td>
<td>EC 3.2.1.15</td>
<td>Bioscouring substituting caustic soda boil</td>
<td>Degrade pectin</td>
</tr>
<tr>
<td>Proteases</td>
<td>EC 3.4</td>
<td>Removal of protein stains during scouring</td>
<td>Split proteins into soluble polypeptides and amino acids</td>
</tr>
</tbody>
</table>
In some textile processes, single enzymes can be applied, whereas in some processes a mixture of enzymes is used to achieve the desired result. Specific enzymes, single or as a mixture, used in various textile processing steps as shown in Table 5.2 (Holmes, 1998).

The roles of surfactants and mechanical agitation are related both to the enzyme structures and characteristic structure of cotton. The presence of nonionic surfactants in the enzymatic solutions favors enzymes’ biological functions. They are compatible with enzymes, while anionic and cationic surfactants may form a complex with enzymes. Mechanical agitation can increase apparent enzyme activity and efficiency in scouring. However, enzymes may be denatured by mechanical agitation with high shear forces (Li and Hardin, 1998).

### 5.2.1 Biodesizing

The most common size applied in textiles is starch or starch derivatives. This serves as a protective coating on yarns during weaving. After weaving and before dyeing and finishing, the size must be removed by treating the fabric with chemicals such as acids, bases, or oxidizing agents in the traditional process. In modern textile industries, desizing may be done by amylase enzymes. Enzymatic desizing process is still the main application of amylase in the textile industry. Amylase application as an additive in laundering detergent formulations has increased recently.

Amylases were the first and the most successful enzymes used in textile industry. The α-amylase can be produced using microbes by submerged fermentation (SMF) or solid state fermentation (SSF), which employs waste products of other processes. The SMF is primarily used for the extraction of secondary metabolites that need to be used in liquid form. It allows the utilization of genetically modified organisms to a greater extent than SSF (Mojsov, 2018).

Amylases are of two types:

1. Dextrinogenic, α-amylases (EC 3.2.1.1)
2. Saccharogenic, β-amylases (EC 3.2.1.2)

<table>
<thead>
<tr>
<th>Process</th>
<th>Enzymes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desizing</td>
<td>Amylase, lipase</td>
</tr>
<tr>
<td>Scouring</td>
<td>Pectinase, cellulase, cutinase</td>
</tr>
<tr>
<td>Bleaching</td>
<td>Oxidoreductase, xylanase</td>
</tr>
<tr>
<td>Dyeing</td>
<td>Oxidoreductase</td>
</tr>
<tr>
<td>Finishing</td>
<td>Cellulase, oxidoreductase, lipase</td>
</tr>
<tr>
<td>Composting of textile waste</td>
<td>Laccases, cellulase, protease, nylonase, polyesterase</td>
</tr>
</tbody>
</table>
They are similar as both hydrolyze glucosidic linkages in the starch molecules, but the point, at which the reaction occurs, is different (Peters, 1967). The α-amylase is capable of acting at random locations along the starch chain to break down long-chain carbohydrates, ultimately yielding maltose from amylase or maltose and glucose from amylopectin. Because it can act randomly on the substrate, α-amylase tends to be faster-acting than β-amylase and is therefore used for textile desizing. A regular amylase may be applied at a pH 5.5–7.0 and at a temperature of 25–55 °C. Medium temperature desizing with amylases can be done at 50–95 °C, whereas high-temperature stable amylase can be used for desizing above 95 °C in the exhaust bath and also by the pad-steam process.

Biodesizing process is considered to be ecofriendly as the amount of wastewater generated is lower and it contains fewer amount of toxic chemicals compared to the traditional desizing process. The end products of the enzymatic desizing process are various types of nontoxic sugars and dextrin. However, they increase the biochemical oxygen demand (BOD) of the wastewater. Enzymatic desizing process can be performed in a continuous process, which consists of three stages such as:

- Impregnation at temperatures above 70 °C in a buffered solution containing calcium (Ca). Alternatively, the fabric may be soaked with the enzyme solution at the optimum temperature before a longer incubation (at a lower temperature) is carried out.
- Incubation for 2–16 h, depending upon the stability and the activity of the enzyme at the processing temperature and pH, the nature of the size, and the nature of the fabric.
- After-wash above 80 °C in an alkaline liquor followed by washing in a neutral liquor.

The recommended incubation times in various machines and methods are shown in Table 5.3 (Cavaco-Paulo and Gübitz, 2003). The amount of enzyme used depends on the activity of the product and there are at least two systems for measuring that activity.

Wetting agents and nonionic surfactants (but not any chelating agents) can be used to enhance enzyme penetration and adsorption, to enhance fiber swelling, and to promote the removal of waxes, soils, and synthetic sizing agents. After enzymatic treatment, the fabrics should be thoroughly washed.

Sometimes beef tallow or other fat is added to the size bath to improve the lubricity of the sized yarn after drying. It is, therefore, proposed that lipase enzymes should be included in the amylase desizing bath to catalyze the hydrolysis of the fat, the hydrolysis products being glycerol and fatty acid. A synergism between amylase and lipase

<table>
<thead>
<tr>
<th>Name of the machine</th>
<th>Incubation time</th>
<th>Temp (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jigger</td>
<td>2–4 turns</td>
<td>60–100</td>
</tr>
<tr>
<td>Winch</td>
<td>30 min</td>
<td>90–100</td>
</tr>
<tr>
<td>Cold pad-batch</td>
<td>6–24 h</td>
<td>15–40</td>
</tr>
<tr>
<td>Hot pad-batch</td>
<td>3–8 h</td>
<td>60–70</td>
</tr>
<tr>
<td>Pad-steam</td>
<td>15–120 s</td>
<td>90–110</td>
</tr>
</tbody>
</table>

Table 5.3 Desizing conditions in various machines.
is possible that results in even more efficient removal of starch than that would occur with amylase alone (Roy Choudhury, 2006).

The optimal performance of amylase depends on pH, oxidative stability, chelator resistance, and temperature behavior. Modified amylases with improved performance (such as thermostable) are developed by protein engineering methods such as random mutagenesis, homology considerations, and site-directed mutagenesis.

5.2.2 Bioscouring

For enzymatic scouring or bioscouring, pectinase is the only enzyme needed for wettablility, while other enzymes may have beneficial effects. Pectinases are a complex group of enzymes involved in the degradation of pectic substances. The optimum scouring temperature is 50–65 °C and pH is 7.5 and 9.0, respectively (Mojsov, 2011). The pectin degrading enzymes can be classified into three major groups, namely:

- Pectin esterases (PEs),
- Polygalacturonases (PGs), and
- Polygalacturonate lyases (PGLs).

Pectin esterases are naturally produced in plants like banana, citrus fruits, and tomato, in addition that they can also be produced by bacteria and fungi (Hasunuma et al., 2003). They catalyze the hydrolysis of pectin methyl esters, forming pectic acid. An extremely powerful alkaline pectinase has been isolated recently.

The major benefit of this type of enzyme in biopreparation is that the enzyme does not destroy the cellulose of the cotton fiber. The enzyme catalyzes hydrolysis of the salts of polygalacturonic acids (pectin) in the primary wall matrix very rapidly.

Pectinase, as the name suggests, hydrolyzes pectin present in cotton as a non-cellulosic impurity. The best kinds of pectinase function under slightly alkaline conditions even in the presence of chelating agents. Such enzymes are called “alkaline pectinases”. Most conventional pectinases are usually inactive under these commercially useful conditions, their optimum activity lying in the slightly acidic region (Shyam Sundar et al., 2007).

A study (Sawada et al., 1998a) showed that the use of a mixture of nonionic surfactants having hydrophilic-lipophilic balance (HLB) value of 13 and a natural organic solvent, D-limonene greatly increases the scouring efficiency of pectinase enzyme system obtained from Aspergillus niger. Further work (Sawada et al., 1998b) showed that the disadvantages of the above aqueous bioscouring process can be minimized by using a reverse micellar system (RMS).

Cellulases are especially suited for scouring of cotton fabrics. Some pectinase enzyme preparations contain cellulase. Those impurities are then removed by subsequent washing. However, the combined actions of both types give greater weight loss and strength loss as compared to the action of pectinase or lipase alone. Cotton fibers, or their blends with other fibers, can be treated with aqueous solutions containing protopectinases for 18 h at 40 °C to give scoured yarn with good tensile strength retention. Pectinases and cellulases are very effective as compared to the proteases and
lipases. The change in water absorbency of cotton is rapidly catalyzed by pectinases, cellulases, or their mixtures. Pectinases can destroy the cuticle structure by digesting the inner layer of pectins in the cuticle of cotton. Cellulases destroy the cuticle structure by digesting the primary wall cellulose lying under the cuticle of cotton. Cellulases and pectinases break the linkage from the cellulose side and the cuticle side, respectively. The result of the synergism is a more effective scouring in terms of the speed and the evenness of the treatment. The destruction of the cuticle during enzymatic scouring of cotton was revealed by the scanning electron microscopy (SEM) images (Li and Hardin, 1998).

The combined enzyme system for simultaneous desizing and scouring may contain amylase, lipase, and pectinase enzymes to achieve the necessary fabric properties, without the use of any harsh chemicals (Karmakar, 1998).

BioPrep 3000L (Novo Nordisk, Denmark) is an alkaline pectinase, free from cellulases (Lange, 2000). It works optimally at pH of 7—9.5 and at temperature up to 60 °C in exhaust systems and at a somewhat higher temperature in pad systems.

A successful strategy for the combined use of α-amylase and hemicellulase/pectinase in the pre-treatment of cotton has been developed (Opwis et al., 2008). The pectin and hemicellulose degrading enzymes are added to the desizing liquor. Besides desizing, the removal of undesired substances can be fulfilled in one step. In the subsequent bleaching step, residual hydrophobic components such as fats and waxes can be mobilized and removed. The enzymatic pre-treated cotton materials have similar or even better properties after a hot bleaching than the conventional desized and alkaline scoured material.

A study (Sancar et al., 2012) showed that application time, water, and energy can be saved by using amylase and pectinase in the same bath, but bleaching by laccase enzyme is not satisfactory for fabrics, which are dyed at light shades.

Scouring of cotton fabrics using combinations of pectinase, cellulase, and protease in a single bath, two steps have been carried out with optimum process parameters obtained from these enzymes individually. The multienzyme scouring can provide good absorbency and residual extractable impurity levels. The weight losses are more in the multienzyme scouring treatment, but the strength losses are more or less similar to that of individual enzyme scouring. Scaling and adjustment factors identified using Taguchi methods for the above response variables are further substantiated by confirmation tests (Saravanan et al., 2010).

A bioscouring padding process for cotton knitted fabrics (Xiaokang et al., 2018) showed that the average catalytic rate of the repeatedly padding method was sixfold faster than the impregnation method. The process time in the impregnation method is 80 min while in that of padding method is 15 min. The wettability of cotton knitted fabrics was better in padding method. In the repeated padding process, with the increasing soaking time from 5 to 25 s, the production of the reducing sugar increased from 1.71 to 3.60 mg/mL in the same process time. When the pick-up increased from 50% to 90%, the reducing sugar concentration first increased from 1.99 to 3.60 mg/mL, then decreased to 1.86 mg/mL. The catalytic rate of pectinase reached the best value of 0.24 mg/ml/min when the pick-up was about 70%.
Das and Ramaswamy (2006) studied the effect of enzyme treatment (savinase, resinase, xylanase, and pectinase) on the physical, chemical, and structural properties of wool and speciality hair fibers. It was observed that xylanase and pectinase treatments had as good a cleaning efficiency as conventional soap scouring. Furthermore, at the concentrations used, neither of these two enzymes caused any physical damage to the fibers, as confirmed by the tenacity and diameter values, and SEM images. The effectiveness of resinase as a scouring agent was, however, not very satisfactory. The results of this study have a lot of implication for the processing of wool and speciality hair fibers in the industry. Enzymes xylanase and pectinase would be very effective as scouring agents for fibers such as llama, alpaca, camel, and mohair. Since the speciality hair fibers possess very little impurities compared with sheep wool, the mild treatment conditions used in this study would be very appropriate with negligible cost of scouring.

Despite all the research on bioscouring, it has yet to be applied on an industrial scale. Highly active, high-temperature, and high-alkali stable pectinases are in very much demand. The targets of the recent research works are:

- Combination of cutinases with pectinases to optimize cotton wax removal in shorter processing times.
- The application of energy (both mechanical and ultrasonic) to speed up the reaction rate significantly.
- The use of mixtures of hydrolytic and oxidative enzymes derived from solid-state fermentation to attack the seed coat fragment.

Bioscouring has several advantages over traditional alkaline scouring. It is performed at neutral pH, reducing total water consumption, minimizing strength and weight loss, and retaining natural softness of cotton fiber. The temperature of bioscouring is much lower (40—60°C) as compared to alkali-boil scouring. Bioscouring can provide the desired hydrophilicity in the cotton fabric, at the same time sufficient residual wax materials are left on the fabric surface so that lesser softeners are required during finishing.

However, due to the relatively low treatment temperature, the waxes are not entirely removed, and achieved whiteness is poor. The seed-coat fragments also do not swell and are not bleached in bleaching (Tavčer, 2013). The cellulases can help to open up the fragments to further chemical attack. The chelating agent such as EDTA can hydrolyze much the seed coat fragments faster than the cotton fabric itself.

Both the biological oxygen demand (BOD) and COD (chemical oxygen demand) levels are reduced with bio-scouring. The BOD and COD levels of enzymatic scouring process are 20%—45% as compared to alkaline scouring (100%). Total dissolved solid (TDS) of enzymatic scouring process is 20%—50% of that of alkaline scouring. The handle is very softer in enzymatic scouring as compared to alkaline scouring process. Enzymatic scouring is energy-saving, non-polluting, and environment-friendly. It also minimizes health risks and the operators are not exposed to aggressive chemicals (Pawar et al., 2002).

However, owing to its small accessible area and contact-catalysis mechanism, enzyme scouring cannot carry out more catalysis in the internal structure of fabrics. The long soaking of the fabrics in the enzyme solution is time-consuming and may
cause strength reduction. In the biological enzyme cold pad-store method, the fabrics are soaked in enzyme solution for 1 h then stored for 4–12 h, which is a lengthy process that is not suitable for industrial application. It is found that bioscouring cotton fabrics by repeated padding (5–15 times, at a lower temperature) can greatly shorten the time of enzyme scouring and are an important means to enhance enzymatic efficiency (Wu et al., 2017).

5.2.3 Biobleaching

The bleaching with glucose oxidase enzyme (GOx) (EC 1.1.3.4) showed higher whiteness index with lower strength loss (Shaikh, 2009). Glucose is oxidized by the enzyme glucose oxidase to gluconic acid and hydrogen peroxide in the presence of molecular oxygen. d-Gluconic acid acts as a sequestering agent during bleaching. Amyloglucosidases, pectinases, and glucose oxidases were selected as they are compatible in their active pH and temperature range. A combination of two or all three preparatory steps with a minimal number of treatment baths and minimum rinse water showed comparable results in whiteness, absorbency, dyeability, and tensile properties of the treated fabrics.

The feasibility of a complete enzymatic one-bath pre-treatment of the cotton fabric at low temperature was investigated by Spicka and Forte-Tavcer (2012). The cotton fabric was enzymatic desized, scoured, and bleached simultaneously with an enzyme mixture of starch-degrading enzymes, pectinases, and glucose oxidases. The whole process continued for 2 h at 50 °C, with the final temperature to 85 °C. The process started at pH 5 and increased to 7.5 after 1 h of treatment to activate the generated peracetic acid (PAA) for bleaching. With less time and less use of water and energy, fabrics of good water absorbency, high tenacity at the maximum load, and high degree of polymerization (DP) were obtained while the whiteness achieved was medium.

The biobleaching of wool was conducted under both oxidative and reductive conditions. The studies showed that hydrogen peroxide bleaching in the presence of protease preparation, Bactosol SI (Clariant) considerably improved whiteness and hydrophilicity. Subtilisins are a family of alkaline serine proteases, secreted by a variety of Bacillus species (Siezen and Leunissen, 1997). The hydrolysis of peptide and ester bonds was catalyzed through the formation of an acyl-enzyme intermediate. Proteases hydrolyze the peptide bonds formed by specific amino acids. A number of protease enzymes, commercially available in the market, are regularly added to laundry detergents to aid in the removal of protein-based stains. However, they are mostly unstable to hydrogen peroxide. Alkaline proteases with improved stability to peroxide have been subsequently prepared such as Durazyme 16.0L (Novo Nordisk). As no significant whiteness improvement was achieved before 1 h of enzyme addition, it was suggested that the whiteness enhancement effect might be due to initial rapid etching of the wool fibers, making them more susceptible to subsequent bleaching. Hence, it is advisable to pretreat wool with the enzyme before peroxide bleaching so that the enzymes unstable to peroxide can be used. The enzyme treatment may be carried out for 1 h at 50 °C and pH 9.0. The bath is to be cooled to 45 °C before adding hydrogen peroxide and
ammonia to pH 8.5—9.0. Whiteness improvement was similar to that obtained in the simultaneous treatment, though slightly inferior. The addition of the protease enzyme (about 0.5%—1%) shortens bleaching time by half for the same whiteness.

Similarly, an appreciable increase in whiteness can be achieved under reductive conditions by treating wool with the protease papain, applied in the presence of a mixture of sodium bisulfite and sulfite at a pH of 6.5—6.9. The process is fairly cheap and rapid as compared to peroxide bleaching, but requires optimization. In both oxidative and reductive modes, a weight loss of at least 3% can be expected. Though such a weight loss is quite acceptable with cotton when treated with cellulase, it may be excessive for expensive wool.

5.2.4 Peroxide killer

Any residual peroxide on the fabric after bleaching can interfere with the dyeing process. Therefore, a thorough removal of peroxide is necessary. The traditional method is to treat with a reducing agent or thorough rinsing with hot water. The treatment with a small amount of catalase enzyme can also decompose peroxide, which is an easier and quicker method.

Catalases (CATs), more correctly hydroperoxidases, catalyze the degradation of \( \text{H}_2\text{O}_2 \) to \( \text{H}_2\text{O} \) and \( \text{O}_2 \). Catalases or hydroperoxidases are an oxidoreductive class of enzyme, which are produced by a variety of different microorganisms including bacteria and fungi (Mueller et al., 1997) and mostly have optimal operating conditions at moderate temperatures (20—50 °C) and neutral pH. In addition to the protein part of the molecule, catalase enzyme contains a non-protein part, which is a derivative of haem and includes metal iron. The advantage of the catalase enzyme (Niels, 2000) is that it attacks only hydrogen peroxide and nothing else. The degradation reaction is as follows (Eq. 5.1):

\[
2\text{H}_2\text{O}_2 + \text{catalase} \rightarrow 2\text{H}_2\text{O} + \text{O}_2 + \text{catalase} \quad (5.1)
\]

Peroxidases effectively degrade hydrogen peroxide at varied pH of 3—9 and temperature between 30 and 80 °C. The reaction rate is extremely fast and under optimum conditions, where one mole of catalase is able to decompose 500 million moles of hydrogen peroxide in 1 min. The catalase is free to decompose more hydrogen peroxide as long as the desired pH and temperature are maintained. The need to neutralize before adding the dye is beneficial since catalase is most active in the pH range of 6—8.

Normally, when using catalase, the number of rinses can be reduced drastically. Instead of applying catalase in a separate bath prior to dyeing, it may be added 5—10 min prior to adding chemicals and dyes in the dyebath. This is acceptable because catalase acts on hydrogen peroxide only and not on any other chemicals or dyes.

The use of a commercial catalase for the elimination of hydrogen peroxide residues from cotton fabrics improved dyeing behavior and the color yield increased considerably with a reactive bifunctional monofluortriazinyl dye (Amorim et al., 2002).
Eren et al. (2009) made a study to develop a new process to desize, bleach, and dye starch-sized cotton fabrics in one bath using enzymes. An amyloglucosidase/pullanase mixture enzyme was used to degrade starch into glucose during desizing. The generated glucose was converted to hydrogen peroxide and gluconic acid by glucose oxidase enzyme during bleaching. The gluconic acid was a good peroxide stabilizer during bleaching and a good sequestering agent during dyeing. The degree of whiteness of the enzyme-bleached fabric was suitable before dyeing with all seed fragments removed. Dyeing was performed in the same bath after catalase treatment in order to remove residual peroxide. The color measurements after dyeing indicated similar color yields for the proposed one-bath method compared to the conventional treatment.

5.2.5 Biofinishing

The use of cellulases on cotton provides a softer textile by removing projected fibers from its surface. The process called biopolishing prevents the formation of pills (Lenin et al., 2009). The hairs or fuzz (the microfibrils) protruding from the yarn or fabric surface are hydrolyzed by cellulases. A ball of fuzz, called pill, can present unattractive knotty fabric appearance. After biopolishing fabric shows much lower pilling tendency. The most popular way to remove fuzz is gas singeing. Cellulase enzymes can also remove fuzz providing a softer and smoother handle and better color brightness of fabric. Cellulase has various effects on man-made cellulosic fabrics such as lyocell (Tencel), viscose, and cellulose acetate. Cellulase alters the handle and drapeability, and removes surface fuzz of both viscose and lyocell. Cellulase also reduces the tendency of viscose to pill and reduces fibrillation of lyocell, but on cellulose acetate, the effects tend to be less. Linen was found to be the most susceptible fiber to enzymatic hydrolysis, followed by viscose, cotton, and lyocell (Durán et al., 2000).

The cellulases used in biofinishing are chemically complex and consist of at least three enzyme systems working synergistically together.

1. **Endo-β-(1,4)-gluconases (EG)** hydrolyze the internal regions of cellulose chain molecules.
2. **Exo-β-(1,4)-gluconases** hydrolyze cellulose chain ends to produce cellobiose. These exo-cellulases may assist disintegration of crystalline regions, making the region more susceptible to hydrolysis by endo-cellulases.
3. **The third enzyme, β-(1,4)-glucosidase** then hydrolyzes cellobiose and other small oligomers into glucose (Holmes, 1998).

The surface appearance and feel of fabrics produced from the new cellulosic fiber, Tencel can be enhanced by cellulase treatment. Two types of cellulases commonly used are:

1. **Acid cellulases** having the greatest activity in the pH range of 4.5—5.5 at 45—55 °C
2. **Neutral cellulases** require a pH range of 5.5—8.0 at 50—60 °C

Surface modification of cellulosic fabrics conferring cooler and softer feel, brighter luminous color, and more resistance to pilling using cellulases is often known as biopolishing, a term created by Novo Nordisk. For cotton, the restriction of the enzyme to the fiber surface is easily achieved because cellulose is highly crystalline material and possesses only small amorphous region, making the interior of the fiber inaccessible.
for the enzymes. Thus, by controlling the type and dosage of the most suitable enzyme, the action of the enzyme can be confined to the surface and the amorphous regions of cotton, thereby leaving the fibers, as a whole, intact.

The elimination of superficial microfibrils of cotton fiber through the action of cellulase enzymes is obtained by the controlled partial hydrolysis of cellulose followed by mechanical treatment, leaving the surface of the fibers free and conferring a more even look. The improvements in fabric softness and smoothness are permanent in contrast to the softeners applied to the fiber surface. Moreover, the water regain is not hampered by the enzymatic treatment as in the case of most softeners. Biopolishing may be carried out at any stage during wet processing, but it is mostly performed after bleaching. Treating fabrics with enzyme after dyeing may affect the shade, so some adjustment in dye formulation may be necessary. It may also be performed in garment form. Biopolishing is preferable in batches using washers, jets, becks, and winches, as pH and temperature can be controlled easily in these machines.

Controlled finishing with cellulase enzyme optimizes surface properties of the fabric but causes a decrease in tensile strength. A weight loss up to 3%—6% and strength loss up to 10% is acceptable commercially. It is also found that cellulase is more active in mercerized cotton than in either 100% untreated cotton or cotton/polyester blends (Hebeish et al., 2012).

The effect of cellulase enzyme treatment followed by dyeing process on the low-stress mechanical properties of the linen fabric was investigated (Kan et al., 2009). During finishing by cellulases strong mechanical agitation of the fabric is provided by some means, for example, rotating-drum waschers and jets. With the increase in the mechanical actions, the dissociation of bound enzymes increases (Cortez et al., 2001). Various levels of agitations are employed in pad-batch, winch machines, and jet systems in practice. However, increasing levels of agitation also reduce the adsorption of enzymes, increase the number of free sites for enzyme hydrolysis, and under extreme mechanical actions, catalytic specificity of the cellulases decrease.

5.2.6 Denim bio-wash

Denim garments are made from warp face cotton fabric in which warp yarns are dyed with indigo dyes. These garments are subjected to a wash treatment to give them a worn look. The indigo dye has poor substantivity for cellulose and hence, it mostly remains at the surface of the fiber after dyeing and as such called ring dyed. Such ring-dyed materials are subjected to treatment with stone or enzymes, which remove dyes randomly from the abraded portions of the fabric exposing white surfaces. This popular style “faded jeans” is utilized in warp-dyed denim fabric. Microscopy reveals that for indigo dyeing, the extent of the penetration of the colorant into the cross-section of the cotton yarn depends on the pH of the bath. When the pH of the dyebath is decreased from 13 to 11, the yarn progressively becomes ring-dyed. Associated with the increasing ring dyeing, more color yield is obtained on the yarn surface making the wash-down process easier. The highest color yield is observed within the pH range of 10.8—11.2 (Schmitt, 1998).
The blue denim is traditionally faded by the abrasive action of pumice stones by a process called stone-washing. Cellulases were first introduced in the 1980s and nowadays more than 80% of denim finishers use cellulases or a combination of stones and cellulases to create the worn look on denim. Cellulases work by loosening the indigo dye on the denim in a process known as “biostoning”. This treatment can be applied to knit and woven cellulosic fabrics such as cotton, viscose, linen, and their blends. An enzymatic stone-wash process requires equipment with sufficient shear forces and mixing, such as a drum washer.

A denim finisher, processing about 1, 00,000 garments a week with stones, typically generates 18 tons of sludge (BioTimes, 1997). This may block drains; therefore, it needs to be filtered out of wastewater. An environmental assessment was performed on jeans (OECD, 1998); it was found that the biostoning process produced very little sludge and proved to be more environmentally friendly than the traditional stoning process using pumice stones.

Inactivation of the enzyme after treatment can be easily realized by shifting the pH (above 10 for 5–10 min) and temperature (above 80 °C) to extreme values for a relatively short period. More recently, some authors showed that laccase (with and without using a mediator) is an effective agent for stonewashing effects of denim fabric (Pazarloglu et al., 2005).

5.2.7 Shrink-proofing for wool

The complexity of wool fiber makes it difficult to find enzymes that are able to modify some of the properties of wool efficiently, while not excessively damaging its structure (Riva et al., 1999). Due to the presence of scales on the surface of the wool fibers, the frictional resistance on the two directions along the fiber axes is different. This causes fibers to entangle and shrink during agitation of fiber mass. A process conventionally used for shrink-proofing of wool is chlorination in which the exo-cuticle of the wool is degraded with the formation of cysteic acid and the loss of protein. This process has been replaced by proteinase enzyme treatment due to its high specificity and much lower environmental impact. However, proteinase treatment leads to protein degradation, resulting in deterioration of fiber strength and limited shrink resistance (Breier, 2002).

Several reports have shown that increasing enzyme size by chemical cross-linking with glutaraldehyde or by the attachment of synthetic polymers like polyethylene glycol can reduce the penetration of enzyme and the consequent reduction of strength loss and weight loss (Schroeder et al., 2006). Some of these processes were tested on an industrial scale (Shen et al., 2007).

Some researchers describe methods to improve the shrink resistance of wool by pre-treating with a gentler oxidizing agent, like H2O2, and then with protease enzyme (Yu et al., 2005). Others refer to processes to achieve shrink-resistance by treating wool with a protease followed by a heat treatment (Ciampi et al., 1996).

The bleaching of wool with hydrogen peroxide in the presence of imino disuccinic acid sodium salt (IDAS), a new ecofriendly chelating agent followed by treatment
with lipoprotein lipase enzyme at 50 °C and pH 7 for 1 h, results in machine-washable, pilling-resistant wool without severe loss of the fiber strength. Some properties of wool such as shrink proofing, anti-pilling, and dyeability (toward anionic and reactive dyes) are improved. The degree of whiteness and wettability of the pre-oxidized wool fabrics were enhanced by enzyme treatment (El-Sayed et al., 2010).

The treatment with 1% enzyme (subtilisin serine alkaline protease) and 1.4% sodium sulfite, applied on wool for 30 min, resulted in complete shrinkage control with strength retention and 3.71% weight loss (Cardamone et al., 2005).

The new protease producing microorganisms with high specificity for cuticles was investigated in order to find an alternative for the existing proteases (Erlacher et al., 2006). Papain, the best-known cysteine protease, was isolated in 1879 from the fruits of Carica papaya. The optimal activity of papain occurs at pH of 5.8—7.0 and at temperature of 50—57 °C when casein was used as the substrate (Kamphuis et al., 1984).

Yoon (1998) filed a patent on the use of laccase from T. versicolor plus a mediator, which increased the shrink resistance of wool. Lantto et al. (2004) found that the wool fibers can be activated with laccase if a suitable mediator is present. Therefore, the use of laccase for anti-shrink treatment of wool seems to be very promising.

The effect of enzyme treatment (savinase, resinase, xylanase and pectinase) on the physical, chemical, and structural properties of wool and speciality hair fibers was evaluated (Das and Ramaswamy, 2006). Xylanase and pectinase treatments had cleaning efficiency as good as conventional soap scouring. Furthermore, at the concentrations used, neither of these two enzymes caused any physical damage to the fibers, as confirmed by the tenacity and diameter values, in addition to the SEM images. The effectiveness of resinase as a scouring agent was, however, not very satisfactory. Since speciality hair fibers possess very little impurities compared with sheep wool, the milder treatment conditions would be very appropriate for the treatment of these fibers.

The presence of any one of the three proteolytic enzymes in the dyebath increases the amount of dye absorbed in all the dyeing processes studied. The action of the enzymes on increasing the dye absorption becomes more evident when the dyeing temperature is lower and this action is greatest when the temperature gets closer to that of the maximum activity of the enzyme (around 50 °C) (Riva et al., 1999).

### 5.2.8 Degumming of silk

Enzyme degumming of silk is very popular in China. The enzymatic process takes more time than that of synthetic detergent but lesser time than that of soap. The action is comparatively milder than that of soap or detergent. It is claimed to produce uniformly degummed material with a soft handle and reduced lousiness. The recommended proteolytic enzymes are trypsin (of animal origin), pepsin, and papain (of vegetable origin). They hydrolyze peptide bonds formed by the carboxyl groups of lysine and arginine. Enzymatic degumming is not a single-step process. The gum is to be swollen before the enzyme treatment. In addition, a treatment with mild alkali is necessary to remove natural wax, soil, and lubricant oils.
Trypsin, a proteolytic enzyme secreted by the pancreas, is most active at a pH range of 7–9. Ammonium bicarbonate (0.1 mol/L) is considered to be a good buffer. For tryptic digestion, 1%–2% enzyme on the weight of material at 37 °C for 1–4 h is considered appropriate.

Papain is used for boiling off cocoons and degumming of silk. Papain, obtained from a vegetable source, papyrus latex, is most active at pH between 5 and 7.5 at 70–90 °C. Original poisonous activators potassium cyanide or hydrogen sulfide are being replaced with sodium thiosulfate, alone or in admixture with sodium hydrosulfide.

Several alkaline, acidic, and neutral proteases which dissolve sericin without affecting silk fiber protein have been studied as degumming agents (Araújo et al., 2008). Alkaline proteases seem to be the best for removing sericin and improving silk surface properties like the handle, shine, and smoothness (Arami et al., 2007), although they are not in commercial use. A bacterial enzyme, alkalase, is very effective in hydrolyzing sericin (Arami et al., 2007). It may completely hydrolyze sericin in 1 h at 60 °C and pH 9.

5.2.9 Degumming of ramie

Ramie fiber is widely used in textile and the biomass industry (biocomposite and biofuel). But ramie fiber could only be used if most of the noncellulose materials are removed by degumming. Its utilization is limited today since the traditional chemical degumming process causes serious environmental pollution, high energy consumption, high production cost, and fiber damage.

A study (Liu et al., 2012) revealed that over 90% of the gum in raw ramie could be removed only with *Pectobacterium* sp. CXJZU-120 in 6 h. The rapid process was not only suitable for the extraction of ramie fibers from different grades of raw material and retaining the inherent morphological structures and textile properties, but also could reduce the production cost up to 20.5%, raise resource utilization by more than 50%, and reduce pollution load by more than 80% compared with the traditional chemical degumming.

The Ca\(^{2+}\)-activated composite enzyme (pectate lyase/hemicellulase/laccase) was employed for degummed ramie fiber. The gum, hemicellulose, and lignin were removed effectively and treated fibers had the typical cellulose I structure suitable for direct textile and other applications. The fiber fineness, breaking strength, whiteness, and residual gum of fibers were largely improved. Flax fiber may also be degummed by this environmentally friendly technique of enzyme application (Zhang and Yan, 2013).

5.2.10 Surface modification of synthetic fibers

The hydrophilicity of hydrophobic synthetic fibers can be improved by alkaline or acid hydrolysis. But this may lead to the deterioration of fiber properties such as irreversible yellowing and loss of mechanical properties. It has been established that the enzymes can act on synthetic materials in addition to the natural fibers as discussed earlier.
Recently environmentally benign methods have been developed for surface modification and hydrolysis of polyester (PET or polyethylene terephthalate) and polyamide (PA or nylon) fibers with enzymes. As compared to the chemical methods, the enzymatic methods adopt milder reaction conditions and highly specific nondestructive transformations with minimum fiber damage.

The advantage of enzymatic treatment over conventional techniques is that the favorable bulk properties of PET remain unaffected because the enzymes are too big to penetrate into the bulk phase of the material. Various research groups have assessed the oxidation or hydrolysis of polyester materials by the enzymes, namely, laccases, lipases, polyesterases (serine esterase), and cutinases.

Yoon et al. (2002) reported the surface modification of PET and polytrimethylene terephthalate (PTT) by polyesterase enzyme. They reported that the formation of terephthalic acid (a hydrolysis product) could be monitored by absorption at 240 nm. The enzymatic treatment resulted in significant depilling, efficient desizing, increased hydrophilicity and reactivity with cationic dyes, and improved oily stain release. Recently, Nechwatal et al. (2006) have tested several commercial lipases/esterases for their ability to hydrolyze oligomers formed during manufacture of PET, which may otherwise create problem after dyeing by deposition on machines and fibers.

Cutinase, lipases, and polyesterases increase hydrophilicity by actual hydrolysis of PET, while laccases oxidize the PET surface. Cutinases (EC 3.1.1.74) are serine hydrolases, which can accept a wide range of substrates such as PET and polyamide. Crystallinity greatly affects the capability of cutinase to hydrolyze the ester bonds. Cutinase possesses relatively high activity toward amorphous polyester and little activity on highly crystalline substrates (Nierstrasz et al., 2009). The structure and properties of cutinases are well described by Carvalho et al. (1998). In contrast to lipases, cutinases do not require interfacial activation and the active site is accessible because it does not have a lid and the oxyanion hole is preformed but considerably flexible in solution. Cutinases seem to have a large potential in the enzymatic surface modification of polyester. The optimum pH and temperature for cutinase from Fusarium solani pisi are 8–8.5 and 25 °C, respectively; however, above 35 °C the enzymatic activity decreases rapidly. Novoenzymes improved the temperature stability to as high as 65–80 °C. Cutinase or lipase treatment does not result in pitting corrosion, as in the case of alkaline treatment. However, cutinase strongly adsorbs to the polyester surface. The adsorbed enzyme can be removed by using proteases or using a thorough washing and extraction method.

Due to poor hydrophilicity, textile materials made from polyamide 6,6 are also uncomfortable to wear. It leads to static cling and stain retention during laundering. The fiber is unsuitable for specific finishing treatments such as coupling of flame retardant or covalent immobilization of proteins. Biocatalytic processes have been developed to modify polyamide surfaces enhancing hydrophilicity. Enzymes that are able to hydrolyze polyamide surfaces are proteases, amidases, and cutinase (Güebitz and Cavaco-Paulo, 2008). The hydrolysis of polyamide is based on breakage of the amide linkages of the polymer surface resulting in amino and carboxylic groups. In addition to hydrolytic enzymes, oxidases from ligninolytic fungi have been shown
to depolymerize polyamides. Nylon-degrading peroxidases attack methylene groups adjacent to the nitrogen atoms and reaction then proceeds in an auto-oxidative manner.

Kim and Seo (2013) assessed the effectiveness of acylase I from *Aspergillus melleus* in the treatment of PA fabric. The hydrolytic activity of acylase was evaluated by measuring the number of carboxylate ions released into the treatment liquid and the color strength (K/S value) of a-bromoacrylamide reactive-dyed fabrics. Since acylase hydrolyzed amide bonds in PA fabrics, the larger number of carboxylate ions were released into the treatment liquid and the number of ionic groups formed on the fabric surfaces was increased. The optimal conditions for the enzymatic treatment of PA fabric were determined to be pH 8.0 at 50 °C with a treatment time of 60 min. The hydrolysis products were formed on the acylase-treated fabric surface stably, as demonstrated by the results for wash fastness. The moisture regain and wettability of the fabric improved due to the newly generated ionic groups formed on the fabric surface by acylase hydrolysis.

A study by Parvinzadeh (2009) confirmed the structural changes of nylon 6 fibers using subtilisin protease by measuring the dyeability, hydrophilicity, chemical changes, and fastness properties. The enhancement of the hydrophilicity of synthetic polymers such as polyester and polyamide is a key requirement for many applications ranging from electronics to functional and technical textiles. The new functionalized fibers can have a totally new range of applications such as filter media, smart, technical, and high-performance materials. Future challenges are in the area of improved activity and better temperature stability. Despite some achievement, the potential benefits of enzymatic modification of synthetic fibers are far from being fully explored (Silva et al., 2010).

The enzymes can form reactive and/or hydrophilic groups at the surface of acrylic and cellulose acetate fibers by hydrolysis of their pendent groups without affecting, in theory, the integrity of the main chain of the polymer. The polyacrylonitrile (PAN) fiber possesses nitrile pendant group. The cellulose acetate fibers possess polysaccharide substituent which supplies ester groups which can be hydrolyzed in a controlled manner, creating hydroxyl groups at the surface. The modification of PAN and cellulose acetate with enzymes results in two types of products: soluble compounds and new chemical groups attached to insoluble fiber substrate. For PAN fiber, only nitrilase and amidase generate soluble product, ammonia; nitrile hydratase generates amide groups as new side chains of the PAN main chain. For cellulose acetate, the hydrolysis of its side chains releases acetic acid to the reaction media and the hydroxyl group is located on the polymer backbone.

The nitrile hydratase and amidase enzymes obtained from different sources (*Rhodococcus rhodochrous* and *A. tumefaciens*) were used for surface modification of PAN fibers. After enzymatic treatment, the fabric became more hydrophilic and the adsorption of dye was enhanced (Fischer-Colbrie et al., 2006).

The enzymatic treatment of PAN has not been industrialized yet, but it would give advantages in the quality of treated fibers, as well as in energy saving and pollution control (Araújo et al., 2008).
Despite different substrates, origin, and amount of enzyme used, it is possible to specifically modify the nitriles of PAN into amides or carboxylic groups at moderate temperature and pH conditions with distinct chemical properties. Several aspects like staining properties and hydrophilicity are clearly improved for PAN fibers. Owing to its excellent mechanical properties stability and low cost, modified PAN is also of interest for filters in reverse osmosis, gas separation, protein immobilization, ion exchange, ultrafiltration, and dialysis (Matama and Cavaco-Paulo, 2010).

### 5.2.11 Textile printing

The use of enzymes in natural and synthetic thickener systems while printing of cotton and wool has been investigated. These studies especially covered their effects on color and surface structure. The efficiency of different enzymes (cellulases, proteases, and laccases) concerning their applicability, i.e., activity and stability within different thickener systems (polysaccharide, acrylic polymer, and their mixtures), was studied. Rheological parameters (viscosity and viscoelasticity) of the printing paste were determined and the color and/or structure effects on the fabric surfaces were assessed (Kokol and Heine, 2005).

Salem et al. (2008) researched on the removal of CMC (carboxymethyl cellulose) thickener by the enzymatic washing of cotton fabrics printed using reactive dyes. The enzymatic washing improves the quality of the printed cotton fabrics. It also decreases the harmful effects of wastewater, and environmental pollution caused by the thickeners. The enzymatic degradation of thickener decreases the process time, as well as the required energy and water needed to achieve a satisfactory quality of the printed fabrics.

### 5.2.12 Laundering

The main application of amylases is still in desizing process, but their application as additives in laundering detergent formulations has increased recently. One of the most important criteria for the use of amylase in detergents is to maintain optimal activity under the oxidizing washing environment. The oxidative stability of \( \alpha \)-amylase was obtained by replacing oxidation-sensitive amino acids such as cysteines and methionines with nonoxidizable residues. Two currently available oxidative-stable \( \alpha \)-amylases are Purastar OxAm (Genencor) and Duramyl (Novozymes).

Lipase and protease enzymes are present in human body. Both the enzymes are added in most of the biological laundry detergents. Lipases break down fats and oils, while proteases break down protein chains. Hence, a mixture of these enzymes works as excellent stain removal.

Modern detergents contain a sophisticated mixture of enzymes to remove stains and to assist cleaning at low temperature. Proteases, lipases, and amylases are generally used to assist in the removal of stains. Cellulase assists in the removal of particulate soils by removing microfibrils from the cellulosic fabrics. Generally, the detergents for this purpose rely on a mixture of enzymes, strong sequestering agents, and soil-release
polymers to provide satisfactory stain removal and soft finish. While the short fiber ends are hydrolyzed by enzymes, additional mechanical agitation is necessary to complete the process of hydrolysis and removal of hydrolyzed products from the fabric surface, which is best attained in rotating drum washers and jets. The effectiveness of a few types of enzymes in removing some common stains is summarized in Table 5.4 (Ramachandran and Karthik, 2004).

The oily and fatty stains have always been troublesome to remove, though protein stains are digested by the enzymes. The removal of grease spots is an even bigger problem, when washing is done at lower temperatures. The problem is particularly severe for the materials made up of a blend of cotton and polyester. The lipase is capable of removing fat or lipid and fatty stains such as fats, butter, salad oil, and sauces and the tough stains on collars and cuffs (Shaikh, 2009).

5.2.13 Enzyme-assisted dye and dyeing

Before the invention of synthetic dyes, many textile dyes (indigo, madder, wood, etc.) were manufactured by fermentation of plants. Many microorganisms produce pigments during their growth, which are substantive as indicated by the permanent staining that is often associated with mildew growth on textile and plastics. Some microbial pigments are benzoquinone, naphthoquinone, anthraquinone, perinaphthenone, and benzo[6]fluoroanthene quinine derivatives resembling vat class of dyes. Microorganisms seem to offer great potential for the direct production of novel textile dyes or dye intermediates by controlled fermentation techniques substituting chemical synthesis (Sowbhagya and Chitra, 2010).

The investigation of laccase-catalyzed coloration toward either wool or the multi-primary amine compound PEI (polyethylenimine) confirmed that amino groups from both wool and PEI are involved in the color formation during laccase catalyzation of catechin and gallic acid. Wool fabrics were successfully dyed into strong muted orange and dark tan colors through laccase-catalyzed oxidation of the phenolic compounds catechin and gallic acid, respectively, followed by further reaction to form their polymeric colorants. The reactive phenoxy radicals from laccase-catalyzed catechin or gallic acid could be nucleophilically attached to the amino groups of wool fibers, resulting in the formation of bonding between polymeric colorants and fibers.

Table 5.4 Enzymes and their effectiveness as stain remover.

<table>
<thead>
<tr>
<th>Name of the enzyme</th>
<th>Effective as a stain remover for</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proteases</td>
<td>Grass, blood, egg, and sweat stains</td>
</tr>
<tr>
<td>Lipases</td>
<td>Lipstick, butter, salad oil, and sauces</td>
</tr>
<tr>
<td>Amylases</td>
<td>Spaghetti, custard, and chocolate</td>
</tr>
<tr>
<td>Cellulases</td>
<td>Color brightening, softening, and soil removal</td>
</tr>
</tbody>
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Therefore, it may be possible to dye wool fibers in situ by laccase with colorless precursors under milder conditions such as lower temperature and weaker acidity. However, laccase-catalyzed coloration of wool is still in the early stage of research (Yuan et al., 2018).

Prajapati et al. (2018) studied a novel process for the coloration of wool and nylon 6,6 fibers via laccase (EC 1.10.3.2) oxidation of aromatic compounds as an alternative to conventional dyeing methods. A diverse color palette is possible to achieve through the investigation of three different aromatic compounds as laccase substrates:

1. 1,4-dihydroxybenzene,
2. 2,7-dihydroxy naphthalene, and
3. 2,5-diaminobenzene sulfonic acid.

The reaction parameters, namely, buffer systems and pH values, laccase and aromatic compound concentrations, and reaction times were investigated, in the absence of additional chemical auxiliaries. Enzyme-assisted dyed fabrics were tested against commercial standards, resulting in reasonably good color fastness to washing.

5.2.14 Biological effluent treatment

The natural microorganisms utilize biodegradable organic matters during the metabolic process as their source of food and energy. Municipal wastewater, industrial effluents, and agricultural (irrigation) return waters are some of the sources containing oxygen-demanding substances. These biodegradable substances include starch, fat, protein, acid, alcohol, aldehyde, ester, etc. The aerobic metabolism of aquatic microorganisms predominates when oxygen is available. The end products of such metabolism are more or less nonobjectionable. One major disadvantage of the aerobic digester is that it generates a considerable amount of sludge (Mittal, 2011).

As soon as the dissolved oxygen level drops, fish and other aquatic lives are threatened and in extreme cases, killed. Subsequently in an oxygen-depleted environment, very quickly anaerobic metabolism commences utilizing the remaining food or substrate. In the anaerobic process, which widely occurs in nature, organic substances are degraded mainly into gaseous substances (principally methane or carbon dioxide) and smaller amounts of solid end products than in the case of aerobic digestion. Microbial population, which exists in anaerobic digestion systems, is different from those of aerobic systems and is sensitive to oxygen. A series of metabolic reactions occur in the absence of oxygen. The end product of such anaerobic metabolism is undesirable and the resulting odor, taste, and color reduce the acceptability and attractiveness of water.

Dyes usually have a synthetic origin and their complex aromatic molecular structures make them more stable and more difficult to biodegrade. A wide range of microorganisms including bacteria, fungi, and algae are capable of efficiently decolorizing a wide range of dyes. Among these microorganisms, fungal biomass can be produced cheaply using relatively simple fermentation techniques and inexpensive growth media. Fungal biomass, which would otherwise be a nonessential product of various industrial fermentation processes, can also be used to remove dyes from
dyehouse wastewater. Most research work to date has concentrated on living fungi for biodegradation and biosorption of the dyes. A study (Fu and Viraraghavan, 2001) showed that the dead fungal biomass of *Aspergillus niger* is effective in removing Acid Blue 29 from aqueous solution. The biomass was pretreated with sulfuric acid at pH 4.0 for 24 h. It was then washed thoroughly to bring pH to 6.0.

Several enzyme preparations from various fungi have been observed (Abadulla et al., 2000) to decolorize triarylmethane, azo, anthraquinone, indigo, and metal chelate dyes. In all the preparations, laccase was a predominant enzyme, but lignin peroxidase and/or manganese peroxidase were also present. All were most active at 50 °C and pH 5.0. The discoloration efficiency depended on the source of the enzyme and the substrate (dye). Some white rot fungi (lignin peroxidase, manganese peroxidase, and laccase) have the ability to decolorize textile dyes and the composition of the media affects the result. Fungi can decolorize dyes faster in the nitrogen-limit medium than in nitrogen-sufficient medium (Hardin et al., 2000).

Azo dyes, even with several azo groups in their structure, are readily decolorized by anaerobic biomass. The removal was not affected by the type of dye used, even at high concentrations. The dispersing agents did not seem to affect the removal of the organic load in any significant way. Anaerobic digestion should be implemented to remove anionic azo dyes and the subsequent color produced by them. The compounds are reduced to aromatic amines, which can be later degraded by an aerobic treatment. Anthraquinone dyes can be removed in 2 or 3 days at a very low concentration (35 mg/L) in order to avoid inhibition of the biomass or else to be removed previously by coagulation or flocculation (Goncalves et al., 2000). Special care should be taken in regard to toxic wastes. As such, these must not be subjected to biological treatment or may be pretreated chemically before biological treatment.

Many synthetic dyes, such as azo dyes, are resistant to microbiological degradation under aerobic conditions maintained in common treatment plants. Many dyestuffs, in particular, disperse, direct, and basic dyes, are removed from wastewater via adsorption on to activated sludge. However, highly water-soluble reactive and acid dyes are poorly adsorbed on activated sludge.

### 5.3 Conclusions and future trends

During the last few years, enzymes have been thoroughly studied and used in order to develop environmental friendly alternative processes for almost all the steps in textile processing. There are already some commercial successful applications, such as amylase used for desizing, cellulose and laccases for denim finishing, and proteases incorporated in detergent formulations.

Although some enzymes already play important role in textile processing, their potential is much higher and their applications are likely to increase in future. The productivity and efficiency are to be improved so that these biotechnologies become economically advantageous over conventional approaches. Further research works...
are necessary for biomodification of synthetic and natural fibers of improved properties. New approaches are needed to understand the metabolism and growth of the host organism better.

Genetic engineering offers new opportunities to produce modified or new enzymes with better properties. The use of genetically modified microbial enzymes of commercial importance can be expected to expand into many other areas of the textile industry thus replacing existing chemical or mechanical processes in the near future.

The enzyme-based processes for the biomodification of synthetic and natural fibers are to be implemented commercially through further research. The researchers are conducting research to find new enzyme-producing microorganisms and enzymes extracted from extremophilic microorganisms. These microbes live under chemical and physical extremes that are usually lethal to cellular molecules, yet they manage to survive and even thrive. In future, many of the textile industries will adopt the ecofriendly enzyme processes to replace the traditional approaches in textile wet processing.

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6.1 Introduction

The production of textile materials has grown significantly in recent years. Global fiber production rose to approximately 111 million metric tons in 2018, a rise over the past decade of 35 million tons, and they expect to grow 3.7% per year to 2025 (Koszewska, 2018). Of the global total, natural fibers accounted for 32 million tons of production during 2018 (cotton production is estimated at 26.72 million tons), an increase of less than 2 million tons in 10 years. The share of natural fibers in global fiber production fell from 41% in 2008 to less than 30% in 2018. Until today the global production of synthetic filament rose to 50 million tons; of this, polyester filament alone was about 45 million tons. Synthetic staple production rose to 22 million tons, and production of cellulosic fibers rose to 7 million tons (Bremen Cotton Report No. 05-06, 2019).

Recently, there have been many efforts at the industrial level to adopt cleaner production processes and technologies. The introduction of a new environmental regulation in European countries called REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) has forced companies to tackle environmental problems by encouraging innovation with the aim of promoting sustainable development (Europa, 2019). Nowadays, textile industries show clear signs of divergence in the face of decades of stagnation with regard to innovative textile processes and products. The progress of the world textile industry, especially in the processing sector, is linked to the changes coming from new research fields such as micro- and nanotechnology, functionalization, and intelligent fabrics. In this context, plasma technologies emerge as a way to achieve significant improvements in almost all phases of the textile processing, modifying conventional treatments, obtaining important results in rising efficiency, and increasing the durability of functional properties such as capacity for adhesion, dyeing, reactivity, grafting of new chemical groups, and coating of polymers (Zille et al., 2015).

Generally, plasma is produced by applying a flow of voltage over a gas to ionize the atoms/molecules. There exist multiple methods to create ionized gases, in which the following are the typical ones. (a) Glow discharge: Plasma is produced by putting a radio frequency of 40 kHz, 13.56 MHz, microwave, and direct current at low frequency 50 kHz voltage through either a pair or a series of electrodes. This method
uses reduced pressure and ensure to reach the greatest level of flexibility and uniformity of all plasma usage. (b) Corona discharge: It is known to be producing plasma using atmospheric pressure by putting it through a pair of different size electrodes at a low frequency or high voltage flow. This method is only compatible to certain types of fabrics due to its inability to achieve uniformity (Zille et al. 2014); if not, it could cause some problems. (c) Dielectric-barrier discharge: It is produced using a pulse voltage flow on a pair of electrode, of which one of them is covered in dielectric material. Its biggest advantage that outweighs corona is the ability to reach uniformity.

Plasma technology is based on a simple physical principle. When energy is supplied to matter, it changes state from solids to liquid, and liquids to gaseous. If more energy is supplied to a gas, it becomes ionized and goes into the energy-rich plasma state, the fourth state of matter into which electrons are free from atoms or molecules allowing both species to coexist. Plasma was first discovered by Irving Langmuir in 1928 and is the most common state of matter in the universe. More than 99% of the visible matter in the universe is in the plasma state (Muthu, 2018).

The development of plasma discharge for application in textile materials is very recent. The first continuous system developed was proposed by Bradley in the year 1971 (Surface Activation Corporation, USA); however, it was a vacuum system, which limited its application due to the high cost involved (Bradley and Fales, 1971). Since then, different systems for application in textile materials have been developed by several manufacturers and research institutes around the world, namely: Sando Iron Works Ltd. (Uzu, Wakayama, Japan); Fraunhofer IGB (Stuttgart, Germany); NIEKMI institute in Russia (Tecnoplasma, S.A); Europlasma (Outdenaarde, Belgium); Polyplas (Emmerthal, Germany); Fourth State (Belmont, USA); Softal Electronic GmbH (Hamburg, Germany); University of Minho (Guimarães, Portugal); Sherman Treater Co (Oxon, UK); Paladin (North Carolina State University); and Dow Corning Plasma Solutions (APGD, AP 100).

There are a large number of plasma types, and an universal classification it is not straightforward; however, they can be primarily divided into thermal and nonthermal plasma (Xi et al., 2008). Thermal plasma can be naturally observed in the stars, lightnings, northern lights, other celestial bodies, and the corona of the sun during an eclipse. Thermal plasmas can be also artificially generated using electrical discharges of DC (direct current) or AC (alternate current), laser, radio frequency, and microwave discharges at near-atmospheric pressure (Gleizes et al., 2005). In thermal plasmas, the temperatures are extremely high, in the order of thousands degrees Celsius, and all the different species contained in the gas are in thermal equilibrium.

Since textile materials are heat-sensitive polymers and they cannot withstand the temperature of thermal plasma, nonthermal plasma (or cold plasma) are the only viable option for textile surface modification and processing (Morent et al., 2008). In cold plasmas, the temperature of the electrons is higher (104–105°C at 1–10 eV) than the temperature of other particles (that can remain at room temperature) since the thermodynamic equilibrium is not reached even on a local scale between the electrons and the neutral atoms or molecules, ions and neutral molecules fragments. Cold plasmas, that can be divided into atmospheric pressure plasmas and low-pressure plasmas, have the major advantage of inducing significant surface
chemical and morphological modifications onto fibrous materials without altering the bulk properties of the materials (Borcia et al., 2005; Oliveira et al., 2010a).

The choice of the process to be applied depends on the processing speed, sample size, and extent of the intended modification (Pappas et al., 2006). Most of the work done to modify polymer surfaces with plasma treatments using different gases and chemicals has been performed at low pressure achieving various effects by etching, polymerization, or formation of free radicals on the surface of the textile substrate (Sarra-Bournet et al., 2006). On one hand, low-pressure plasma technology are considered noncompetitive since the running costs are higher due to the expensive vacuum pumping system and the Meissner trap (cryogenic coil) often required to avoid the water evaporation in the vacuum chamber during unwinding of textiles (Mohammad et al., 2011). These factors have seriously limited the commercial viability of this technique in the textile industry (Pappas et al., 2008). On the other hand, atmospheric cold plasmas are suited because they do not need expensive vacuum equipment and allow continuous and uniform processing of fiber surfaces.

In the last 10 years, plasma technology has become a very active, and high growth research field, assuming a great importance among all available material surface modifications in textile industry. There are several benefits of applying plasma technology, which are best suited with the current vital aspects of sustainability. The benefits are:

- Endless opportunity for the modification of surface properties, by appropriate gases.
- Plasma technology reduces the use of water, chemicals and energy, in comparison with the conventional wet method.
- In terms of economic benefits, the elimination of water sources and chemicals can be more cost-effective.
- Plasma treatment, especially closed plasma process, is environmentally friendly.

The main objective of this chapter is to provide an overview on the most important applications of plasma technology for the fashion and textile industries such as the dyeing and printing processes and the hydrophobic and hydrophilic surface treatments. This chapter also provides a brief description of other areas of application in fashion and textiles, advantages, and drawbacks of the new sustainable technology.

### 6.2 Plasma in textile dyeing and printing processes

Conventional dyeing processes have a low yield, and the dye lost in the effluents can reach up to 50%, creating obvious environmental problems. Most importantly, dye wastewaters without an appropriate treatment can persist in the environment pollution creating problems not only to the photosynthetic processes of the aquatic plants but also to all the living organisms (Schneider et al., 2004). Plasma technology can be used in this context for the removal of the natural or synthetic occurring grease and wax in textile fibers, but also to improve the diffusion of dye molecules into the fibers enhancing color intensities and washing fastness of several natural and synthetic textile materials (Karahan et al., 2008; Nourbakhsh et al., 2008; Souto et al., 2011; Raffaele-Addamo et al., 2006; Hossain et al., 2009; Shahidi et al., 2007; Yaman et al., 2009; Cai and Qiu, 2008; El-Zawahry et al., 2006; Jocić et al., 2005;
Ratnapandian et al., 2011). Plasma application improves dye exhaustion, dyeing uniformity; decreases the amount of applied dyestuff and water; and allows the reuse of effluents contributing to a significant diminution in costs and environmental impact (Deshmukh and Bhat, 2011; Shah and Shah, 2013; Radetic et al., 2007).

In the last 10 years, atmospheric pressure plasmas have proved to be an effective alternative to low-pressure plasma in dyeing. Excellent results were obtained by dyeing polyamide, polyester, and wool fabrics using different dyestuff such as acid and disperse dyes (Oliveira et al., 2009, 2014; Hossain et al., 2007; Lehocký and Mrácek, 2006; Gotoh and Yasukawa, 2010; Goresek et al., 2009; Mirjalili and Karimi, 2013; Kamel et al., 2011; Salem et al., 2011). The dyeing properties of fibers treated with plasma are correlated with the surface chemical composition and surface modifications (Ren et al., 2011; Xiaoliang et al., 2007; El-Nagar et al., 2006; Gawish et al., 2011; Naebe et al., 2009; Motaghi et al., 2009; Ghoranneviss et al., 2011; Fakin et al., 2009; Ke et al., 2008; Barani and Maleki, 2011). However, the increase in dyeability also depends on the exposure time, gas mixture composition, and applied energy (Kerkeni et al., 2012; Yaman et al., 2011; Carneiro et al., 2005, 2006; Patiño et al., 2011).

In the last 10 years, inkjet printing technologies have demonstrated improved properties over the traditional textile printing methods, such as roller, screen, and transfer printing. These digital technologies are becoming widespread in textile industries displaying excellent quality, low pollution, and very adaptable to the today rapid fashion changes. Despite inkjet printing allows visual effects such as tonal gradients and infinite pattern, the lack of an opportune pretreatment can considerably low the print quality due to the lower capacity to retain water, inks, finish and embossing agents of some textiles. Atmospheric plasma is a very effective pretreatment method to improve inkjet pigment uptake (Fang and Zhang, 2009; Radetic et al., 2000; Kan, 2007; Payamara et al., 2010; Kan et al., 2011; Yuen and Kan, 2007; Zhang and Fang, 2009, 2011; Wang and Wang, 2010; Rashed et al., 2009; Maamoun and Ghalab, 2013; Chvalinova and Wiener, 2008; Nasadil and Benesovsky, 2008).

Overall it is clear that over the last 10 years, atmospheric plasma technologies have significantly improved the dyeing and printing efficiency of textile materials. However, in some cases (e.g., cotton, polyester, and polypropylene fabrics), the low-pressure plasmas remain the most applied technology. Table 6.1 describes the application of plasma in textile dyeing processes by various researchers. Similarly, Table 6.2 and Table 6.3 describe the research studies on hydrophilic and hydrophobic treatments of textile substrates, respectively.

### 6.3 Improving textiles hydrophilicity and hydrophobicity by plasma

Plasma technology is broadly used to improve surface wettability and/or hydrophilicity of numerous textile materials (Demir et al., 2011; Ren et al., 2008). The increase in hydrophilicity of numerous fibrous materials such as polyamide, polyester, polyethylene, polypropylene, silk, aramid, carbon fibers, wool, and cellulose has been
Table 6.1 Plasma application in textile dyeing processes.

<table>
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<tr>
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<th>Dye (C.I.)</th>
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<tr>
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Plasma corona

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**Dielectric barrier discharge plasma (DBD)**

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**Low-pressure plasma (LPP)**

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demonstrated (Riccardi et al., 2005; Masaeli et al., 2007; Li et al., 2009; Huang et al., 2013; Bessada et al., 2011; Šimor et al., 2010; Wang and Qiu, 2007; Vander Wielen et al., 2006). Plasma treatments in air or using different carrier gases are able to introduce hydrophilic functional groups such as $-COOH$, $-OH$, and $-NH_2$ on the fabric surface. The increase in wettability is attributed to the generation of these new functional groups.

### Table 6.1 Continued

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Table 6.2 Plasma technology in hydrophyllic treatment of textiles.

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**Low-pressure plasma (LPP)**

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<td>SiCl₄</td>
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<td>Negulescu et al. (2000)</td>
</tr>
<tr>
<td>PET</td>
<td>O₂, N₂, H</td>
<td>n.a.</td>
<td>Costa et al. (2006)</td>
</tr>
<tr>
<td>PET</td>
<td>O₂, N₂</td>
<td>0.4</td>
<td>Vatuña et al. (2004)</td>
</tr>
<tr>
<td>PET</td>
<td>Air</td>
<td>7.7</td>
<td>Riccardi et al. (2003)</td>
</tr>
</tbody>
</table>
chemical groups and/or to the reduction/elimination of polymeric layers on the fabric surface. The wettability of a textile material is directly related to its surface energy and defines surface and interfacial phenomena including chemical reactivity, adsorption, desorption, wet processing, and adhesion (Kale and Desai, 2011).

The use of plasma discharge to improve various properties in low surface energy textile materials (e.g., polyethylene, polypropylene, and polyester) today is a deep-rooted technology (De Geyter et al., 2008; Samanta et al., 2009; Leroux et al., 2009; Thurston et al., 2007; Aouinti et al., 2003; Kabajev and Prosycevas, 2004). The increase in surface wettability is certainly one of the simplest studied properties to identify surface modification of plasma-treated textile materials. However, plasma-surface interactions are not yet fully comprehended because they are influenced by complex factors such as the chemistry of plasma gases, the nature of the substrate, and the operating parameters. Moreover, the energy or power density is one of the most important parameters to calculate plasma treatment costs and benefits, and at the same time it is also the most omitted parameters in literature (Abd Jelil et al., 2013) (Table 6.2).

The most commonly used methodologies to hydrophobize a textile substrate can be divided into three categories: (1) plasma treatment, (2) plasma etching (or ablation), and (3) plasma polymerization (Roth, 2001; Bahners et al., 2008). Plasma treatment uses inert gases such as argon (Ar), helium (He), nitrogen (N₂), and chemically active molecules such as oxygen (O₂) or ammonia (NH₃), as well as fluorinated gases such as carbon tetrafluoride (CF₄), hexafluoroethane (C₂F₆), perfluor (C₃F₈), perfluoroisobutylene (C₄F₈), decfluorocyclopentane (C₅F₁₀), trifluoromethane (CHF₃), sulfur hexafluoride (SF₆), and other (larger size) fluorine-containing molecules such as perfluoroalkyl acrylates (Zille et al., 2015; Morent et al., 2008; Yim et al., 2013; Gotoh et al., 2017; Vietro et al., 2015; Tendero et al., 2006; Table 6.2 Continued

<table>
<thead>
<tr>
<th>Textile substrate</th>
<th>Carrier gas</th>
<th>Power (W)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>PET</td>
<td>O₂</td>
<td>0.38ᵃ</td>
<td>Verschuren (2005)</td>
</tr>
<tr>
<td>PP</td>
<td>O₂</td>
<td>300</td>
<td>Wei et al. (2005)</td>
</tr>
<tr>
<td>PP</td>
<td>O₂</td>
<td>500</td>
<td>Masaeli et al. (2007)</td>
</tr>
<tr>
<td>Viscose</td>
<td>O₂</td>
<td>500</td>
<td>Persin et al. (2012)</td>
</tr>
<tr>
<td>Wool</td>
<td>O₂</td>
<td>300</td>
<td>Sun and Stylios (2004)</td>
</tr>
<tr>
<td>Wool</td>
<td>N₂</td>
<td>60</td>
<td>Canal et al. (2007)</td>
</tr>
<tr>
<td>Wool</td>
<td>O₂ – N₂</td>
<td>60</td>
<td>Canal et al. (2007)</td>
</tr>
<tr>
<td>Wool</td>
<td>O₂</td>
<td>60</td>
<td>Canal et al. (2007)</td>
</tr>
</tbody>
</table>

ⁿᵃ, not available.
ᵃPower density (W cm⁻²).
ᵇPower (W).
ᶜFrequency (MHz).

Plasma technology in fashion and textiles 131
Sparavigna, 2008; Jafari et al., 2013). The plasma-activated gases introduce chemical functionalities or create and deposit free radicals onto the target surface that can be subsequently used to cross-link or surface-graft other molecules to attain specific surface properties (very often more hydrophilic surfaces).

Another method consists of the immersion of the fabric in a fluid of hydrophobic fluorinated prepolymer with added initiators followed by a plasma treatment leading to the grafting on the surface of the fabric. Plasma etching occurs when the substrate is bombarded with ions from the plasma to clean, sterilize, or enhance surface adhesion of the fabrics. For example, dry plasma etching can be accomplished by using CF$_4$ in a plasma discharge to create active species capable of reacting chemically with the layer to be etched (Sigurdsson and Shishoo, 1997).

Plasma polymerization is a process where a monomer in vapor phase such as CF$_4$, C$_2$F$_6$, C$_3$F$_8$, or larger fluorinated molecules such as fluorodecylacrylate is converted into reactive fragments, which polymerize at the surface (plasma-induced

<table>
<thead>
<tr>
<th>Atmospheric plasma</th>
<th>Low pressure plasma</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Refs:</strong> (Yim et al., 2013); (Gotoh et al., 2017); (Tendero et al., 2006); (Zille et al., 2015); (Sparavigna, 2008); (Morent et al., 2008)</td>
<td><strong>Refs:</strong> (Vietro et al., 2015); (Zille et al., 2015); (Sparavigna, 2008); (Morent et al., 2008); (Jafari et al., 2013); (Hochart et al., 2003b); (Hegemann, 2006)</td>
</tr>
<tr>
<td>C$_{11}$H$<em>7$F$</em>{13}$O$_2$</td>
<td>CF$_4$</td>
</tr>
<tr>
<td>C$_{13}$H$<em>7$F$</em>{17}$O$<em>2$/C$</em>{15}$H$<em>7$F$</em>{21}$O$_2$</td>
<td>C$_2$F$_4$</td>
</tr>
<tr>
<td>Unidyne TG-571®</td>
<td>C$_3$F$_6$</td>
</tr>
<tr>
<td>CF$_4$</td>
<td>C$_2$F$_6$</td>
</tr>
<tr>
<td>CF$_3$CHF$_2$</td>
<td>C$_3$F$_8$</td>
</tr>
<tr>
<td>CHF$_3$</td>
<td>C$<em>4$F$</em>{10}$</td>
</tr>
<tr>
<td>C$_3$F$_6$</td>
<td>C$<em>6$F$</em>{14}$</td>
</tr>
<tr>
<td>C$_2$F$_6$</td>
<td>C$_4$F$_8$</td>
</tr>
<tr>
<td>C$<em>9$F$</em>{17}$CH$_2$CH$_2$OCOCH=CH$_2$</td>
<td>CF$_3$CHF$_2$</td>
</tr>
<tr>
<td>C$_3$F$_8$</td>
<td>SF$_6$</td>
</tr>
<tr>
<td>C$_{13}$H$<em>7$F$</em>{17}$O$_2$</td>
<td>CF$_3$SO$_3$H (co-monomer)</td>
</tr>
<tr>
<td>SF$_6$</td>
<td>C$_2$ClF$_3$ (co-monomer)</td>
</tr>
<tr>
<td>H$_2$C=CHCO$_2$CH$_2$CH$_2$(CF$_2$)$_7$CF$_3$</td>
<td>C$_6$F$_6$ (co-monomer)</td>
</tr>
<tr>
<td>C$<em>6$H$</em>{13}$F$_3$O$_3$Si (FAS-3)</td>
<td>HC$_6$F$_5$ (co-monomer)</td>
</tr>
<tr>
<td>C$_6$F$_5$Si(OC$_2$H$_5$)$_3$ (FAS-5)</td>
<td>CF$_3$(CF$_2$)$_7$CH=CH$_2$</td>
</tr>
<tr>
<td>C$<em>{13}$H$</em>{13}$F$_{17}$O$_3$Si (FAS-17)</td>
<td>1,1,2,2, tetrahydroperfluorodecyl acrylate</td>
</tr>
</tbody>
</table>
polymerization) or combine with polymers in the gas phase (plasma-state polymerization) to be deposited on the substrate (Sigurdsson and Shishoo, 1997; Li and Jinjin, 2007; Artus et al., 2012; Sun and Stylios, 2006). The deposition can occur while the plasma is excited or in a two-step process: (i) creation of radicals on the fiber surface by plasma in inert gas (e.g., argon) and (ii) reaction of these radicals with unsaturated monomers (Morent et al., 2008).

Numerous studies with different plasma discharges were conducted with the objective of increasing the hydrophobicity of various textile fibers such as polyesters, polyacrylonitrile, polypropylene, cotton, and silk. (Sigurdsson and Shishoo, 1997; Hegemann, 2005; Ji et al., 2008; Leroux et al., 2008; Hochart et al., 2003a; Höcker, 2002; Mattheus, 2005; Kim et al., 2006; Caschera et al., 2013; Vasiljević et al., 2012; Suanpoot et al., 2008). Nowadays, fluorocarbons are used to reduce the fiber friction due to their low frictional coefficients and hydrophobic properties. Despite the price of these fibers remains high, fluorocarbon fibers remain the most efficient solution to provide effective anti-stain to both water and oil at the same time (Bertaux et al., 2009).

The majority of plasma-based textile treatment processes for the production of hydrophobic and oleophobic surfaces (but also for some polymer coating, flame retardant, and medical antimicrobial fabrics) reported in the technical literature are based on nonthermal plasmas generated at low pressure (between 1 mTorr and 1 Torr) and in few cases at atmospheric pressure (Table 6.3). However, atmospheric plasma source designs based on corona discharges, glow discharges, dielectric barrier discharges (DBDs), plasma jet, capacitive or inductive coupled discharges, and radio frequency— or microwave-induced discharges have been intensively studied (Zille et al., 2015; Morent et al., 2008; Gotoh et al., 2017; Vietro et al., 2015; Tendero et al., 2006; Sparavigna, 2008; Jafari et al., 2013; Sigurdsson and Shishoo, 1997). Most of these technologies are still at an emerging stage although some of the manufacturers have developed commercial scale machinery and applications for specialized textiles that are currently being implemented at industrial scale.

6.4 Other applications and barriers

Compared with the traditional finishing processes, plasma technology has several advantages of improving the surface functionality, enhancing the interaction between fibers and reducing the usage of chemicals and energy, hence, cost saving. Plasma technology can be applied to fibers, yarns, fabrics, and garments; nonwovens; coated fabrics; and composites to enhance surface functionality. Plasma technology has the potential to be applied in a range of areas which includes antimicrobial treatment, UV resistant finish, self-cleaning, and flame retardant finish. Textiles with higher durability and fastness properties can be achieved with this technology without changing the textile bulk properties. The other areas of plasma application includes:

* Removing surface hairiness of textile materials.
* Scouring of cellulosic materials and synthetic materials such as polyester and nylon.
* Enhancing the electrical conductivity of yarns by plasma deposition.
Antishrink treatment of textiles.
* Improved adhesion between various textile substrates.
* Desizing of textile materials.
* Producing stain-resistant finishing in the fabrics.
* Silicone coating on textile substrates such as airbags.
* Reducing color variation of textile materials.

Plasma technology has some barriers that need to be addressed in order to make this technology successful. The major problem is the availability of commercial machinery for industrial applications, gaps in the applied research to commercialize the technology, slow development in industrial system, and less transparency of the results achieved. Although the cost of running the machinery is low in plasma technology, the initial invest will be high, which restricts the plasma application of textiles. Furthermore, the whole procedure and components must be carefully selected and monitored during the processing. Continuous processing of some plasma treatment can cause technical problems, which also needs to be addressed. Some low-pressure plasma systems are available in the European market. However, in many other countries, there are not many manufacturers of industrial machinery.

6.5 Conclusions

The application of plasma technology into fashion and textiles is gaining impetus due to its eco-friendliness. Plasma technology is a dry, nonpolluting and worker-friendly method to achieve surface functionality of fashion and textile materials without modifying the bulk properties of the materials. For textile applications, atmospheric nonthermal plasma application is best suited as most textile materials are heat-sensitive polymers. In the last decade or so, plasma technology has become a very active, high growth research field, due to its great potential for the surface modification of textile substrates in the textile industry.

The introduction of plasma treatment in textile industry has improved the sustainability factor, since plasma technology helps to reduce the use of water and chemicals, which are essential in traditional processes. It is very effective with many properties modification without affecting bulk properties of the textiles. Moreover, economy-wise, plasma treatment gains huge advantages over conventional wet methods with reduction in cost and energy. On the other hand, initial purchases of the system, especially the vacuum pumps are fairly expensive and it must go through meticulous inspections for optimal outcome. With all the benefits plasma technology convey, its potential in the future is very promising.

Several research studies have been done in the last couple of decades on the low-pressure plasma applications to achieve various functionalities. A range of fibrous materials including plastics, polymers, resins, metals, ceramics, bio- and inorganic materials have been intensively researched and produced promising results. The surface modification include hydrophilicity, hydrophobicity, adhesion, sterilization, chemical resistivity, and inertness. Plasma technology has a promising future to achieve technical results economically.
Despite the high potential advantages and the environmentally friendly approach, the application possibilities of plasma technology in textile industry is still limited due to potential problems. The major problem is the availability of commercial machinery or industrial application systems, gaps in the applied research, and less transparency of the results achieved. In future, the textile and fashion manufacturers in developing countries will adopt this technology when these problems are overcome.

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Vasiljević, J., et al., 2012. The surface modification of cellulose fibres to create super-


Ultrasound applications in textiles and apparels

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The efficient mass transfer, mixing, and blending at lower temperature make the ultrasound one of the best suitable choice in textiles and apparels in various applications. This chapter gives insight on various applications of ultrasound in textile and apparel production as a tool to minimize thermal energy, water, auxiliaries, dyes, and finishes since starting from extraction of natural dyes, preparation of stock solution, size paste, printing paste to various wet processing operations such as desizing, scouring, bleaching, retting of bast fibers, degumming of silk, dyeing of different textile materials, drying, sterilization and finishing, cutting and sewing of apparels. Ultrasound applications in decolorization and deterioration of toxic substances from effluent have also been discussed as bioremediation tool for moving towards sustainable textile wet processing.

7.1 Introduction

Energy plays a pivotal role in all industrial processes. In all processes, energy is absorbed, released, or transformed from one form to another. Early evolution of Earth saw just a few forms of energy; amongst them, all sound energy can be termed as an earliest form of energy for communication. With advancements in technology, sound waves are not limited to communication but have promising applications in various industries, medical field, surgery, underwater acoustics, nondestructive testing and evaluation, food and packaging industry, surface acoustic wave electronic devices, music, architecture, aerospace and aviation.

This chapter is an insight to ultrasonics and their applications to the discipline of textiles and apparel manufacturing. Ultrasonic refers to sound waves that vibrate at a frequency higher than that of human range of audibility (higher than about 20,000 Hz) (Kadam and Nayak, 2016). In simplest terms, any vibrating sound wave that passes a point at least 20,000 times per second is referred to as ultrasound as shown in Fig. 7.1 (Ensminger and Bond, 2011; Graff, 1981). The study that investigates the effect of propagation of ultrasound and their interaction with matter is termed as ultrasonics. Broadly speaking, ultrasonics also includes the diverse range of applications of ultrasound to engineering, sciences, and medicine.
Ultrasonics are propagating waves that deal with very old principles of elasticity and inertia. The cause of ultrasound generation is rapidly vibrating dense material. The air or liquor surrounding the material starts vibrating at the same frequency. These vibrations then spread out in the form of ultrasound. Ultrasonics initially called supersonics became a subject of scientific research when Langevin discovered quartz ultrasonic transducer during World War I in 1918. The discovery of ultrasound is accounted to Lazzaro Spallanzani. In 1794, he confirmed the navigation system of bats in dark is based on ultrasound (Woo, 2002). Very high–frequency sound waves were generated first of all by Francis Galton when he invented the Galton whistle in 1876 (Jacke, 1970). Being stress waves in nature, ultrasound requires a medium for transmission. It was only after 1877 when Lord Rayleigh published "The Theory of Sound," the research of sound vibration, propagation, transmission, and refraction gained impetus (Graff, 1981; Kowalski and Rybicki, 2017; Mason, 1976; Stephens, 1975).

![Fig. 7.1 Frequency range of subsonic, audible, and ultrasonic waves and their applications.](image-url)
Further, echo sounding techniques created a breakthrough when piezoelectric effect was discovered in certain crystals. Employing piezoelectric devices, underwater navigation techniques were developed in submarines that played a focal role in World War I (Woo, 2002; Wu et al., 2013). This chapter discusses on various applications of ultrasound in textile and apparel production as a tool to minimize thermal energy, water, auxiliaries, dyes, and finishes since starting from extraction of natural dyes, preparation of stock solution, size paste, printing paste to various wet processing operations such as desizing, scouring, bleaching, retting of bast fibers, degumming of silk, dyeing of different textile materials, drying, sterilization and finishing. The sustainability aspects of applying ultrasonic in fashion and textiles have also been discussed.

7.2 Phenomenon of cavitation

The core physical phenomenon underlying ultrasound is cavitation. Microbubbles appear, grow, and oscillate exceedingly rapid when a liquid is irradiated by ultrasound of suitable range. They collapse intensely as soon the acoustic pressure is high enough. Fundamentally, cavitation implies formation, growth, and collapse of cavities or vapors bubbles already present as suspension in the solid—liquid interface swayed due to pressure difference in the medium. Microjets and shock waves are generated when the collapse occurs near a solid surface. Cavitation increases the micromixing in the surrounding liquid, consequential in heat and mass transfer, and also diffusion of species inside the pores. Cavitation was first studied by Sir John Thornyroft and Sidney Barnbay in 1895. On the basis of pressure variation, cavitation can be categorized in to various groups as given below (Chen et al., 2011; Mason, 1990; Suslick, 1986):

- **Hydrodynamic cavitation**: Change in geometry of the conduit causes variation in the velocity of flow of liquid resulting in pressure variation.
- **Particle cavitation**: Liquid ruptured inside bubble chamber by an elementary particle is known as particle cavitation.
- **Acoustic cavitation**: It is the consequence of pressure variation in the liquid due to passage of an acoustic wave.
- **Optic cavitation**: When liquid is ruptured due to high-intensity light such as laser, it causes optic cavitation.

Here, it is essential to mention that only hydrodynamic cavitation and acoustic cavitation can be applied for large-scale industrial applications due to restrictions of cavitation parameters such as frequency range, size of the bubble, bubble location, and high cost parameters. The other two categories can be safely used in research and lab study.

7.2.1 Crux of cavitation

The theoretical pressure amplitude as calculated for cavitation in water depends on surface tension of water and van der Waals distance between molecules. The theoretical
formula is \(2\sigma/\text{Re}\) (here, \(\sigma\) is the surface tension of water and \(\text{Re}\) is van der Waals distance between molecules). Pure liquids have very high tensile strength, and creation of cavitation is difficult. There must be a large number of nuclei in the medium to initiate cavitation. The impurities present in the liquids in form of small solid particles, preexisting dissolved gases, or more especially, the trapped gas vapor decrease the tensile strength of liquid and facilitate in creation of cavitation.

The frequency and intensity of ultrasound play a vital role in generating stable cavitation or transient cavitation for few acoustic cycles. The high-intensity acoustic field produces transient cavitation in which microbubble grows very rapidly for one life cycle or for a few acoustic life cycles, whereas the low-intensity acoustic field produces cavitation bubble slowly over many acoustic cycles. The size of the microbubble varies from approximately 170 \(\mu\)m (at \(\sim 20\) kHz) to 3.3 \(\mu\)m (at \(\sim 1000\) kHz) (Vajnhandl and Majcen Le Marechal, 2005).

When a solid textile surface lies in the vicinity of a collapsing bubble, very high velocity microjets are formed directed towards the solid surface. These microjets are affected by initial size of bubble, distance between center of bubble, and solid surface along with intensity of ultrasound that causes the bubble to collapse. During the process, large amount of energy is released. Overall localized conditions of very high temperature and pressure are created in the reactor simultaneously, allowing ambient conditions for effective chemical reactions to occur. Transient cavitation dictates for pressure greater than 1 atm and frequencies less than 100 kHz. It is assumed that collapsing of bubble results in increase of temperature of about 2100–5500 °C inside the bubble, and liquid surround the cavity with high pressure up to 100 MPa within the collapsing cavity. Although this drastic effect is limited to a very small region, hence surrounding liquid in bulk remains at the ambient temperature only (Gogate et al., 2003; Vajnhandl and Majcen Le Marechal, 2005).

### 7.2.2 Factors affecting cavitation

Cavitation is mainly affected by (Suslick, 1986; Vajnhandl and Majcen Le Marechal, 2005):

- **(i)** Properties of the solvent
- **(ii)** Properties of gases present as nuclei
- **(iii)** Intensity of ultrasonic waves
- **(iv)** Frequency of ultrasonic waves
- **(v)** Temperature of the liquid
- **(vi)** Vapor pressure of the liquid

Cavitation is less with high-frequency ultrasonic waves as enormous energy destabilizes the cavitation. If the frequency is moderately low, less power consumption and heating favor cavitation at low intensities. The temperature of the medium plays a vital character affecting the intensity of the waves. Thus, as temperature is raised, the effect of intensity on cavitation is reduced. It has been reported that cavitation is several times greater in heterogeneous system than in a homogeneous system.
7.3 Ultrasound equipment

To all intents and purposes, ultrasound equipment comprises a generator and a convertor or cleaning bath. The generator is an ordinary power supply that converts the regular 50/60 Hz alternating current to high-frequency electrical energy, further fed to transducer and transformed to mechanical vibrations. Contemporary equipment’s use piezoelectric crystals (such as lead zirconate titanate) that expand and contract when subjected to alternating voltage. The transducer vibrates longitudinally in turn transmitting the sound waves in the liquid medium leading to cavitation.

7.4 Applications of ultrasound in various industries

Ultrasound applications have wide potential in efficient mass transfer with lesser energy requirements (Warmoeskerken et al., 2002). Thus, ultrasonic has numerous applications in chemical, pharmaceutical, food, textile industries etc., as illustrated in Fig. 7.2. Beside these, ultrasound computed tomography has great applications in process control, temperature monitoring, medical, construction, agriculture, and...
Food industry being nondestructive-based testing (NDT). The instrument consists ultrasonic wave generator and ultrasonic sensing modes along with measurement system (Khairi et al., 2019).

### 7.5 Applications of ultrasound in textile wet processing

Good looks are an appealing aspect driving human race to the next level. By birth a person may not be beautiful, but good attire sense and fashion trend is running the globe, rather ruining the world in true sense. Long before, three basic needs of humans were food, clothing, and shelter (Singh and Jajpura, 2016). Today, clothing is not simpler and graceful in sense but has evolved many changes. The textile and apparel industry is required to produce material that follows the latest trends. The textile industry plays a vital role in any country’s economy (Jajpura and Singh, 2015).

The industry entails fiber manufacturing, spinning or yarn manufacturing, weaving or fabric manufacturing, textile processing and finishing, and garment manufacturing units. The processing of textiles is complicated as it involves removal of natural and man-made added impurities in conjunction to dyeing, printing, and finishing of raw fabrics. The employability of ultrasonic especially to textile wet processing operations (scouring, bleaching, mercerization, dyeing, printing, and finishing) has raised considerable inclination as it saves a lot of energy (Nayak et al., 2008; Pai et al., 2004).

Dyes, finishes, or auxiliaries are transferred via processing liquid medium onto textile substrate in wet processing activity that is dependent on time and temperature. Compromise in any of the two affects the quality of the product. The conventional processes are tedious and consume lot of energy in controlling parameters so as to achieve uniformity in results (Jajpura, 2015). Ultrasound offers advantages in saving process time, energy, and chemicals alongside improvement in product quality. Conventional wet processing of textiles consumes large quantities of water, electricity, and thermal energy (Jajpura et al., 2004). Most processes engage chemicals for accelerating, assisting, or retarding the rate of reaction along with prerequisite of particular temperature so as to transfer mass from liquid medium across the surface of the textile material in reasonable time.

In recent times, ultrasound has taken a significant place in chemical and physical activities of the processing industries as a very effectual and unpolluted method of activation. The concerns over the environmental disorders throughout the globe restrict the discharge of effluents from process industries of chemical, leather, textile, etc. The approach of ultrasound in such processing being environment friendly and energy efficient is gaining impetus, although ultrasonic generator or ultrasonic machines may create sound pollution that needs to be dealt cautiously by the help of suitable sound absorbent solutions (Kadam and Nayak, 2016; Nayak and Padhye, 2016; Pal et al., 2015). The ultrasound has numerous applications in textile and garment manufacturing units as discussed below.


7.5.1 Preparation of homogenized solutions or pastes of sizes, auxiliaries, dyes, and finishes

These applications include preparation of solution or thickening paste of auxiliary bath, i.e., preparation of sizes, emulsions, dye dispersions in stock solution, and finishing agents.

7.5.1.1 Ultrasound-assisted size paste preparation

Sizing of yarn enhances the strength of yarn (Khandual et al., 2004). Due to sizing, the yarn can withstand mechanical forces of tension and abrasion during weaving. Starch and other sizing ingredients are mixed in water and heated above the gelatinization temperature for an hour or above and applied on to yarn surface. The conventional method of preparing viscous starch paste needs high temperature for prolonged time along with high-speed stirring for getting homogenized paste free from any lump particles. Ultrasound application in conjunction with conventional mechanical stirring reduces requirement of boiling at high temperature for prolonged time. Thus, size paste can be prepared at lower temperature in lesser time with more homogenization. Proficient homogenized sizing paste shows greater weaving efficiencies as their high adhesive power reduces the consumption of sizing materials and coats the yarn uniformly.

7.5.1.2 Ultrasound-assisted printing paste preparation

Preparing homogenized printing paste is a tedious task as various chemicals and auxiliaries need to be mixed in a thickener appropriately without any lump formation. Thus, ultrasonic-based mixing provides good efficiency in getting uniform printing paste. The ultrasonication improves blending as well as emulsification of printing paste.

Beside these, ultrasound application improves preparation of dye solutions, finishing baths, emulsification, formulation of chemicals, degassing, mixing, emulsification, microencapsulation, washing and cleaning of instruments (Jajpura et al., 2016a).

7.5.2 Application of ultrasound in preparatory wet processing

Heterogeneous systems having textile substrates subjected to ultrasonic waves are studied in this section. The ultrasonic system finds usage in almost all preparatory wet processing operations such as desizing, scouring, bleaching, washing, degumming, and retting. The rationale behind preparatory wet processing is to get rid of added and natural impurities from the fiber surface and interior to improve the absorbability of textile material for getting better penetration and diffusion of dyes and chemicals into fiber during dyeing and finishing processes. Treatment of ultrasound has been reported to enhance reaction rates, hence reducing process time of desizing and scouring even at lower temperature alongside improvement in fabric absorption and whiteness index of textile materials. Observed effects are ascribed to cavitation. When cavitation occurs at a solid—liquid interface (fiber—chemical interface), an
asymmetric thrust creates microsteam on the solid surface by disturbing diffusion interlayer and supporting mass transport in the same direction.

7.5.2.1 Ultrasound-assisted desizing

Sizing process makes the fabric harsh and less absorbent. Hence, desizing of the fabric is important to remove chemicals applied during sizing. Studies have proved that desizing with ultrasound effectively removes size and starch absorbed during sizing of the fabric. Ultrasonic-assisted desizing saves energy and chemicals in contrast to conventional sizing and desizing. Moreover, it reduces fiber degradation in supplement to increased whiteness and wetting ability of the fabric (Thakore and Abate, 2017).

7.5.2.2 Ultrasound-assisted scouring

Raw cotton comprises 4%—13% impurities based on the weight of cotton. Wax, ash, protein, pectin, and miscellaneous substances such as pigment, reducing sugar, and hemicellulose are the usual impurities found in it. The percentage of these impurities varies from region to region. Hence, purification of cotton fiber, yarn, and fabric is a must priority before its further processing. Pigments can be removed by bleaching process, while all the other listed impurities can be removed by scouring, employing alkali treatment to cotton. Usually in scouring process, cotton is boiled in sodium hydroxide (NaOH) solution consequentially increasing absorbency of fabric.

Like cotton, the other fibers such as wool, silk, and polyester, have impurities that are removed by scouring. Impurities of grease and vegetable matter are removed from wool through milder alkaline scouring using soda ash and detergent. In silk, the degumming process removes impurities. By means of ultrasound, the energy efficiency is increased as less water is required at low temperature in comparison to conventional scouring processes (Agrawal et al., 2008).

Researchers have found that ultrasound-scoured wool is more ecological having good fiber strength than conventional-scoured wool as fiber properties and rate of processing are improved via ultrasonic (McNeil and McCall, 2011). Wool fabric shows less migration of wool fibers under ultrasonic in comparison to conventional method (Hurren et al., 2008).

7.5.2.3 Ultrasound-assisted bleaching

In process of bleaching, natural coloring content is decomposed or decolourized so as to achieve desired whiteness of the fabric. Oxidants such as hydrogen peroxide are widely used in progression of cotton. Conventionally, two methods, cold bleach and boiling, are generally employed. While cold bleaching process takes approximately 16 h, boiling could achieve same effects within 2—3 h. The ultrasounds have proven to be an energy-efficient and time-saving option and hence are of great interest for bleaching process.

It has been reported that the consumption of hydrogen peroxide and bleaching efficiency of cotton material (yarn, woven, and knitted cloths) in ultrasound for 1 h are
significantly higher than those in cold bleaching for 16 h and close to those in boil for 2 1/2 h (Mistik and Yükselğolu, 2005; Moses and Jagannathan, 1996).

Similarly, investigations of the effect of ultrasonic energy on the processing of flax fibers indicated that whiteness improved over conventional scouring and bleaching operations.

### 7.5.2.4 Ultrasound-assisted preparatory wet processing of jute

Scouring, bleaching, and dyeing of jute fabric with reactive and basic dyes were studied under sonication to compare their results with traditional pretreatment and dyeing operation (Hassan and Saifullah, 2018). It was found that scoured and bleached fabric under sonication has more whiteness index and weight loss than traditional scoured and bleached fabric.

### 7.5.3 Application of ultrasound in preparatory wet processing by enzymes

Enzymes play important role in eco-friendly wet processing of textiles (Shukla et al., 2003). Being biocatalyst, they reduce activation energy of reaction and replace various traditional chemicals (Jajpura, 2018). Enzymes are extracted from bacteria, fungi, or slaughter house waste (Jajpura, 2020). Pawar and Rathod studied uricase and alkaline protease production by irradiating the fermentation broth under ultrasound (Pawar and Rathod, 2018). Fermentation broth consisted bacterial cells for multiplication with suitable nutrients in optimum conditions. It was found that yield of uricase and alkali protease was enhanced by a factor of 1.9–3.8 and 1.2–2.2, respectively (Pawar and Rathod, 2018). Thus ultrasound shows potential in improving enzyme yield in commercial production too.

In bioprocessing applications, amylases (Shukla and Jajpura, 2004), lipases, cellulose (Khandual et al., 2011), endoglucanase, cutinase, pectinase and protease, and laccase (Jajpura, 2014a), are extensively used in different preparatory wet processing operations of textiles. Although being macromolecular structure, their diffusion inside the textile substrate is limited. It is observed that mechanical agitation improves mass transfer of enzymes towards the textile substrate in various enzymatic operations.

It is reported that power ultrasound also enhances mass transfer of enzyme into the solid surface successfully (Erdem and İbrahim Bahtiyari, 2018; Szabó and Csiszár, 2013, 2017).

Idalina Gonçalves et al. (2014) employed ultrasound-assisted bleaching of cotton with combined laccase–hydrogen peroxide process. It was found that ultrasound processes enhance whiteness index of the bleached fabric.

### 7.5.4 Application of ultrasound in dyeing

Dyeing of textiles is an aspect that can never be mistreated as it brings fashion to life. For years, dyeing using ultrasound has been a subject matter of study. Both low- and high-frequency ultrasonics have been tested to study the consequences on the quality
of dispersal of dyes, change in solubility of water soluble dyes, and dye uptake by textile materials. It can be accounted that using ultrasound for dyeing, the desired results can be obtained at comparatively low temperature. Some of the dyeing studies under ultrasound are discussed in the following sections.

7.5.4.1 Ultrasound-assisted dyeing of cotton

Knitted cotton fabric was dyed by reactive dye at low temperature under the ultrasound having energy input of 0.7 W/cm² (Tissera et al., 2016). It was found in particle size analysis that hydrolyzed dye molecules were deagglomerated by ultrasonication during dyeing. Thus, higher color strength up to 230% was obtained even with dyeing at 30 °C using ultrasound as compared to normal dyeing at high temperature without ultrasound.

7.5.4.2 Ultrasound-assisted dyeing of wool

The traditional wool dyeing with acid leveling dye is carried out at 98 °C, although exposure of wool sample at this high temperature for prolong time causes fiber damage. Certain wool protective agents are being used in the dye bath to avoid the fiber damage, but most of them are toxic in nature. Thus, to overcome this difficulty, dyeing of wool fabrics was studied in the temperature range between 60 and 80 °C using mechanical agitation and ultrasound agitation of bath either alone or in combination to compare the results (Ferrero and Periolatto, 2012). It was found that dyeing with ultrasound coupled with mechanical stirring gives better synergistic results of dyeing as ultrasound enhances absorption rate constants by at least 50%, at each temperature in comparison to mechanical stirring alone.

Dyeing of wool with acid dyes in presence of ultrasound can be done even at 60 °C with satisfactory dyeing results, i.e., good wash and rubbing fastness properties. Hence, by the help of ultrasound, sustainable wool dyeing can be done at lower temperature without use of any toxic wool-protecting agents (Eren, 2012; McNeil and McCall, 2011).

7.5.4.3 Ultrasound-assisted dyeing of jute

Ultrasound was also employed in dyeing operation of jute with reactive and basic dyes. Results showed that sonication improved the color strength of dyed samples with similar color fastness properties to light, washing, and rubbing to conventional dyeing methods indicating that no degradation of dyes occurred during sonicated dyeing (Hassan and Saifullah, 2018).

7.5.4.4 Ultrasound-assisted dyeing of polyester

Polyester fiber having crystalline polymeric structure and higher glass transition temperature (Tg) needs higher dyeing temperature (130 °C) than other textile materials. Therefore, polyester dyeing is carried out at high temperature and high pressure in special pressurized closed vessels that increase the cost of dyeing operation. Although
dyeing can be performed at atmospheric pressure by using carriers, they are not eco-friendly in nature. While using ultrasound, the polyester dyeing can be accomplished at nearby 100 °C temperature and atmospheric pressure sustainably. Ultrasonic dyeing reduces the energy requirement in dyeing operation along with providing uniform dyeing.

7.5.4.5 Ultrasound-assisted dyeing of cellulose acetate

Dyeing of cellulose acetate with Disperse Red 50 was studied under the ultrasound to reduce energy and auxiliaries consumption (Udrescu et al., 2014). The study showed that best results of dyeing were obtained at 80 °C with ultrasound coupled with mechanical agitation without auxiliaries (90% dye exhaustion). It was found that ultrasound-assisted dyeing without using any additional chemicals/auxiliaries into the dye bath gives same level of color yield in remarkably shorter time as compared to dyeing alone in mechanical agitation. The fastness ratings of dyed samples even without auxiliaries under ultrasound techniques were also found good.

7.5.4.6 Ultrasound-assisted dyeing of polylactic acid

Polylactic acid (PLA) is corn-based renewable ester fiber. It is similar to polyester in number of characteristics, but it is sustainable being biodegradable and good sustainable substitute to various nonbiodegradable synthetic textile and packaging materials. PLA fiber has hydrolytic sensitivity at higher temperature used for polyester dyeing, i.e., 130–135 °C being its lower melting temperature than polyester (170 °C compared to 260 °C of polyester). Thus, dyeing of PLA fiber with disperse dye is carried out at 110–115 °C at pH 4.5–5 for 15–30 min.

Application of disperse dye on PLA fiber under the ultrasound generator was studied, and it was observed that there is increase in color strength of dyed fabric sample in certain disperse dyes. The observed improvement in color strength and brightness in PLA dyed samples was attributed to better dye dispersion in dye bath due to disaggregation of dye particles (Burkinshaw and Jeong, 2012; Lee and Kim, 2001; Wang et al., 2010).

7.5.5 Application of ultrasound in extraction of natural colorants for textiles and foods

Ultrasounds improve drying effectiveness of biological wet materials such as fruits and vegetables by convective heating. Ultrasonication is also getting interest in microwave and IR drying industrial sector due to the achieved encouraging results (Kowalski and Rybicki, 2017).

Plant-based materials are full of polyphenols and flavonoids. These materials have numerous applications in herbs as well as in coloration of textiles, foods, and good prospects in medical textiles (Jajpura et al., 2016d). But traditionally used high temperature–based extraction process has detrimental effects on valuable antioxidant properties of plants (Rani et al., 2017a; Rangi and Jajpura, 2017a,b).
Trojanowska et al. proposed ultrasound-assisted extraction and concentration of the biologically active compounds by nanofiltration (Trojanowska et al., 2019).

Application of natural coloring and finishing agents in food, textile, and leather is getting significant attention due to increase in awareness toward sustainability as well as health issues (Jajpura et al., 2016b, 2017, 2018). Hence, natural colorants derived from natural sources at cheaper cost with eco-friendly natural mordants as alternative to toxic synthetic dyes are prime research areas nowadays (Jajpura et al., 2016c; Rani et al., 2017c).

Traditionally natural extracts are extracted in aqueous media via conventional high-temperature heating, but it deteriorates various important properties of natural extract as discussed above (Rangi and Jajpura, 2017a,b; Rani et al., 2017a; Unnati et al., 2017). Thus, there is a dire need to find out suitable alternatives such as IR drying and vacuum drying alone or in conjunction with ultrasound (Souza da Silva et al., 2019).

In one of the similar study, natural colorant was extracted from harda, tamarind seed coat, turmeric, and henna using conventional and ultrasound approaches. It was found that the extent of color extraction was higher in the case of ultrasound-assisted extraction as compared to that of conventional method (Sheikh et al., 2016). In similar study, ultrasonic extraction of colorant from beetroot gave better results than conventional extraction at lower temperature and lesser time with reduction in energy consumption (Sivakumar et al., 2009).

7.5.6 Application of ultrasound in laundering and sterilization operation

The textile washing and laundering processes are energy-consuming operations due to requirement of efficient mass transfer. The process requires long processing time and large amounts of water and chemicals. Beside these, conventional operation is carried out at high temperature to intensify the mass transfer that may cause damage in textile material (Bhardwaj et al., 2018). Increasing temperature and flow rate is not always suitable as it may damage delicate multiporous complex structure of textile materials. It was observed in various experiments that generated microjets due to cavitation phenomenon improve laundering operation (Warmoeskerken et al., 2002; Xu et al., 2016). Similarly, it was also observed that ultrasonic improves detergency action in removal of particulate soil particles from textile materials (Choi et al., 2016; Gotoh and Harayama, 2013).

Decontamination or bactericidal and bacteria control of textile materials is carried out by various methods, i.e., autoclaving, UV light, plasma, natural (Jajpura et al., 2016b; Rani et al., 2017b) and chemical disinfect or finishes, for various designated medical or hygiene purposes. Similarly, decontamination of water, fresh fruits, and vegetables are also prerequisite before consumption by human beings to prevent various bacterial- and fungi-borne infections and diseases. In the same aspect, fruits were exposed to ultrasonic and the results were promising (Bilek and Turantas, 2013). Thus sterilization by ultrasonic can be also explored for textile materials fragile to high-temperature autoclaving.
7.5.7 Ultrasound in biopolymer applications in textiles

Biopolymers have numerous applications in textile and medical fields being renewable, biodegradable, and sustainable in nature (Jajpura, 2014a; Rangi and Jajpura, 2017a,b), but their macromolecular structure and solubility create problems in achieving homogeneous solution as well as uniform application on textiles surface.

One of the known biopolymer in textile is chitin obtained from sea food wastes (Martinou et al., 1995; Mima et al., 1983). It is having excellent antibacterial characteristics and applicable as finishing and auxiliary agent in various dyeing and finishing operations (Jajpura, 2014b; Jajpura et al., 2017; Ravi Kumar, 2000), although chitin is insoluble and hinders biological applications in this inert form (Jaipura et al., 2006). Thus, chitin needs to be converted into its soluble chitosan form by alkali deacetylation conversion. The ultrasound irradiation has been successfully used to improve conversion of chitin to chitosan by N-deacetylation reaction in milder condition (Zhu et al., 2019). Similarly, ultrasound also helps in formation of nanoparticle-based finishes from various biopolymers such as starch, cellulose, and sericin (Almeida et al., 2019; Rangi and Jajpura, 2015).

7.5.8 Application of ultrasound in remediation of textile effluent

The textile wet processing industry is one of the major environmental polluters being associated in discharging effluents containing various toxic, non-biodegradable chemicals, auxiliaries, dyes, and finishes. There is a dire need to deteriorate or convert harmful chemicals into less or nonharmful by-products. Among all impurities, nonbiodegradable dyes, pigments, and other coloring compounds have more adverse effects on aquatic biodiversity as they affect the aquatic life by their toxicity as well as decrease transmission of sunlight that hampers photosynthesis in aquatic plant causing depletion of dissolved oxygen in water. Thus, there is a dire need to decolorize the dyes and pigments before discharging into effluent.

It was observed that cavitation phenomenon created microbubble, which acts as microreactor, and during collapsing, it produces various free radicals and reactive species. These free radicals such as hydroxyl, hydrogen, and hydroperoxyl deteriorate various organic and inorganic compounds by oxidation and reduction reaction. Beside that, these free radicals react with each other and produce some new molecules such as hydrogen peroxide that has also great potential in oxidizing and decolorizing dyes and pigment in localized high-temperature and pressure condition of microbubble generated in ultrasonic bath (Vajnhandl and Majcen Le Marechal, 2005).

In the same concern, various researchers employed ultrasound alone or in conjunction with other technique of advanced oxidation processes such as ozonation (Ince and Tezcanlí, 2001) photocatalysis, and Fenton process (Dutta et al., 2002), electro-oxidation (Lorimer et al., 2000), or irradiation with UV (Poon et al., 1999) or plasma, for decolorization of dyes. Catalytic degradation of textile dyes and toxic chemicals (aromatic amine, phenols) was also performed under the presence of reduced graphene oxide enveloped copper phthalocyanine nanotube (Samanta et al., 2018); potassium...
permanganate (Liang et al., 2016); and TiO$_2$ (Mrowetz et al., 2003). In all the studies, it was observed that ultrasound enhances the decolorization of dyes efficiently and makes the effluent free from toxic dyes and chemicals sustainably.

### 7.5.9 Application of ultrasound in apparel production

The traditional method of fabric sewing either by lock stitch or chain stitch is very complex as it involves various moving parts of sewing machine and sewing threads (Nayak and Padhye, 2015). Beside these, formed needle hole in sewn fabrics has limitations in certain applications such as swimming suits, and parachutes, where permeation in fabric is not acceptable. In these regards, generated thermal energy of high-frequency ultrasound (20–40 kHz) can be utilized for fusing and joining of thermoplastic textile materials that contain at least 40% synthetic fibers (Ibar, 1998). This concept is being utilized in ultrasonic sewing machines for thermoplastic fabrics such as nylon, polyester, acrylic, and polythene, and their blends.

In industrial ultrasonic sewing machines, fabric layers to be sewn are fed continuously between a rotating supporting wheel and fixed vibrating horn (ultrasound generator) that generates sufficient heat to fuse the polymeric fabric layers at seam line. Machine may have sewing speed of about 30 m/min, even though quality and performance of seam are dependent on thermoplastic blend proportions as well as yarn and fabric structure (Devine, 1998).

This ultrasonic sewing operation is simpler, energy efficient, and cheaper than conventional sewing machine as it does not have moving parts such as needle, bobbin, pressure bar, etc., as well as foreign needle and bobbin threads (Ghosh and Reddy, 2009; Petrie, 2015). Sewn fabric does not have needle holes as well as extra fabric at the edge can be removed simultaneously by ultrasonic cutting from the sewing edge. Although, lower seam strength and slightly stiffer joints in comparison to traditional sewing are a great challenges in industrial exploration of ultrasonic sewing.

### 7.6 Conclusions

In a nutshell, most of the textile wet processes such as extraction of natural colorants and finishes, desizing, bleaching, dyeing, printing, finishing, and laundering, in presence of ultrasound show superior mass transfer and hence give appropriate pretreatment, dyeing, and finishing effects with reduction in consumption of energy, time, and water. In supplement, cheap overall processing costs along with environmental improvements in textile industry and apparels can be attributed to ultrasound. Ultrasound being less hazardous, sound and vibrant technology does not affect the health of textile laborers and it is cost-effective, safe, and environmental friendly and energy efficient technology. It opens avenues to use high-intensity ultrasound irradiation in eco-friendly textile and apparel production. Conclusively, ultrasound in textile and allied sectors can be an effective bioremediation tool for moving towards sustainable future.
References


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Application of laser technology

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8.1 Introduction

The textile and garment industry is one of the oldest and largest export industries. Since the industrial revolution happened in the 18th century in Britain, the nature of work in textile industry has changed from hand production to machines to automatic machines (Wulfforst et al., 2006). Nowadays, with continuing technological innovations in machinery, synthetic fibers, logistics, and globalization of the business, the whole industry is facing dynamic challenges including shorter lead times, cost pressures, higher quality demands, and environmental responsibility.

Laser is being used in apparel industry from the 19th century. Recently, the use of laser in apparel industry is increasing in cutting garment patterns, patterning designer neckties, 3D body scanning, cutting, denim fading, and engraving leather. The major reasons for wide use of laser in garment manufacturing can be attributed to reduced cost, flexibility, and anticounterfeiting. For example, the artwork of high-end necktie producers is digitally stored rather than physical patterns to lower the theft risk. When needed, the digital patterns are converted into physical samples using lasers. Recently, the application of laser in denim engraving is increasing rapidly for value addition by replacing the traditional denim-distressing technics, which will take the denim segment to a height of sophistication that can be realized by nonlaser methods. The unique nature of the garment manufacturing industry needs laser applications, which combine performance with reduced cost by eliminating the handling systems used on nonlaser workstations.

This chapter gives an overview of environmentally friendly laser technology that is being introduced in order to satisfy the growing demand for environmentally friendly finishing processes while maintaining functionality of textiles. This chapter also discusses various basic applications of laser in textile and garment manufacturing such as inspection, printing, cutting, welding, cleaning, and drilling. Laser applications to enhance surface functionality such as morphological and chemical modification, adhesion property modification, water repellency, color fading, and dyeing modifications are also covered.
8.2 Introduction of laser

8.2.1 Background of laser

“LASER” is an acronym for “Light Amplification by Stimulated Emission of Radiation” (Gross and Herrmann, 2007). The definition of the LASER is explained term-by-term, as follows:

L: “Light” describes the type of electromagnetic radiation produced which includes not only the light visible to human eyes but also what is not because they are either longer or shorter in wavelength.

A: “Amplification” means increasing the amount of light. During the process of stimulated emission, an input wave stimulates an atom or molecule to release energy as a second wave, which is identically same as the input wave. The stimulated wave can continuously stimulate other atoms or molecules to emit duplicate waves, causing further amplification, resulting in more light.

S and E: “Stimulated Emission” refers to a unique process of laser light production. Atoms and molecules spontaneously emit energy in the form of light or other types of electromagnetic radiation. However, for laser light, atoms and molecules are stimulated to emit extra energy as light.

R: “Radiation” means electromagnetic radiation, a massless form of energy that travels at the speed of light.

By definition, laser means the ability of light to stimulate the emission of light that creates the situation in which light can be amplified. The light generated by laser is very intense and contains a concentration of power within a very narrow beam in the electromagnetic spectrum regions extending from the near-infrared (above 700 nm), through the visible 400 nm (violet) to 700 nm (red) to the ultraviolet (below 400 nm) as shown in Fig. 8.1.

Laser is basically a light source, and the radiation it emits is not fundamentally different from any other form of electromagnetic radiation. However, there are several

![Fig. 8.1 The electromagnetic spectrum.](image-url)
unique properties, taken as a whole, that are not available from any other light sources to the extent that they are obtained from a laser. These unique properties are:

- High monochromaticity (small wavelength spread)
- High degree of directionality (primarily due to small beam divergence)
- High brightness (primarily due to small beam divergence)
- High degree of both spatial and temporal coherence (strong correlation in phase)
- Linear polarization
- Capability of very low (microwatts) to very high (kilowatts) continuous power output for different types of lasers.
- High peak power (terawatts) and large energy (hundreds of joules) per pulse in pulses output lasers.
- Capability of being focused to a small diffraction limited spot size (on order of the wavelength of the light).

### 8.2.2 Principle of laser

Laser action starts with establishment of a population inversion by the excitation process. When photons travel through the active medium and pass near atoms or molecules, they stimulate excited atoms or molecules to undergo radiative transitions. Since the photons are in phases and travel in the same direction and have the same polarization, amplification happens. Photons that travel nearly parallel to the axis of the optical resonator pass through a substantial portion of the active medium while others are reflected back to the active region, thus building up as stimulated radiation. The combined action of resonator and stimulated emission produces an extremely bright light source even though with only a small power.

### 8.2.3 Different types of laser

Laser types can be categorized in a number of ways. In general, they are mainly gas lasers which may include carbon dioxide lasers, carbon monoxide lasers, HeNe lasers, and excimer lasers; liquid lasers such as dye laser and solid-state lasers involve Nd: YAG (neodymium-doped yttrium aluminum garnet) lasers, Nd: glass lasers, ruby lasers, and semiconductor lasers.

#### 8.2.3.1 Gas lasers

Carbon dioxide lasers
Carbon dioxide laser (CO$_2$) is the most efficient engraving laser (Ready, 1997; Ortiz-Morales et al., 2003; Rajagopal, 2008) as its advantages include large beam size, easy operation, use of nontoxic gases, and low cost. Especially, CO$_2$ pulsed laser, unlike other infrared lasers, overcomes the shortcoming of continuous wave mode and causes no thermal damage effect (Fatima and Helena, 2007). CO$_2$ laser is not a good conductor of heat and electricity since its wavelength can be absorbed by textiles easily (Yuan et al., 2011). In general, CO$_2$ is used as lasant in addition to N$_2$ and He (Luxon and Parker, 1992). The design of a CO$_2$ laser, in common with all other lasers,
is built around the requirement of cooling; in this case to cool CO₂ gas. Firstly, the gas mixture in the laser is around 78% He for good conduction and stabilization of the plasma, 12% N₂ for coupling effect, and 10% CO₂ to do the work. The main radiation of CO₂ laser is at 10.6 μm wavelength, which is in the mid-infrared. Other properties of CO₂ laser are summarized in Table 8.1. Applications of this laser are numerous, including cutting, hole piercing, welding, heat treatment, scribing, and marking. The number of materials that can be worked is also varied, including paper, plastic, wood, glass, cloth, ceramics, and most metals.

Carbon monoxide lasers
The carbon monoxide (CO) laser is constructed in a way similar to the CO₂ laser. It has the advantage of quantum efficiency of nearly 100%, and thus it promises wall plug efficiency twice that of the CO₂ laser. However, the CO laser currently operates best at very low temperature of around 150 °K and requires extensive power for refrigeration, which may affect this potential efficiency advantage.

Excimer lasers
Excimer laser derives its name from the contraction of excited dimer (molecule made up of two similar atoms) molecules (diatomic molecule in an excited state), which are the lasing species and refer to a class of lasers that produce radiation in the UV region of the spectrum. The molecules in an excimer laser are made up of a halogen and an inert gas atom. Such molecules are only formed when halogen atom is in excited state. Although the bond is very strong, the excited molecules are very short lived. When the halogen atom undergoes a transition to the ground state, the bond breaks and releases a comparatively high energy photon. The transitions are then stimulated and laser action is achieved. Several gas mixtures are used in an excimer laser, usually noble

<table>
<thead>
<tr>
<th>Table 8.1 Performance characteristics of CO₂ lasers (Luxon and Parker, 1992; Perriere et al., 2006).</th>
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</thead>
<tbody>
<tr>
<td>Wavelength (μm)</td>
</tr>
<tr>
<td>Lasant</td>
</tr>
<tr>
<td>Operation mode</td>
</tr>
<tr>
<td>Average output power (W)</td>
</tr>
<tr>
<td>Pulse energy (J/pulse)</td>
</tr>
<tr>
<td>Beam diameter (mm)</td>
</tr>
<tr>
<td>Beam divergence (mrad)</td>
</tr>
<tr>
<td>Repetition rate (pulses/s)</td>
</tr>
<tr>
<td>Excitation techniques</td>
</tr>
</tbody>
</table>
gases (Table 8.2). Because of the short lifetime of the excimer molecules, the pulses are usually very short, around 20 ns, but very powerful, typically around 35 MW.

**HeNe lasers**

HeNe is the first gas laser with a wavelength of 1.15 nm near-infrared beams and is used as pilot-laser. Today, HeNe laser with a wavelength of 633 nm (Hecht, 1992) is the most common visible output laser. This laser operates with He as the host and Ne as the lasant. It is a highly reliable but low-cost laser, and its power levels can range from microwatts to about 50 mW continuous. The mean of excitation of this laser is a DC glow discharge. Unlike other gas lasers, gas atoms that participate in the process are not ionized and thus HeNe laser is recognized as a neutral gas laser. The output wavelength is 0.6328 nm for most applications such as displacement measurement, holography, pattern recognition, communications, and surface finish analysis.

### 8.2.3.2 Liquid lasers

**Dye lasers**

Dye lasers are one of the most readily turnable lasers (Perriere et al., 2006). They can operate at high power from milliwatts to watts. The lasant is an organic dye as it can fluoresce in a large number of lines so the laser can emit over a wide range of wavelengths by changing the concentration of the dye as well as pressure (Bridges, 1964).

<table>
<thead>
<tr>
<th>Gas mixture</th>
<th>Wavelength (nm)</th>
</tr>
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<tbody>
<tr>
<td>F₂ (fluorine)</td>
<td>158</td>
</tr>
<tr>
<td>ArF (argon fluoride)</td>
<td>193</td>
</tr>
<tr>
<td>KrCl (chromium(III) chloride)</td>
<td>222</td>
</tr>
<tr>
<td>KrF (krypton difluoride)</td>
<td>248</td>
</tr>
<tr>
<td>XeCl (xenon monochloride)</td>
<td>308</td>
</tr>
<tr>
<td>XeF (xenon monofluoride)</td>
<td>354</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dye chemical class</th>
<th>Wavelength (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oligophenylenes</td>
<td>320–420</td>
</tr>
<tr>
<td>Coumarins</td>
<td>400–620</td>
</tr>
<tr>
<td>Xanthenes</td>
<td>520–700</td>
</tr>
<tr>
<td>Merocyanines</td>
<td>620–720, 810–880</td>
</tr>
<tr>
<td>Cyanines</td>
<td>720–1200</td>
</tr>
</tbody>
</table>
Table 8.3 shows the emission wavelength for various dye chemical classes. The output of this laser is normally pulsed, which is pumped by xenon lamps, argon lasers, nitrogen lasers, excimer laser, or frequency multiplied Nd-YAG lasers. Its applications include spectroscopy, photochemical, reaction studies, pollution detection, and surgery.

8.2.3.3 Solid-state lasers

The main industrial solid-state lasers include Nd$^{3+}$:YAG, Nd:glass and ruby lasers. The advantage of solid-state lasers is their excited states have a relatively long lifetime, which could allow a higher and better energy storage than other lasers. Very high peak powers in short pulses can be achieved in solid-state lasers.

Nd:YAG lasers

Nd:YAG stands for neodymium-doped yttrium aluminum garnet, which is a colorless synthetic crystal with chemical formula of Y$_3$Al$_5$O$_{12}$. The lasant of these lasers is the triple-ionized neodymium atoms (Nd$^{3+}$) and the output wavelength is 1.06 nm, which is near the infrared region. Applications of Nd:YAG lasers are welding, cutting, hole piercing, and excitation of dye lasers.

Nd:glass lasers

Nd:glass lasers are similar to Nd:YAG lasers in that both have Nd$^{3+}$ atoms as the lasant and operate at the wavelength of 1.06 nm. It operates at pulsed mode with low repetition rates, approximately 1 Hz, due to the poor thermal characteristics of glass. Compared with Nd:YAG lasers, Nd:glass has a better energy conversion and thus extremely high peaks of power can be achieved. Nd:glass lasers are usually applied on cutting, hole piercing, and laser fusion experiments.

Ruby lasers

The first ruby laser for commercial use was introduced by Maiman (Maiman, 1960). Aluminum oxide (Al$_2$O$_3$) and Cr$^{3+}$ (triple-ionized chromium ions) are the host and the lasant for ruby lasers, respectively. This laser operates in pulsed mode with an output wavelength of 0.6943 nm. Capacitive discharge through flash lamp is necessary as the means of excitation. As it can generate many joules of energy in a single pulse, it has been applied for drilling diamonds, sending pulses to the mood, spot welding, hole piercing, and pulsed holography.

Semiconductor lasers

Semiconductor lasers are the most important tool for (i) direct application to surface heating and welding and (ii) pumping solid-state lasers. One example of semiconductor laser is diode laser, which is currently the most efficient device for converting electrical energy into optical energy. It is a distant cousin of the light-emitting diode (LED) in that it is a semiconductor diode, which emits light. However, in
comparison, diode laser emits coherent radiation with a much narrower wavelength
spread than the incoherent emission of an LED. Although diode laser is small with
only 250 µm on a side by 50 µm thick, it can emit peak power of many watts in
100–200 ns pulses with an average power output of several milliwatts at a wavelength
close to 0.9 nm. Applications of these lasers can be found in fiber-optic communica-
tions, pattern recognition, pollution detection and control.

8.2.4 Factors affecting laser treatment

8.2.4.1 Dots per inch—intensity

The resolution is refined as a variable to control the intensity of the laser spot in a
particular area, which is expressed in terms of dots per inch. A higher number
of dots per inch means more dots per square inch and a higher resolution
(Kan et al., 2010).

8.2.4.2 Pixel time—time variation of output power

It is the time of the laser head positioning on each image point. Pulse beams generated
by laser vary in length, typically from milliseconds (10⁻³ s) to femtoseconds (10⁻¹⁵ s).
Generally, pulses are repeated within a range from once a minute to billions of times a
second. The unit of repetition rate is hertz or pulses per second. A longer pixel time
means that more energy will be focused on the fabric.

8.2.4.3 Laser power energy—beam power

Beam power measures the amount of energy a laser beam delivers per unit time. It is
measured in watts and defined by the formula

$$\text{Power} = \Delta \text{energy}/\Delta \text{time} \quad \text{(Hecht, 2008)}$$

One watt of power equals to one joule (of energy) per second. The power of steady
laser beams ranges from less than a milliwatt (0.001 W) to kilowatts (thousands of
watts).

8.2.4.4 Gray scale percentage

Besides setting processing parameters like resolution and pixel time, the pattern to be
engraved on the fabric is required to be converted into gray scale before treatment. So
color intensity of the image is crucial to result in terms of the color shade on the fabric
after treatment. The higher the color intensity of the image, the lighter is the color
shade as more dye molecules are removed.
8.3 Application of laser technology

8.3.1 General application

Since the first laser became operational in 1960, created by pumping flashes of light into a small cube of ruby crystal (Garwin and Lincoln, 2003), hundreds of developments of different laser varieties and thousands of applications ranging from precision measurement to materials processing to medicine have been reported in literature.

A large number of studies focused on laser have been conducted since the first laser ablation was reported in 1982 (Kawamura et al., 1982; Srinivasan and Mayne-Banton, 1982; Srinivasan and Leigh, 1982). During the past 20 years, technologies required for various key areas of material processing based on customer demand have motivated the development of novel alternative techniques, which are able to respond to the need for more precision, higher resolution, variability, flexibility, and better surface. In this case, laser as one of the major inventions of the 20th century, helps meet different requirements of certain applications. Its intrinsic properties make it a powerful tool, and it is playing a unique role in structural or morphological modifications of materials in modern science and technology (Folkes, 1994).

8.3.2 Inspection

Laser can be used for identifying defects, reading barcodes and fingerprints, and detecting debris. Mechanism of detecting defects using laser is through either by focusing the laser beam as a line or by scanning the surface of an object. The size of the defects can be as small as 0.25 mm wide and 3 mm long, and the location of the defects can be automatically marked (Cowdery, 2002; Steen and Mazumder, 2010).

Supermarkets routinely read barcodes with scanning systems (Fig. 8.2). The barcode reader consists of a laser that could scan the barcode by passing it through a set of lines. The reflected light from the barcode is detected by a photodetector, which could record the frequency pattern and compares this with a directory to identify the goods (Steen and Mazumder, 2010). The laser is usually a diode or an He–Ne laser operating in the red waveband (Perriere et al., 2006).

Fingerprint detection is achieved by using laser to create fluorescence. Besides fingerprint, another example of using fluorescence generated by laser can be found in explosive detection at airports and other public places. A single laser pulse violet is directed across the luggage conveyor and the pulse may break down any TNT (trinitrotoluene) vapor into Nitrogen oxide giving a fluorescent signature. This technique is able to detect nitrogen-based explosives from approximately 10 m distance (Hogan, 2002).

8.3.3 Analytical technique

Chemical sensing known as laser-induced mass spectroscopy (LIMS) and laser-induced breakdown spectroscopy (LIBS) are accomplished by striking the material to be analyzed, which evaporates a small part of the surface. The vapor is sucked
into a mass spectrometer and analyzes it for the prior one. The latter one is through analyzing the spectrum from laser-generated sparks on the surface of the material. Different plastic materials for recycling can be sorted automatically using these kinds of techniques (Perriere et al., 2006; Nayak et al., 2008).

8.3.4 Heat source for textile processing

The radiation from a CO₂ laser can be typically focused to around 0.2 mm diameter. The power density is 0.6 × 10⁵ W mm⁻². Thus, laser offers a high power density available in extremely short periods of time. It is one of the most flexible and easily automated industrial energy sources to be used in industry. Today, CO₂ laser is used for the production processes in cutting, welding as well as surface treatments. CO₂ laser can also be applied for heat treatment, alloying, direct metal deposition, cleaning, marking, and engraving. Besides all these, it can be considered for replacing the traditional method for ignition of howitzer shells to avoid logistic and storage problems as well (Perriere et al., 2006).

8.3.5 Medical use

The interaction of laser radiation with biological tissue has led to phototherapy, which uses laser as a heat source to cut and weld tissue and encourages fluid flow within the body. To be specific, laser applications in medical aspects include eye surgery, general surgery, and dermatology (Perriere et al., 2006).
8.3.6 Printing
Laser printers are popular because of the high-speed printing they offer, with the capability of scanning 21,000 lines per minute from digital data. The high speed is made possible by forming an electrostatic field on a selenium drum and the pattern of the field is then transmitted by the laser beam driven from the computer data string (Perriere et al., 2006).

8.3.7 Laser cutting
Laser can be applied for industrial cutting, and it can provide neatest and fastest profile in the cutting processes (Nayak and Padhye, 2016). During cutting, the laser evaporates the material and the hole is traversed to make a cut. There are many advantages of using laser cutting instead of traditional methods, which are mentioned below (Dawson, 1996):

- A very narrow kerf width can be produced,
- The cut edge can be smooth and clean without burr,
- The operation is fast as nearly all materials can be cut,
- In the case of cutting die board, the laser process takes around one-tenth of the time the traditional method takes,
- In some cases, even stacks of materials can be cut as the process is flexible with mainly program changes,
- Not many tool changes are required,
- Relatively little fume and dust are produced during cutting which gives a better working environment, and
- Since the process is a noncontact cutting, no tool wear occurs which is highly preferable compared to traditional methods.

CO₂ laser, YAG, and excimer lasers are found to be commonly used for laser cutting (Perriere et al., 2006). The applications of laser cutting are numerous, from cloth cutting, fiber glass cutting, ship building, paper cutting to aerospace materials. One of the largest applications is in prototype car production (Roessler, 1990; Steen and Mazumder, 2010).

8.3.8 Laser drilling
Laser can be used for drilling holes in diamond dies for wire extrusion. Recently, precision laser-drilled holes can be used for different of applications with the advantages of fast drilling speed, precise control of size of diameter, and shape of hole to be drilled at any angle. One of the major applications of laser drilling is boundary layer film cooling in jet engine components such as turbine blades and combustion chambers (Steen and Mazumder, 2010).

8.3.9 Laser welding
Welding is the process of joining materials, usually metals or thermoplastics. Laser welding facilitates high speed with high quality and is easily incorporated in automated
welding tools when compared with different traditional welding processes. Applications of laser welding include three-dimensional welding of car and aircraft components, shipbuilding, welding fabrics for joining fabric without stitching through heat sealing (Perriere et al., 2006), and even underwater welding, which cannot be done through electric arc or flames at high pressure underwater, but a laser beam can pass through fiber even several kilometers below the surface (Shannon et al., 1997).

### 8.3.10 Laser cleaning

The implementation of many industrial activities such as automotive, aerospace, or rail requires precise control of different surfaces involved in the processes. For instance, metallic surfaces must be cleaned before welding because the presence of oxides increases the tendency of brittle behavior of the joint and decreases its mechanical strength (Perriere et al., 2006). Cleaning is one of the major steps in preparation of these surfaces. With the introduction of the Montreal protocol which proposes long-term reduction of organic solvents such as chlorofluorocarbon (CFC) that are often used in industrial cleaning, laser cleaning is growing in importance.

Applications of laser cleaning are found in a wide range of fields including cleaning of artworks and antiquities, nuclear and biological decontamination, mold cleaning in aeronautic industry, and particle removal in microelectronics and optronics. Among all these applications, the main area of current usage of laser cleaning is in the conservation of cultural heritage (Steen and Mazumder, 2010). It can selectively remove the polluting layers and leave the original delicate surface unaffected. Applications may include removal of polymerized material from painting and restoration of paintings (Georgiou et al., 1998), cleaning of marble and limestone sculptures (Cooper et al., 1992; Cooper, 1998) which may involve removal of biological encrustation like fungi or lichen on the surface, cleaning and restoration of manuscripts (Kolar et al., 2010), and conservation of a wide range of museum artifacts (Steen and Mazumder, 2010).

Removal of surface soiling using Nd: YAG laser is reported to be used on organic fibrous materials such as linen, cotton, silk and wool (Tam et al., 1998; Georgiou et al., 1998). The cleaning process is based on laser ablation of three main mechanisms, which are thermal, mechanical, and photochemical. Lasers used for the development of cleaning processes are pulsed lasers, mainly UV excimer lasers and YAG lasers (Perriere et al., 2006).

### 8.4 Laser application in fashion and textile industry

The surface structure of fibers has a great influence on their properties in processing and usage (Kesting et al., 1990). The irradiation of polymeric materials by laser generates characteristic modifications of the surface topography of the polymer. The resulting surface properties may have an important impact in textile processing as they can improve technical properties of fibers such as friction, wetting behavior, adsorption ability, reflection of light, and adhesion properties of fiber or fabric, which
may include improvement in adhesion of dyestuff pigments in dyeing process (Bahners et al., 1992). This not only affects the processing but also defines a textile’s properties in certain applications such as dyeing (Lau et al., 1997). Besides the above applications, it is also shown that laser has the potential for application in design of the optical appearance of fibers through the modification of fiber surface topography (Bahners et al., 1992).

Surface modification using laser in order to improve surface performance can take place in a variety of forms, depending on the laser type and material. Three main types of laser used in surface modification are carbon dioxide (CO\textsubscript{2}) laser, Nd:YAG laser, and the excimer laser (Folkes, 1994). In surface modification, the interaction time between laser and substrate determines which process will occur. For the two commonly used IR lasers, CO\textsubscript{2} laser and Nd:YAG laser, surface modification usually takes place through a heat-related process. Excimer laser is a type of UV laser, which modifies the substrate through a photochemical process (Folkes, 1994).

### 8.4.1 Morphological and chemical modifications

Surface morphology and chemical structure of polyester fibers are found to be altered after UV excimer laser irradiation (Watanabe and Yamamota, 1997; Knittel et al., 1997a,b; Zeng and Netravali, 2006). Periodic, roll-like, or ripple structures in range of microns are created, perpendicular to the axis of the fiber from laser ablation (Kesting et al., 1990; Wong et al., 2001a,b). Also, mean distance between rolls increases with increasing number of pulses applied and laser fluence (Knittel et al., 1997a,b). A more coarse structure is formed due to the merging together of tiny rolls created from early pulses. This induced structure has proven to be durable against acidic or alkaline solutions and other conditions during textile processing (Lau et al., 1997).

Changes of chemical structure after laser treatment include conversion of ester groups to carboxylic acid groups, which results in a decrease of ester group and C—O stretching vibration (Watanabe and Yamamota, 1997). There is also an increase of O:C ratio due to the degradation reaction on surface of PET (polyester) fabric. Laser irradiation also causes decrease in the size of crystalline regions and increase of amorphous region (Bahners et al., 1992).

Moreover, surface luster and air permeability of polyester fabric improved after UV excimer laser irradiation (Kesting et al., 1990; Lau et al., 1997). Laser-treated polyester fabric has a lower glossiness, which means the fabric surface is more natural silk-like that diffuses the incident light more evenly and eventually reduces the specular reflection (Lau et al., 1997). The air permeability improves due to the ripple structure created on the fiber surface which provides more air space between fibers and fabrics and thus more air can pass through the fabric.

Besides polyester fibers, ripple-like structures of micrometer size perpendicular to the fiber axis are also found in polyamide fibers after treatment with UV excimer laser (Yip et al., 2004). The formation of these ripple-like structures induces the increase of surface roughness which greatly enlarges the fiber surface area and diffuses reflection (Yip et al., 2002).
There is also change to the chemical structure of polyamide after laser treatment (Yip et al., 2004). Carbon content and amount of amine end groups are both changed according to different amounts of laser energy and number of pulses applied during treatment (Yip et al., 2003a,b, 2004). Oxygen content is found to be increased after laser treatment which is due to the subsequent reaction of the laser irradiated surface with atmospheric oxygen during irradiation, and this further leads to oxidation of hydrocarbon groups to hydroxyl groups on the fiber surface (Wong et al., 2001a,b; Yip et al., 2003a,b). Degree of crystallinity can be slightly reduced using laser through thermal effect. During the laser treatment, due to thermal gradient (Yip et al., 2002), a very thin layer of polyamide polymer melts and cools down so rapidly that it does not have enough time for recrystallization. However, this drop of crystallinity is not very significant, thus UV excimer laser is regarded as good on polyamide’s surface treatment, since it does not alter the fiber bulk properties (Yip et al., 2002).

8.4.2 Modification of adhesion property

Dark shade is usually difficult to obtain in case of synthetic fibers due to their smooth surface. According to the laws of light reflection, about 5% of the incident light is directly reflected (toward the observer’s eye) (Knittel and Schollmeyer, 1998a,b). By using UV excimer laser before dyeing, greater depth of shade can be achieved in polyester and polyamide fabrics (Kesting et al., 1990; Watanabe and Yamamota, 1999; Yip et al., 2002). The improvement in dyeing is due to the change of morphology, formation of ripples structure, which increases the overall surface area of the fiber (Lau et al., 1997). Dye particles are believed to be captured in the ripple-like structure, and the unevenness of the fiber surface causes scattering of light (Yip et al., 2002). Besides, laser ablation also causes change of chemical structure with the increase of amorphous regions and decrease of crystalline regions, all of which result in greater dye uptake. Due to the above reasons, adhesion properties of the fabric to the dyestuff is improved and dye is able to be diffused and absorbed into the fibers more easily, quickly, and in larger amounts (Lau et al., 1997; Watanabe and Yamamota, 1999), and so dyeability is improved.

Besides improved adhesion between dyestuffs and the fibers, laser is also reported to have resulted in enhancement of fiber-particle adhesion for clean-room applications such as filtration in surgical rooms or electronic industry (Kesting et al., 1990; Bahners et al., 1992). Through laser treatment, grooves are created on the fiber surface, and this helps to collect very small dust particles smaller than 5 μm, which would not be captured on a smooth fiber.

Another area of adhesion improvement is in pigment printing of synthetics. In pigment printing, a major prerequisite is strong adherence of polymeric binder system to the fabric. It has been proved that laser treatment can improve the adhesion of the binder and improves both washing and rubbing fastness of polyester and polyamide fabrics (Dawon and Hawkyard, 2000).
8.4.3 Water repellency

Hydrophobicity of polyester fibers is reported to be enhanced after UV excimer laser treatment (Lau et al., 1997; Wong et al., 2001a, b). Since the fiber surface roughness is increased due to the formation of ripple structure from laser irradiation, this provides room for air to be trapped between liquid and solid interface. It is known as composite interface in preventing water penetration (Chan, 1994). Also, during laser treatment, there is deposition of yellow to brown or black materials called debris (Yeh, 1986; Taylor et al., 1988; Knittel and Schollmeyer, 1998a, b). This debris is ionized and is carbon-rich material that finally gets condensed and forms higher aggregates (Gutfeld and Srinivasan, 1987; Srinivasan et al., 1987), resulting in a more hydrophobic surface (Knittel and Schollmeyer, 1998a, b).

8.4.4 Color fading effect on denim fabric

The production of discolored denim fabric is possible by using Nd:YAG and CTH (chromium, thulium, holmium):YAG laser (Dascalu et al., 2000; Ortiz-Morales et al., 2003) rather than conventional technologies to prevent any by-products such as large quantities of polluted water. Besides, the laser-faded material does not lose its qualities. Instead, some properties such as tear strength and shrinkage, are better than the treated materials produced by conventional technologies (Ortiz-Morales et al., 2003). The removal of indigo from textiles by using laser can be done through four physical phenomena: vaporization, photoablation, plasma-induced ablation, and shock waves (Niemz, 2010). For the case of Nd:YAG, it was reported that interaction of phenomena are plasma-induced photoablation and shock wave generation (Dascalu et al., 2000).

8.4.5 3D body scanning

Three-dimensional body scanning using laser technology is one of the many techniques used for human body measurement. Laser scanning technology uses one or multiple thin and sharp stripe lasers to measure body size. Cameras are also used in laser scanning technology. The body measurements are derived by applying simple geometrical rules. In order to confirm the harmlessness of the beam, only eye-safe lasers can be used. The laser 3D body scanning is shown in Fig. 8.3.

8.5 Application of CO2 laser in textile industry

8.5.1 Importance of CO2 laser in textile industry

There are several advantages of CO2 laser over other types of lasers, which make it unique for application in textiles industry (Nayak et al., 2008). The advantages are summarized in Table 8.4.
Table 8.4  Advantages of CO\textsubscript{2} laser.

<table>
<thead>
<tr>
<th>Ease of application</th>
<th>The energy from the laser can be applied directly on the object with controllable power and intensity to obtain desired results.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide range of applications</td>
<td>The application range of laser is wide from cutting to modifying characteristics of different kinds of materials.</td>
</tr>
<tr>
<td>High efficiency</td>
<td>CO\textsubscript{2} laser has higher efficiency than other types of lasers, which makes it suitable for application on fabric.</td>
</tr>
<tr>
<td>Computer control</td>
<td>The computer-aided infrared CO\textsubscript{2} laser has large beam size, ease of operation, and flexibility to allow replication.</td>
</tr>
<tr>
<td>Nature of gas</td>
<td>Use of CO\textsubscript{2} gas is nontoxic and is relatively inexpensive.</td>
</tr>
</tbody>
</table>

Fig. 8.3 Three-dimensional body scanner using laser technology.  
8.5.2 Dyeability and chemical modification

8.5.2.1 Polyamide

It is reported that polyamide fabrics pretreated with CO₂ laser before dyeing can result in a darker shade because of improvement of dye absorption (Fatima and Helena, 2007; Bathiyari, 2011). After laser modification, it was found that there is breakage of the amide linkages and formation of free amino groups (Bathiyari, 2011). The decrease of crystallinity and increase of amorphous region caused by laser irradiation allow more dye uptake and thus improve the dyeability of polyamide fabrics.

8.5.2.2 Polyester

Crystallinity of polyester in the surface region decreases and amorphism increases after CO₂ laser irradiation (Dadsetan et al., 1999). Formation of oxidized groups like hydroperoxides, hydroxyl, and additional carbonyl functions from the interaction of peroxy radicals were also reported on polyester after laser irradiation, which can lead to the decrease of contact angle (Dadsetan et al., 1999). Thus, dyeability of polyester fibers can be improved (Fatima and Helena, 2007).

8.5.2.3 Cotton

Chemical and elemental composition of cotton changes after laser irradiation (Chow et al., 2011a,b). It is reported that intensities of oxygen and nitrogen increase as carbon decreases after laser treatment. The decrease of carbon could be due to the etching away of some parts of surface fibers, causing carbonization. On the other hand, the reason for increased intensities of oxygen and nitrogen may be thermal oxidation at the fiber surface. Also, since the treatment is carried out in atmospheric condition, there is subsequent reaction of laser irradiated surface with atmospheric oxygen and nitrogen.

8.5.3 Physical modification of surface morphology

The purpose of polymer fiber surface treatment by laser irradiation is to modify the surface layer so that fiber properties such as wettability, printability, and dye uptake can be enhanced while maintaining other desirable bulk properties (Liston et al., 1993; Chou et al., 2010; Folkes, 1994). Surface treatment can be applied through the introduction of functional or polar groups onto the fiber surface.

8.5.3.1 Wool

Surface morphology of wool fibers can be modified through laser treatment, and this can reduce the felting shrinkage of wool fabrics (Nourbakhsh et al., 2011). The etching effect on wool fibers causes removal of scale edges by laser irradiation, which is an alternative wool processing method to replace traditional environmental contaminating chlorine treatment. Through the antifelting effect caused by laser treatment, dimensional stability of wool fabric is improved.
8.5.3.2 Cotton

CO\textsubscript{2} laser affects the structure of textile fibers (Dascalu et al., 2000) and can cause spongelike structure with pores and craters of various sizes on cotton fibers (Chow et al., 2011a,b; Stepankova et al., 2011). The formation of pores is due to thermal degradation of cotton (Ferrero et al., 2002; Kan et al., 2010). During the treatment, the fibers absorb thermal energy produced by laser treatment and at the same time, gaseous products such as water vapor and carbon dioxide are generated, leading to swelling and expansion of the fiber due to increment of internal volume and thus, fiber surface is exposed, with the result that pores are formed on its surface (Kan et al., 2012). The effect is limited to surface or a few layers of fibers only due to the low penetration of laser irradiation (Stepankova et al., 2011). Due to the etching away of cotton fibers from laser treatment, short fibers with free ends emerge. This causes unevenness and increases fiber surface roughness.

8.5.3.3 Polyester and polyamide

Surface modification of microfiber of polyamide and polyester has been successfully performed through the use of pulsed CO\textsubscript{2} lasers (Brannon and Lankard, 1986; Dyer et al., 1989; Dadsetan et al., 1999). Morphological modifications on polyester fibers after laser treatment include irregularity of the surface and certain roughness caused by the thermal effect (Fatima and Helena, 2007).

8.5.3.4 Linen

Linen treated with laser irradiation presents surface degradation with spongelike structure presumably due to the swelling and evolution of gaseous products (Ferrero et al., 2002).

8.5.4 Wettability

Hydrophilicity is a characteristic of materials exhibiting an affinity for water which can be expressed in terms of wettability (Dadbin, 2002). Hydrophilic materials readily absorb water.

8.5.4.1 Wool

Wettability of wool fabrics can be improved through laser treatment as it can remove fragments of epicuticle from fiber surface (Shirin et al., 2011).

8.5.4.2 Polyethylene

Wettability of polyethylene fibers is increased with the exposure of CO\textsubscript{2} laser (Dadbin, 2002). Since laser irradiation is carried out under an atmospheric environment which contains some quantity of diffused oxygen, the diffused oxygen reacts quickly with the free radicals generated on irradiation and causes oxidation.
The oxidized structure of polyethylene after laser treatment results in increase of hydrophilic sites on the fiber surface. Hence, the fiber can readily absorb more water.

### 8.5.5 Wicking

Wicking property of cotton fabrics is improved with CO\textsubscript{2} laser treatment (Chow et al., 2011a,b). Due to the etching effect of laser irradiation, fiber surface gets modified with pores of various sizes which increases the roughness of the surface and hence, liquid can spread easily along those pores and produce a sufficient capillary action to transport and retain the liquid.

### 8.5.6 Color fastness

There is an improvement in color fastness of indigo-dyed cotton fabric after it is subjected to laser treatment (Chow et al., 2011a,b). During the treatment, dyed fiber and unfixed dyes are removed by the laser etching effect. Thus, less of unfixed dye gets removed and transferred on rubbing.

### 8.5.7 Design

#### 8.5.7.1 Color fading effect

Decolorization of indigo-dyed cotton fabric or denim is done by using CO\textsubscript{2} laser, which has higher efficiency than other lasers (Dascalu et al., 2000; Ortiz-Morales et al., 2003; Ozguney et al., 2009; Kan et al., 2010, 2012; Stepankova et al., 2010). The focused laser beam is swept over the interaction area by combining two perpendicular movements of either the laser head or the table in both directions. The faded pattern consists of a raster-type “image” of closely spaced scan lines. In the CW mode the scan lines are continuous, while in pulse mode they consist of small circles partially overlapped (Ortiz-Morales et al., 2003).

After treatment, the fabric has a paler surface (Kan et al., 2012) because of the irradiation, which causes decomposition of dye (Stepankova et al., 2010) or photodecomposition of the coloring agent by thermal effect while leaving the underlying textile material undamaged (Dascalu et al., 2000; Kan et al., 2010). Vaporization happens when the fabric surface continuously absorbs energy from laser irradiation during treatment. The dye on the fabric surface is vaporized and diffused away into the surrounding atmosphere (Dascalu et al., 2000; Kan et al., 2010). Different process parameters can be used, and dye on the fabric can be removed with different depths to create different shades and hence, a color fading effect. Color fading of textile fabrics with laser treatment yields better properties such as higher tear strength and resistance to shrinkage than fabrics treated with conventional methods (Ortiz-Morales et al., 2003).

#### 8.5.7.2 Pattern creation

Designs or patterns can be created on textile materials by changing dye molecules in the fabric and alternation of its color quality values by directing laser to the material
It is reported that with the use of laser, patterns can be produced on cotton fabrics in a much shorter time compared with pigment printing, and also patterns created by laser show a better fastness property (Ozguney, 2007).

**8.5.7.3 Novel decorative fashion design**

Besides engraving sophisticated patterns with different shapes and gray colors with different grades on fabrics, CO₂ laser can be used to create three-dimensional visual effects similar to tie-dye effect without the use of chemicals or dyeing (Yuan et al., 2011). Fabrics are arranged into different shapes such as crumpled, pleated, and tied so that after laser engraving, floral, pleated, and even tie-dyed patterns with diverse gradient effects can be produced.

**8.5.8 Microfiber production**

Microfibers like polyester, nylon 6, and polypropylene can be produced by heating from irradiation of CO₂ laser, and the annealed fiber has the same tensile properties (Suzuki and Mochizuki, 2003; Suzuki and Kamata, 2004a,b; Suzuki and Narusue, 2004). Production of microfiber using CO₂ laser is easier than conventional technologies, such as conjugate spinning, melt blowing, and flash spinning. Also, through the application of CO₂ laser, polyester and nylon 6 fibers are produced with improved mechanical properties such as high strength (Suzuki and Mochiduki, 2001; Suzuki and Ishihara, 2002).

**8.6 Artificial neural network prediction of color properties of laser-treated fabric**

Using laser rather than conventional techniques can offer the advantage of less pollution without chemicals and water consumption (Ortiz-Morales et al., 2003; Tarhan and Sariisik, 2009; Dascalu et al., 2000). At the same time, laser allows short time and high-precision process with little or no damage and deformation of the texture of the fabric (Dascalu et al., 2000; Ozguney, 2007). Since color properties play an important role in determining the color fading effect during laser treatment (Ortiz-Morales et al., 2003; Dascalu et al., 2000; Ondogan et al., 2005), it is necessary to examine effects of different processing variables and also the gray scale (lightness percentage) of image being transferred to be set, in order to have better control during treatment, for achieving the desired effect. Before inputting the image to the laser system, conversion of the image from colored into gray scale is required. The gray scale which expresses the lightness percentage of the image affects color properties of fabrics after laser treatment. On the other hand, literature review shows that there is a wide application of artificial neural network (ANN) approach in the textile field. They include fabric hand prediction (Yu et al., 2010), prediction of spirality degree of fibers.
(Murrells et al., 2009), and fabric properties prediction (Majumdar and Majumdar, 2004; Beltran et al., 2006). Through the ANN, Kan’s group achieved very good results in color properties prediction on different types of cotton fabrics, e.g., 100% cotton knitted fabric (Kan and Song, 2016), denim fabric (Hung et al., 2014), cotton-spandex fabric (Hung et al., 2012), and 100% cotton woven fabric (Hung et al., 2011).

8.7 Conclusions

The tailor makes the man. There is no doubt that consumer behavior toward clothing is changing nowadays requiring not only protection and warmth but also stylish and individuality. With the prevailing trend of fast changing fashion, fast supply chains, and high flexibility, e.g., “quality and quantity” have to be achieved not only for the first time, but also for every time in a quick approach. Thus, traditional finishing methods are not enough to fulfill the needs of this fast changing market. With the current concern over environmental issues that is reaching a feverish pitch, new finishing technologies are required and expected. The concept of laser technology with computer integration not only saves water and chemicals which give valuable environmental benefits but also allows customers to involve in design stage through information technology.

In garment manufacturing, the major type of laser is CO2 gas lasers, which has many successful applications. Laser technique is entirely different from traditional textile processes, as it has the flexibility in design and operation without any pollution or waste material. There are several other advantages of using laser over the conventional methods in textile and garment manufacturing. In addition, laser involves lower risk of product damage, use of low consumables, and free from disposing of toxic by-products, as there may be with some methods.

According to the discussed session, laser technology is mainly applied during cutting and cleaning in general applications. In textile industries, it is used in cutting, engraving, embossing, denim fading, and other applications such as after treatment for denim. Further applications of laser technology can be explored, especially with the increasing demand of knitted and blended fabrics (cotton polyester blend), pretreatment can be applied on it for surface structure and properties modification.

8.8 Acknowledgments

This work is part of PhD thesis submitted by Dr. On-na Hung (Thesis title: A Technological Study of Computer-Aided Laser Finishing on Cotton-Based Fabrics) in partial fulfilment of the requirements of the degree at the Institute of Textiles and Clothing, The Hong Kong Polytechnic University. Authors would like to thank The Hong Kong Polytechnic University for the financial support for this work.
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Natural colorants and its recent developments

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9.1 Introduction

There is a growing awareness regarding the effect of human interaction, both short and long term, with the environment (Nicholson, 1987). The growing public awareness has been expressed through an expanding premium market for goods and services that carry “natural” or “eco-safe” or “green” or similar labels (Bansal and Roth, 2000; Esty and Winston, 2009). This provides an excellent focus point for the textile sector. Sustainable clothing includes all aspects of clothing manufacture and recycling. This chapter describes coloring matter derived from nature and highlights advancements in their applications onto textile substrates.

The textile coloration sector uses dyes (coloring matter), chemicals (whose reaction ensures the coloring of textiles), and auxiliaries (chemicals that promote coloration) in addition to consuming large quantities of water. Unfixed dye, chemicals, auxiliaries, and water not picked up by the fiber material are collectively discharged at the end of coloration as effluent. Marine life would be adversely affected if these effluents, usually colored, were discharged without treatment into the water body (Walsh et al., 1980). Further, such effluents affect riverbeds, soil, and crops (Ajmal and Khan, 1985; Kaushik et al., 2005). The intimate relationship between textile coloration and environment offers enormous scope for development on the eco-conservation trend (Reid, 1996; Abrar et al., 2009). Efforts in this area may be summarized as:

1. Reducing the quantity of consumables by increasing process efficiency and reclaiming and reusing resources such as chemicals, water, and energy.
2. Using materials and processes with a lower environmental impact; and
3. Increasing the use of renewable resources such as natural fibers (silk, cotton, and wool) and natural dyes.

The growing niche market for sustainable products is prompting the reintroduction of natural dyes on a commercial scale. However, the dominance of synthetic dyes for the past 150 years has stifled in-depth studies on industrial-scale use of natural dyes. Hobbyists and craftspersons, a minority, who continue to use natural dyes for textile coloration, adhere primarily to the conventional home-scale exhaust dyeing method. Such methods are not readily compatible with commercial application methods.

This chapter highlights the types of dyes used in textile coloration. A detailed description has been given on the type of natural dyes, their chemical structure, sources
of extraction, and application methods. In addition, the recent developments and assisted techniques in natural dyeing are also included in this chapter.

9.2 Textile coloration

Colors not only increase the beauty of textile but also serve to identify, warn, or even indicate social status. Therefore, textile coloration has developed into an art and science. Textile materials acquire the desired color(s) by the application of appropriate dyes.

9.3 Dyes

Coloration of textile is achieved by application of dyes. Dyes are complex chemicals that are absorbed by and react with suitable substrates to yield a colored product. This process includes various methods and machineries. There are two broad dye categories based on origin, namely natural dyes and synthetic dyes. J. W. Slater published the first book in 1870 that provided comprehensive data on dyes and pigments used in textile coloration (Burdett, 1982). Today this information is available as the Color Index (CI) published jointly by the Society of Dyers and Colourists (SDC) and American Association of Textile Chemists and Colourists (AATCC) (Clark, 2011). The index scientifically classifies the wide variety of dyes based on chemical structure, color, application methods, fastness properties, manufacturer, synthesis route, and date invented.

9.3.1 Synthetic dyes

Dyes employed in the modern industry are termed as synthetic dyes because they are synthesized or manufactured to specifications usually from petroleum derivatives. These dyes are characterized by low cost, wide variety, standardized application method, repeatable results, and stringent performance standards (Trotman, 1984; Zollinger, 2003; AATCC, 2012; Standards-Australia, 2012). Consequently, this is a US$16.2 billion global industry (Freedonia-Group, 2009). Various synthetic dye classes and their prominent features are depicted in Fig. 9.1 (Ratnapandian, 2013). The scope of this chapter does not allow to discuss in detail on synthetic dyes. Hence, a detailed discussion of natural dyes will be covered in this chapter.

9.3.2 Natural dyes

The name natural dye applies to all coloring matter derived from natural sources, such as plants, animals, and minerals. The use of natural dyes has been recorded across the globe since ancient times. They were the only dyes available and used until 1856 when Sir W. H. Perkin discovered the first synthetic dye “mauviene,” a basic dye. Plants, animals, or minerals form the source for natural dyes. The sources have been identified across the globe since ancient time (Bechtold and Mussak, 2009; Ramakrishna, 1999). Tyrian purple is a well-known example used by Greek and Roman emperors. The use
of natural dyes started to decline after the discovery of “mauviene,” a basic dye by W. H. Perkin in 1856 (AATCC, 2012; Standards-Australia, 2012).

Dye extraction and purification uses simple techniques such as boiling and filtering. Usually complex procedures are not needed. Indigo, however, is an exception. The dependence on nature imparts unavoidable inherent variation to quality and quantity to these dyes. Hence, repeatability in shades is possible by skillful dyers who utilize complex recipes. Generally, it is accepted that natural dyes yield unique shade for every batch. Researchers have demonstrated that natural dyes can produce diversity of colors similar to synthetic dyes. Today the Color Index includes natural dyes and classifies them in scientific manner (Bechtold and Mussak, 2009; Cardon, 2007; Hummel, 1898).

The degree of affinity to textile forms the basis of classifying natural dyes into being either adjective or substantive. Substantive dyes, with a high affinity for textiles, maybe classified as vat, acid, direct, and pigment classes (Hummel, 1898; Patel, 2011). However, these are a minority, and majority require the use of mordants to fix the dye on to the fabric. Such dyes are called as mordants or adjective dyes (Gulrajani and Gupta, 1992). Mordants were believed to eat away the surface or open up the pores in a fiber and thus facilitate dye absorption (Bhattacharyya, 2010).

**Fig. 9.1** Classification of synthetic dyes.

<table>
<thead>
<tr>
<th>Synthetic dyes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct – simplest, wide variety of colors</td>
</tr>
<tr>
<td>Vat – insoluble in water, leuco form used to achieve dyeing</td>
</tr>
<tr>
<td>Sulfur – deep muted shades, dyes have complex structures</td>
</tr>
<tr>
<td>Azoic – bright shades formed in situ by coupling reaction</td>
</tr>
<tr>
<td>Reactive – fast colors, react with substrate, mono and bi-functional dyes</td>
</tr>
<tr>
<td>Acid – used to dye wool, silk and nylon, classified as mordant and premetallized dyes</td>
</tr>
<tr>
<td>Disperse – used mostly for polyester, requires unique application process</td>
</tr>
<tr>
<td>Basic – used in acrylic dyeing, cationic in solution</td>
</tr>
<tr>
<td>Pigments – insoluble in water, requires binders</td>
</tr>
</tbody>
</table>
They have now been identified as “bridging chemicals” that link dyes and fibers (Cardon, 2007; Bhattacharyya, 2010). Mordants, in turn, may be classified as single or bi-metallic salts, tannins, and oil mordants (Patel, 2011). Mordant dyes may further be divided into monogenetic and polygenetic dyes (Fereday, 2003; Bhattacharyya and Shah, 2000; Bird, 1963).

As the names suggest, the first type of dye yields only one shade, while the second yields different colors according to the mordant (metallic) employed (Hummel, 1898). Naturally occurring salts of aluminum, copper, potassium, and iron were commonly employed as mordants. Their quality, in terms of purity, affects the richness and dura-
bility of the shades obtained (Cardon, 2007). Advancements in chemistry have made aluminum sulfate, potash-aluminum sulfate, stannous (tin) chloride, copper (II) sulfate, and iron (II) sulfate to become the mordants of choice today. Chromium salts have been banned because of potential health hazard (Giles, 1944). At times, tannin—metal complexes and oil—metal complexes served as mordants for other nat-
ural dyes (Nalankilli, 1997). Mordants facilitate dye aggregation and free radical ab-
sorption, thereby increasing fastness properties (Gupta, 1999a).

Gulrajani and Bhattacharyya have cited that mordanting may be classified as premordanting, metamordanting and postmordanting, which are discussed below (Gulrajani and Gupta, 1992; Bhattacharyya, 2010):

**Premordanting**—In this process, textile material is first treated with the mordant and then dyed. Intermediate drying allows storage of the mordanted material and helps in absorption of the dye liquor. Multicolored pattern may be obtained by using poly-
genetic dyes in combination with patterns printed with different mordants. Prolonged storage of premordant textiles can cause damage if the metal is corrosive. Another source of color variation is leaching of mordant into the dye bath.

**Metamordanting**—In this process, fabric is dyed in a single bath containing both mordant and the dye. Uneven dyeing is caused by aggregation of dye-mordant com-
plex in the dye bath and the inability of resultant large complex to be absorbed by the substrate.

**Postmordanting**—The mordant is applied after the dye has been applied. This method yields deeper penetration of the dye, hence, a level shade. Prolonged storage of dyed fabric prior to mordanting has to be avoided in order to minimize loss of color by fading or rubbing.

An intense area of research is that of determining the optimum amount of mordant required and developing a theory that explains the precise role of the mordant. The problem faced is complexity of dye molecule that hinders understanding of the binding mechanism and exact role of the mordant (Cardon, 2007).

The major source for natural dyes is plants. In many cases, different parts of the same plant such as leaves, flowers, seeds, roots, and bark have been reported to yield different shades. Table 9.1 lists some typical colors obtained using natural dyes and their plant sources (Cribb and Cribb, 1981; Dyer, 1976). Mineral colors are naturally occurring metal salts such as chrome yellow, iron buff, and mineral khaki. Two ancient animal dyes are Tyrian purple obtained from shellfish (Murex brandaris) and cochineal obtained from insects (Dactylopius coccus). Lichen and fungi are also known to yield dyes but their slow rate of growth severely limits commercial
exploitation. Some of the important chemical groups present in natural dyes are given in Fig. 9.2 (Ratnapandian et al., 2012).

### 9.3.2.1 Indigoid dyes

These dyes consist of indigo derived primarily from the indigofera, isatis, and polygonum species (Cardon, 2007; Balfour-Paul, 2006). Tyrian purple extracted from murex species of mollusks is another noted member of this group. The main shade obtained is blue. Indigoid dyes were the primary vat dyes with a typical two carbonyl (C=O) structure. Consistent with existing practices, dyeing was possible only after

### Table 9.1 Typical shades of natural dyes.

<table>
<thead>
<tr>
<th>Shade</th>
<th>Source</th>
<th>Chemical group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue</td>
<td><em>Indigofera tinctoria</em></td>
<td>Indigo</td>
</tr>
<tr>
<td>Red</td>
<td><em>Caesalpinia sappan</em></td>
<td>Anthocyanin</td>
</tr>
<tr>
<td>Yellow</td>
<td><em>Bougainvillia glabra</em></td>
<td>Flavonoid</td>
</tr>
<tr>
<td>Green</td>
<td><em>Urtica dioica</em></td>
<td>Chlorophyll</td>
</tr>
<tr>
<td>Black</td>
<td><em>Haematoxylum campechianum</em></td>
<td>Tannins (Prorobinetinidin and Profisetinidin)</td>
</tr>
<tr>
<td>Brown</td>
<td><em>Acacia catechu</em></td>
<td></td>
</tr>
<tr>
<td>Orange</td>
<td><em>Bixa orellana</em></td>
<td>Carotenoid</td>
</tr>
</tbody>
</table>

![Fig. 9.2 Typical chemical groups of natural dyes.](image)
conversion into the leuco form. Usually this was brought about via inconsistent fermentation (Bechtold and Mussak, 2009; Cardon, 2007; Patel, 2011; Agarwal, 2011; Buhler, 1951; Vetterli, 1951).

### 9.3.2.2 Flavonoids

Weld, saw-wort, and fustic are the popular sources for these dyes. The chemical involved is luteolin with resultant yellow shade. It may be noted that flavonoids form the largest group of natural dyes. Luteolin is the primary colorant in these dyes. The major disadvantage is poor fastness to light. This has been proved by the selective fading of old tapestries (Bechtold and Mussak, 2009).

### 9.3.2.3 Anthocyanins

Red and blue color of flowers and fruits are the result of anthocyanins. These anthocyanins are water-soluble flavonoids widely employed as water color. The shade obtained is sensitive to pH and light (Melo, 2002). In the case of anthocyanidins the glycosides of the anthocyanins are replaced by hydroxyl groups. Logwood is an excellent example of this class of dyes.

### 9.3.2.4 Carotenoids

These colorants are named carotenoids as they were initially isolated from carrots. These are direct dyes producing yellow to orange-red shades. Common sources are carrots, sweet peppers, turmeric, and tomatoes, while saffron is an expensive source (Cardon, 2007).

### 9.3.2.5 Anthracenes

Safflower, madder, and cochineal are the well-known sources for dyes containing anthracenes. Diverse sources, such as plants (flowers, bark, and roots), lichens, and insects, exist for these dyes. The two main groups of this class are (1) anthraquinones with yellow, pink, and red pigments (Saidman et al., 2002) and (2) napthoquinones with brown, pink, or purple pigments (Gulrajani et al., 1992).

### 9.3.2.6 Chlorophyll

This is the essential green pigment used by the plants for photosynthesis. Commercially chlorophyll a and chlorophyll b are available in this class of dyes. Difficulty in application and poor light fastness (browning on exposure to light) make chlorophyll unpopular as a textile dye (Patel, 2011).

### 9.3.2.7 Tannins

Tannin is the term introduced by Seguin in 1790 to describe plant extractions that can convert rawhide to leather. They are primarily used for converting hides to leather. Their reactivity is rated based on the astringency to touch, taste, and the propensity
to give a greenish or bluish-black hue in the presence of iron salts. *Galling* or *sumach-ing* is a textile application of this reaction, wherein the tannin serves as a mordant. At times they serve the dual purpose of mordant and colorant due to their close association with some of the other coloring groups such as flavonoids and quinones (Haslam, 1966). Tannins are identified as polyphenols. They may be subclassified as hydrolyzable (gallo-tannins and ellagi-tannins) and condensed (proanthocyanidins) tannins.

### 9.4 Fabric coloration

Textile coloration can be carried out at fiber, yarn, fabric, and garment stages. Fabric stage coloration is the most popular. This is achieved by employing a wide variety of machines and methods. Dyeing and printing are the broad classifications of textile coloration. A simplistic description of dyeing is that the fabric acquires a single color uniformly throughout. Similarly, printing may be defined as a process where one or more colors are applied in a desired pattern on the fabric (Clark, 2011; Broadbent, 2001). Fig. 9.3 schematically describes the different methods of dyeing and printing (Ratnapandian, 2013; Clark, 2011; Broadbent, 2001; Chakraborty, 2010).

### 9.5 Advancements in natural dyeing

A knowledge gap exists on how to use natural dyes in modern dyeing facilities. Their reduced use over the last 150 years has resulted in:

- Loss of knowledge about extraction and application process due to absence of written records

![Fig. 9.3 Fabric coloration methods.](image-url)
- Extinction of some dye sources and nonidentification of new sources
- Slowing down of scientific research on natural dyes, leading to stagnation in recipe development, modernization, and optimization.

The increasing demand for natural dyes has produced scientific publications relating to dye sources, extraction and application methods, dye chemistry, and performance of natural dyes (Gulrajani and Gupta, 1992; Ratnapandian et al., 2012). The following subsections discuss some of these findings.

### 9.5.1 Sources and extraction

A wide variety of plant sources for natural dyes have been identified (Cardon, 2007; Cribb and Cribb, 1981; Dyer, 1976; Adrosko and Furry, 1971; Dean, 1999). In India alone, Mohanty et al. (1987) have described more than 300 potential sources. The plants range from undesirable weeds to those that can be cultivated. Efforts have been made to identify the plant parts such as leaves, flowers, bark, seed pods, and roots that yield the maximum color (Cribb and Cribb, 1981; Dyer, 1976). New sources namely by-products and waste products such as wood chips and sawdust (timber industry), grape pomace (wine making), and olive pomace (oil extraction) have been reported. (Bechtold et al., 2006; Meksi et al., 2012). Recombinant DNA technique is being explored to induce microorganisms to produce dyes (Nerurkar et al., 2011; Alihosseini, 2009; Han et al., 2008a,b).

Simplest dye extraction technique is steeping, boiling, or fermentation followed by simple filtration, settling, and evaporation to obtain the final dye in paste, cake, granule, or powder form. This process not only reduces cost of transportation of raw material but also yields standardized product. Clustering of extraction and application industries would prove economically beneficial (Bechtold and Mussak, 2009). Spraydrying and supercritical carbon dioxide (SCCO\(_2\)) extraction are the new developments in this sector. Commercial quantities of some natural dyes are now available. Companies such as Alps Industries and Atul Dyes in India are advertising availability of large quantities of natural dyes (Hill, 1997; Anonymous, 2001).

### 9.5.2 Application techniques

Traditionally, natural dyes are applied by long-liquor exhaust dyeing for textile coloration and hand or simple mechanical methods for printing. These methods are laborious, time-consuming, and sometimes convoluted compared to present-day coloration techniques (Broadbent, 2001). Recipe collection authored by enthusiasts are available for use by hobbyists (Dyer, 1976; Flint, 2008; Adrosko and Furry, 1971).

Self-help groups conduct classes to promote use of natural dyes as source of income. Numerous conventions are held to popularize the natural-dyeing concept. Interest groups conduct classes to disseminate their knowledge as well. However, a common disclaimer among these protagonists is “These are my results. Your results will vary and you are welcome to try your own version.”
Exhaust dyeing recipes have been reexamined, optimized, and standardized. The efforts in this area have eliminated unnecessary steps and auxiliaries, reduced the dyeing cycle time, and increased shade consistency and repeatability (Cardon, 2007; Chavan, 1995; Chavan, 2001; Gulrajani and Gupta, 1992; Gulrajani, 1999). The compatibility of natural dyes and commercial exhaust dyeing have been evaluated and determined to be feasible by Bechtold (Bechtold and Mussak, 2009). Cardon (Cardon, 2007) has collected and published information about natural dye chemistry and application techniques from across the globe. Gulrajani (Gulrajani and Gupta, 1992; Gulrajani, 1999) has evaluated diversity of colors that can be obtained by utilizing and reports that natural dyes are on par with synthetic dyes in this regard. The efforts of such researchers are providing increasing comprehension about chemistry of dyes and their interaction with textile substrates. In accordance with present-day demands, substrates not only include natural fibers but also include regenerated and synthetic fibers (Cardon, 2007; Gulrajani and Gupta, 1992; Kumaresan et al., 2012; Bechtold et al., 2003).

Continuous dyeing method by padding technique has been investigated for coloration of textiles using natural dyes. Mordanting sequence, dye to mordant ratio, and padding parameters were the critical elements in these studies. The researchers concluded that the repeatability and uniformity of shade was possible using natural dyes from this technique. However, large-scale (industrial) trials and detailed work are necessary for individual dye-mordant combination and dye concentration (Ratnapandian, 2013; Shahid and Mohammad, 2013).

9.5.3 Performance of natural dyes
Natural dyes have been used to produce a variety of shades. However, with exceptions such as indigo, cochineal, and madder, most natural dyes cannot perform to the fastness standards set for synthetic dyes. There is a constant scientific effort to improve this deficiency. The role of mordants for increasing fastness ratings has been studied by several researchers. Certain natural dyes have been shown to impart antimicrobial activity and UV protection. Thus, research on natural dyes provides scope for innovative developments.

9.5.4 Objections to natural dyes
Common resistance to change has been seen with the idea of reintroducing natural dyes to industrial use. The question of whether natural dyes can provide the desired variety of shades has been answered positively by several researchers [10,28,32,98]. The limitations indicated are quantity and quality. There are doubts about the agricultural feasibility of replacing synthetic dyes with natural dyes. It should be noted that there is no move for complete replacement and natural dye consumption in Europe would probably constitute only 5% by volume of total dye consumed there. Research has revealed that this can be met by utilizing a small portion of nonagricultural semi-arable land in Europe. Modern farming methods have made dye crop cultivation a viable commercial proposition in some countries.
Queries regarding sustainability, safety, and pollution with respect to natural dyes, for example, the use and discharge of metal salts for mordanting, have to be considered. The above arguments bring out the knowledge gap and highlights the need for research to commercialize natural dyeing.

### 9.5.3 Assisted dyeing techniques

#### 9.5.3.1 Use of enzymes

Enzymes are biological proteins that help in digestion and assimilation of food. These proteins have been utilized in industrial reactions including textile wet processing to improve cleaning (scouring and bleaching), increasing dye uptake, and improving fastness properties. Researchers have published data regarding improving the dye performance of natural dyes on various textile materials by employing enzymes in a pretreatment step. Enzymes serve to modify the physical and chemical surface properties or introduction of functional groups on the surface of textile fibers (Shahid and Mohammad, 2013). Vankar and coauthors studied the effect of three enzymes lipase, diasterase, and protease on dyeing characteristics of *Terminalia arjuna, Punica granatum, Rheum emodi* (Vankar et al., 2007), *Acacia catechu, Tectona grandis,* and *Delonix regia* (Vankar et al., 2008) on different types of textile fabrics.

Natural fibers on treatment with enzymes such as trypptase, amylase, and others have been reported to exhibit enhanced dye uptake without changes with fastness properties when colored using different natural dyes (Akçakoca Kumbasar et al., 2009; Montazer et al., 2009; Parvinzadeh and Technology, 2007; Liakopoulou-Kyriakides et al., 1998; Tsatsaroni et al., 1998). Another important area is enzymatic reduction of indigo in both coloration and washing processes (Novo enzymes, private communication). An important consideration for increased benefits of enzyme treatment is dye-enzyme compatibility (Zhang et al., 2011). Enzymes are attracting increased consideration by the industry in view of their ecological benignness and improved process performance.

#### 9.5.3.2 Use of chitosan

Chitosan is a bio-polysaccharide obtained by the deacetylation of chitin. Chitin is a by-product of seafood industry, as it is predominantly present in the inedible shells of crustaceans (crabs, lobster, and shrimp) (Sanford, 1989). As depicted in Fig. 9.4, it is poly-cationic with three reactive groups, namely the amino (−NH₂) group at C-2 and the two hydroxyl (−OH) groups at C-6 and C-3 in each repeat unit. This poly-cationic character of chitosan has been utilized in different areas, such as

![Fig. 9.4 Schematic structure of chitosan (Sanford, 1989).](image)
cosmetics, weight loss, health care, water treatment, and textile dyeing (Sanford, 1989; Majeti and Kumar, 2000).

The ability of chitosan to agglomerate dyes has been used to improve the dye-ability of cotton and wool by pretreatment. It has been proposed that chitosan forms a film and increases the number of reaction sites on the substrates for dyes (Majeti and Kumar, 2000; Knorr, 1983). An improvement in dye uptake leading to darker shades has been reported for both synthetic and natural dyes (Canal et al., 1998; Gupta and Haile, 2007; Davidson and Xue, 1994; Kittinaovarat, 2004; Shin and Yoo, 2010; Giridev et al., 2009). Variations in shade due to fiber maturity and damage have been minimized with the help of chitosan (Rippon, 1984; Davidson and Xue, 1994). Ratnapandian (Ratnapandian et al., 2013) reported that careful use of chitosan while padding with natural dyes increases the depth of shade. However, beyond the critical point, chitosan interfered with the dyeing process. On a functional level, chitosan imparts durable antimicrobial properties to textile materials. Such an enhancement of properties opens the market for medical textiles or other similar materials.

9.5.3.3 Use of ionic liquids

Ionic liquids (ILs) are salts with melting temperatures below 100°C. They evolved from traditional high-temperature molten salts. Presently, they are being investigated for “green chemistry” applications (Wilkes and Zaworotko, 1992). ILs are used as catalysts, solvents, and electrolytes (Zhao et al., 2002). Pretreatment of wool with IL has been reported to increase the depth of shade and reduce contact angle so as to improve dyeing cycle efficiency (Yuan et al., 2010). Bianchini and Barbaro (Bianchini and Barbaro, 2002) investigated dyeing of cotton, wool, and polyester with disperse red 13 using IL as the sole additive. Their results revealed that the use of IL significantly reduced the consumption of water and other auxiliaries, thereby lowering the environmental impact of dyeing process.

9.5.3.4 Plasma pretreatment

Plasma, also known as the fourth state of matter, is defined as a collection of nearly equal numbers of positive and negative charges obtained by ionization of a gas. This mixture of excited ions, molecules, electrons, neutrons, protons, and free radicals (Fig. 9.5) is highly reactive (Muguntharajan and Saminathan, 2009). The plasma gas is ionized by addition of energy in the form of temperature or the application of a high

![Fig. 9.5 Schematic representation of plasma (Muguntharajan and Saminathan, 2009).](image-url)
electric field. Nonthermal or “cold” plasma, generated by the application of a high electric field, exists at near room temperature and is better suited for treating textile materials (Muguntharajan and Saminathan, 2009; Hwang, 2003).

Shishoo (Shishoo, 2007) classifies plasma into low-pressure (vacuum) and atmospheric pressure plasma (APP), depending on the gas pressure at which the plasma is generated. The former operates at vacuum pressures between $10^{-2}$ and $10^{-3}$ mbars and generally used in nontextile applications. The latter, operating at atmospheric pressures, is subdivided into corona treatment, dielectric barrier discharge, and glow discharge, based on shape and positioning of electrodes. Glow discharge imparts uniform treatment by generating the plasma between two parallel-plate electrodes in an inert atmosphere. Treatment by either vacuum or APP yields comparable results in terms of the functionality achieved (Hwang, 2003; Ceria et al., 2010). APP for textiles is a fairly recent development, it is economical and convenient for continuous production as it avoids working under a vacuum (Shishoo, 2007).

A typical characteristic of all plasma treatment is that it affects only the surface (<1000 Å, 1 Å = 1 × 10^{-10} m) and leaves the bulk properties unaffected. Desirable functionalities such as altered moisture relations (absorbance or repellence), antimicrobial property, soil repellence, stain resistance, soft handle, and improved dyeing are widely achieved on textiles by wet finishing processes. Such processes employ a variety of chemicals (Broadbent, 2001). Plasma pretreatment followed by wet finishing has been employed to impart similar functional finishes to textile materials with lesser amount of chemicals and in some cases without the use of chemicals or water (Sadova et al., 1983; Ulesova et al., 2008; Wakida et al., 1993, 1998; Sun and Stylios, 2004; Shekar and Bajpai, 2000; Deshmukh and Bhat, 2011; Karahan and Özdoğan, 2008).

The effect of plasma treatment may be altered by varying process parameters such as supply frequency, discharge power, treatment time, type, and pressure of gas. For example, oxygen or helium plasma increases moisture absorbance, while fluorocarbon increases water repellence. Several surface phenomena such as adsorption, desorption, etching, cleaning, surface activation, and cross-linking occur singly or in combination on exposure to plasma (Karahan and Özdoğan, 2008; Subbulakshmi et al., 1998; Höcker, 2002). A concise comparison between traditional finishing and plasma treatment is given in Table 9.2 (Shishoo, 2007).

Consistent with the above discussions, treatment of wool with plasma has been reported to affect the lipid layer and surface cuticle without changing the bulk properties. This results in higher wettability and increased dye uptake, leading to improvements in the depth of shade and evenness. The available literature relates only to different classes of synthetic dyes (Kan et al., 1998; Kan and Yuen, 2007; Lehocký and Mráček, 2006). It has also been suggested that intrinsic dye hydrophilicity is a deciding factor in this improvement (Naebe et al., 2010). On this basis of the APP, treatment of wool was proved to improve padding with natural dyes (Ratnapandian, 2013).

### 9.5.3.5 Ultrasound application

Ultrasound refers to all sound waves with the frequency above audible frequency of 20,000 Hz (Kadam and Nayak, 2016). Such sounds are widely used in medical imaging. Ultrasound is considered as part of the clean processing technique in textile
industry. This technique works by means of cavitation in liquid medium in addition to other mechanical effects such as dispersion, degassing, diffusion, and intense agitation of liquid (Ahmed and El-Shishtawy, 2010). Cavitation is the formation, growth, and implosive collapse of small gas bubbles caused by ultrasonically induced alternating compression and rarefaction waves. The cavitation bubbles oscillate and implode, thus enhancing molecular motion and stirring effect in the dyebath. When cavitation occurs at fiber–dyebath interface, the asymmetric implosion promotes mass transport in the direction of the fiber (Vankar et al., 2008). This increases the dyeing rate; economizes energy and time consumption without causing any apparent fiber damage (Vankar et al., 2008).

Experiments have demonstrated that ultrasound-assisted natural dye extraction, mordanting, and dyeing are more efficient when compared to traditional methods (Mansour et al., 2011). The above statement has been verified by work on cochineal, lac, saffron (Shahid and Mohammad, 2013), catechu, tectona, and madder (Vankar et al., 2008). Xinsheng et al. (Xinsheng et al., 2008) have reported similar results for protein fiber coloration using natural dyes. An increase of nearly 50% dye uptake apart from improved fastness characteristics have been reported by Guesmi et al. (Guesmi et al., 2013) while working with indicaxanthin natural dye on modacrylic. Dye extraction from beetroots, green wattle barks, marigold flowers, pomegranate rinds, 4'O clock plant flowers, and cockscomb flowers has been reported to be increased with the assistance of ultrasound (Sivakumar et al., 2009, 2011). The benefits of ultrasonic-assisted natural dyeing may be summarized as:

1. Low temperature dyeing and reduced processing time resulting in energy savings.
2. Lower demand of auxillary chemicals and increased dye exhaustion reduces pollution.

<table>
<thead>
<tr>
<th>Table 9.2</th>
<th>Plasma processing</th>
<th>Traditional wet chemistry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium</td>
<td>No wet chemistry involved. Treatment by excited gas</td>
<td>Water based</td>
</tr>
<tr>
<td>Energy</td>
<td>Electricity—only free electrons heated (&lt;1% of system mass)</td>
<td>Heat—entire system mass temperature raised</td>
</tr>
<tr>
<td>Reaction type</td>
<td>Complex, multifunctional, and simultaneous</td>
<td>Relatively simpler, well established</td>
</tr>
<tr>
<td>Reaction location</td>
<td>Surface-specific, unaltered bulk properties</td>
<td>Bulk of material is usually affected</td>
</tr>
<tr>
<td>Potential for new processes</td>
<td>Rapidly developing field</td>
<td>Low technological growth</td>
</tr>
<tr>
<td>Equipment</td>
<td>Experimental, laboratory and prototype, rapid development</td>
<td>Mature, slow evolution</td>
</tr>
<tr>
<td>Energy consumption</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Water consumption</td>
<td>Negligible</td>
<td>High</td>
</tr>
</tbody>
</table>
3. Minimizes damage to fibers during dyeing.
4. Increases industry competitiveness.

9.5.3.6 Advantages and key consideration of natural dyes

There are several advantages of using natural dyes, which includes reduced environmental impact, renewable resource, safe working, and safe to wear. As natural dyes are derived from nature, they are not harmful. The amount of toxicity of wastewater is much lower in the case of natural dyeing. In addition, natural dyes are biodegradable, hence, the final disposal of natural dyed clothes does not cause environmental pollution. The use of natural dyes will be more sustainable as they are obtained from renewable sources. For soft and soothing shade of textiles, natural dyes are preferred over their synthetic counterparts. Many of the natural dyes are safe to work and does not cause skin irritations while wearing. Even some natural colors such as carmine present in lipsticks are not harmful when ingested. In spite of these advantages, there are certain limitations of natural dyes, which needs to be overcome to replace the synthetic dyes.

Some well-known drawbacks of natural dyes are insufficient supply, unavoidable variation due to changes in growing condition, low color yield, and low efficiency during cultivation and dyeing (Fereday, 2003; Dyer, 1976; Adrosko and Furry, 1971; Gulrajani and Gupta, 1992; Samanta and Agarwal, 2009). Although natural dyes can produce wide range of shades, most of them are not able to perform up to the standards of synthetic dyes in term of desirable properties. Indigo, cochineal, and madder are exception to these statements (Bechtold and Mussak, 2009; Cardon, 2007; Gulrajani et al., 2001). In an effort to overcome this deficiency, the role of mordants has been investigated (Gupta, 1999a,b; Cristea and Vilarem, 2006). Some natural dyes have inherent antimicrobial, insect repellent, and UV protection properties (Singh et al., 2004; Gupta et al., 2005). Thus research on natural dyes provides scope for innovative developments in future.

Several queries regarding reintroduction of natural dyes on an industrial scale have been answered. Researchers have proved that natural dyes can provide wide variety of colors (Bechtold and Mussak, 2009; Cardon, 2007; Fereday, 2003; Gulrajani et al., 2001). The limitations indicated are quantity and quality. It should be noted that the natural dyes cannot replace synthetic dyes completely. Plant-based natural dyes would primarily been grown on semi-arable farm land and would prove to be source of supplementary income for farmers (Hill, 1997; Angelini et al., 2007; Guinot et al., 2006). Modern farming methods have made dye crop cultivation a viable commercial proposition in some countries (Hill, 1997). Queries exist regarding sustainability, safety, and pollution with respect to natural dyes, for example, the use and discharge of metal salts for mordanting, have to be considered (Glover, 1993).

9.6 Nontextile applications

Natural dyes have been widely accepted to possess medicinal properties. Therefore, they have been used as food colorant, for example, saffron and turmeric. They may
be used to obtain hues ranging from green through yellow, orange, red, blue, and violet, depending on the source of colorants (Bakowska-Barczak and Sciences, 2005). Natural dyes are claimed to increase efficiency and extend the life of solar cell (Furukawa et al., 2009).

## 9.7 Conclusions

Natural dyes have been used for many centuries around the world. However, their use in textile coloration was temporarily stopped because of discovery of synthetic dyes. The colorants of the ancients, natural dyes, will not become extinct nor be eradicated. The growing consumer awareness about the environment and sustainability is creating resurgence in the industrial use of natural dyes. It is widely known that health issues and environmental pollution are caused by synthetic dyes. Therefore, interests on natural dyes will be growing continuously. The scientific database about chemistry and application of natural dyes continues to expand. Global research is been carried out not only to obtain an intimate understanding about natural dyes but also to merge these traditional dyes with emerging technology. Therefore, there will be no more hazards on people and planet by switching from the synthetic dyes to the natural dyes.

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Natural finishes, technologies and recent developments

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10.1 Introduction

Textile industry is a major contributor in polluting the environment by generating harmful toxins in effluent during manufacturing of fabrics and by emitting poisonous and greenhouse gases (Jajpura et al., 2004). Fashion keeps on evolving and clothes are made according to fashion trend, resulting in an increase in waste generation (Fletcher, 2013; Kant et al., 2017). The natural fibers are renewable, but cause great harm to the environment due to the involvement of pesticides, synthetic fertilizers, and excessive irrigation (Singh and Jajpura, 2016). Besides that synthetic fibers are nonbiodegradable, often end in landfill or incinerated (Jajpura and Singh, 2015).

According to data from the United States Environmental Protection Agency (EPA), in 2010, around 11 million tons of textiles were dumped as landfill across the country. Dumped clothes contain dyes and finishing chemicals that can leach into the surface thereby contaminating groundwater (Wallander, 2012). Adoption of environmental safe chemicals by replacing hazardous chemicals is much required in fashion, textiles and other consumer products. Synthetic finishes are widely available at economical price, but releases undesirable toxic chemicals during synthesis (Kumar and Adwaita, 2011). Usage of these types of hormone disruptors and carcinogenic chemicals causes illnesses like cancer, behavioral problems and immune deficiency.

In the past few years, environmental organizations have created public awareness in the issues of climate change and depletion of natural and human resources. Sustainability is being promoted in all aspects and hence consumers are becoming more rational about environmental and health issues (Dalby, 1993). The increasing environmental pressure has motivated textile industry to use environmental friendly natural finishes (Şahan and Demir, 2016). Several researchers are working to develop zero-discharge processing technique to make textile industry a green industry (Lee et al., 2001).

Growing concern for the environment has created demand of sustainable products (Hooda and Rangi, 2015), which has created a niche market for the industrial scale use of natural dyes and finishes. In recent years, great attention has been devoted to bio-polymers because of their biocompatibility and biological functions, and consequently they are suitable to textile, biomedical and pharmaceutical fields.
In this chapter, an attempt has been made to give an overview of natural finishes for fashion and textiles, so, it is very relevant to current scenario of growing interest to take textile industry towards sustainability. This chapter also highlights various types of natural finishes, their application techniques, advantages and disadvantages. Furthermore, the recent developments in extraction of natural finishes and green nanoparticles are also discussed in this chapter.

10.2 Natural finishes

Natural finishes cover all the finishes derived from natural sources like plants, animal, microorganisms and insects with certain common properties as illustrated in Fig. 10.1. Most of the natural finishes are nonsubstantive and must be applied on textiles by the help of cross-linker or by surface modification of fiber by irradiation techniques.

10.2.1 Advantages and limitations of natural finishes

In the recent years, there has been trend in textile industry to move towards sustainable and eco-friendly processes. Natural dyes are taking their place back in the dyeing industry, but natural finishing still needs more attention. Just like the natural dyes, natural finishing agents also have some advantages and limitations which are discussed below.

10.2.1.1 Advantages

- Natural finishes are biodegradable and have the potential to reduce carbon emissions.
- Use of natural finishes reduces the effluent load and saves land and water from pollution.
- Unlike synthetic finishes, natural finishes are sustainable and most of them are renewable.
- Natural finishes are biocompatible and nontoxic.
- Some natural dyes have dual character; in addition to coloring the fabric, they also add functional properties like antibacterial, UV protection, etc., to it.

![Variation from batch to batch](image)
![Presence of other components](image)
![Lack of technical knowledge](image)
![Expensive](image)
![Non durable](image)
![Lack of awareness among consumers](image)

![Biodegradable](image)
![Reduce carbon emissions](image)
![Reduce effluent load](image)
![Sustainable and renewable](image)
![Biocompatible and nontoxic](image)
![Some adds multifunctionality to substrate](image)

**Fig. 10.1** Resources of natural finish and their properties.
Despite the advantages, natural finishing agents do carry some disadvantages which hinder their growth and popularity as discussed below.

10.2.1.2 Limitations

- The variation in agro products from place to place, weather conditions, and one crop season to another crop season makes it difficult to standardize the recipe for natural finishes.
- Many secondary materials are also present in natural finishes along with the active ingredients.
- Although these finishes are derived from nature, lack of precise technical knowledge of application makes it expensive.
- As these finishes are nonsubstantive, they require the use of cross-linker of other technique to make them durable.
- Lack of awareness among consumers.

10.3 Major natural finishing agents

10.3.1 Chitin and chitosan

Chitosan is one of the most abundant biodegradable, renewable and nontoxic biopolymer available in nature, which is suitable for replacing some synthetic polymers. Chitosan, as shown in Fig. 10.2 is a polymer having β-1, 4-linked glucosamine residue and is usually obtained through deacetylation of chitin of shrimp and other shells with concentrated sodium hydroxide solution (Islam et al., 2017).

Chitin is almost insoluble in water, dilute acid and alkali; it is soluble in formic acid, methanesulfonic acid; whereas chitosan is also almost insoluble in water but soluble in aqueous organic acids, including formic and acetic acid. Chitosan is one of the few naturally occurring cationic polyelectrolytes.

10.3.1.1 Synthesis of chitosan

Deacetylation of the chitin to form chitosan is achieved by treatment with aqueous 40%—50% sodium hydroxide at 110—115 °C for several hours, with exclusions of

![Chemical structure of chitin and chitosan.](image)

Fig. 10.2 Chemical structure of chitin and chitosan.
oxygen. The chemical method consumes high energy and wastes a lot of concentrated alkaline solution, resulting in a pollution of the environment. Therefore, as eco-friendly alternative chitin can be converted into chitosan by the help of enzymatic (chitin-N-deacetylase) treatments (Horton and Lineback, 1965).

Chitin and chitosan are promising natural raw materials for industrial use due to their high percentage nitrogen content compared to synthetically substituted cellulose (Hirano, 1996). Chitosan is an antimicrobial agent and an effective biopolymer for applications in textile, agriculture, food science, pharmaceutical, chemical, cosmetics and food processing industries (Dhineshababu et al., 2014; Jaipura et al., 2006; Reddy et al., 2016; Yılmaz Atay and Çelik, 2017).

Chitosan dissolves readily in dilute acetic acid and has free amino groups (−NH2−), which act as the active sites for many chemical reactions (Tsigos et al., 2000). The applications of chitosan in textiles have received great attention in numerous studies due to its several unique properties like nontoxicity, biocompatibility, biodegradability, antimicrobial activity and chemical reactivity (Jajpura, 2014a). Application of this biopolymer gives wrinkle-free finishes to textiles with added antimicrobial property. This also acts as a bridge between fiber and nonsubstantive natural dyes. So natural dyes applied along with chitosan not only add antimicrobial property but also improve the fastness properties of natural dyes (Jajpura et al., 2016b,c, 2017). Chitosan plays an important role in pretext of eco-friendly textile finishing (Niekraszewicz, 2005).

It is a best example of sustainable polymer or natural finishing agent as it utilizes waste of sea food industries in its production and replaces various harsh chemicals in textile and chemical industries. In future, its production and application will increase many folds due to its ecologically and environmentally friendly properties.

### 10.3.2 Sericin

The sericin is natural, eco-friendly, proteinous and biodegradable biopolymer, which is obtained as a by-product from silk industries. Silk consists of 70%–80% of crystalline and water insoluble fibrous protein called fibroin and 20%–30% of an amorphous matrix of a water-soluble globular protein called sericin. The hydrophilicity of sericin is due to the presence of hydroxyl groups consisting serine (33.4%) and aspartic acids (16.7%) (Padamwar and Pawar, 2004; Rangi and Jajpura, 2015; Wu et al., 2007). Chemical structure of sericin is shown in Fig. 10.3. Sericin acts like a gum to hold

![Fig. 10.3 Chemical structure of sericin](image-url)
the fibroin filaments together. The gummy sericin material has to be removed from raw silk in the degumming procedure to give luster to silk.

Silkworm is the only source generating sericin; hence, sericin is attained from cocoons, silk fabric, and silk waste or from the degumming liquor of silk industry. Across the world, the annual cocoon production is around 400,000 metric tons and so from the degumming process only 50,000 metric tons of sericin are junked in effluent every year (Wu et al., 2007).

Nowadays most of the sericin is retrieved from silk degumming process. Large amount of sericin can be attained from cocoon waste or silk waste as compared to silk degumming liquor. However, very less consideration was given to it, but now sericin is becoming the center of attraction to researchers as it shows several important useful properties, such as antioxidant, antityrosinase, UV absorbing, and moisture absorbing properties. Restoration of sericin from the degumming liquor can lighten the load in effluent, thus lowering the environmental pollution and helps us to get a biopolymer having untold profitable properties.

Sericin can be utilized as a finishing agent for natural or manmade textiles. Sericin is a good moisturizer and when synthetic fibers are treated with sericin, the hygroscopic property of fibers increases tremendously. In conjunction, coating with sericin increases the weatherability of the material along with its functionality. In recent years, sericin is apposite for wide applications in many industries such as cosmetics, food, medical, pharmaceuticals, etc., owing to its important inherent properties like gelling, moisture absorption and antioxidant.

Sericin can be removed from silk by acid, alkali, soap and enzymatic degumming methods. Time and temperature of extraction play a key role in the amount of sericin extracted. Extraction is carried out by heating the degumming bath by traditional methods at atmospheric pressure or by advance heating methods such as as HTHP (high temperature, high pressure), IRs (infrared radiations), microwaves and ultrasound. After the extraction, sericin is reformed to powder form by various processes such as simple dyeing, membrane filtration, ethanol precipitation, freeze-drying, tray drying and vacuum drying (Rangi and Jajpura, 2015).

### 10.3.3 Starch

Starch is one of the primitive and most important finishes applied to the cotton goods to make improvements such as wrinkle-free, soil-free, lustrous appearance, weight gain and stiffening. Besides these, it is used extensively in preparation of size, back filling and printing paste as it is abundantly available at low cost (Khandual et al., 2004). It is mainly produced from maize, rice, wheat and potato, for various industrial applications. Starch polymers are carbohydrates that decompose into two distinct substances: (a) amylose and (b) amylopectin, as shown in Fig. 10.4. The thickening effect of starch is mainly due to the long and branched amylopectin chains. Starch gives a nondurable stiffening finish to various garments. However, its market share has declined with the introduction of more durable synthetic finishing agents.
10.3.4 Dextrin and cyclodextrin

Starches have poor solubility and require certain rheological behavior for industrial applications. Thus, they are modified by hydrolysis to soluble dextrins or British gum by roasting, acid hydrolysis or enzymatic reactions.

Cyclodextrins are cyclic oligosaccharides linked by $\alpha$-1,4-glycosidic bonds and are composed of glucose units (Bhaskara-Amrit et al., 2011). Cyclodextrin units have hydrophilic and lyophilic parts. The outer part of the cyclodextrin molecules is hydrophilic and inner cavity is lyophilic. The inner cavity can act as a host for hydrophobic guest molecule. No hydrogen bonds are formed or broken during the formation of host–guest complexes of hydrophobic molecules with cyclodextrin (Singh et al., 2002). Cyclodextrins are classified into three types depending upon their molecular structure $\alpha$-, $\beta$-, or $\gamma$-cyclodextrin as shown in Fig. 10.5.

In textile industry, $\beta$-cyclodextrin is widely used in microencapsulation applications (Jajpura et al., 2016a). $\beta$-cyclodextrin is one such polymer, which can impart new functionality to the fabric. The combination of $\beta$-cyclodextrin and textiles received lots of attention over the last decade to create new functionalized fabrics. Textile substrates treated with $\beta$-cyclodextrin can be important for medical and hygiene textiles. The applications of cyclodextrin in textiles are: controlled release of drugs and flavors, removal of dyes and auxiliaries from dyeing effluents, retarding effect in dyeing and finishing baths, and protection of dyes from undesired aggregation and adsorption.

The strong ability of controlled release of fragrances (Martel et al., 2002) and antibacterial agents by cyclodextrin has great applications in specialty textiles such as perfumed textiles, medical textiles, wipes and sanitary napkins. $\beta$-cyclodextrin is unreactive, hence several kind of binders and polyfunctional reagents are being used to link $\beta$-cyclodextrin on textile substrates (Voncina and Le Marechal, 2005). Besides these, modified $\beta$-cyclodextrins with reactive anchor groups are available for textile finishing. This anchor group reacts with the cellulose hydroxyl groups and forms permanent covalent bonds (Aurelia and Octavian, 2011).

![Chemical structure of: (a) amylose and (b) amylopectin.](image)
Fig. 10.5 Molecular structures of α-cyclodextrin.
Besides these, the low cost, biocompatibility and effective degradability of β-cyclodextrins make them suitable agent for bioremediation (Bardi et al., 2000). It can absorb numerous toxic chemicals from effluents. The amount of aromatic organic pollutants (phenols, aniline, formaldehyde and others) can be reduced from the wastewater by using cyclodextrins, which can be immobilized on a water insoluble organic support. The new concept for modification of textile substrates is based on permanent fixation of supramolecular compounds—cyclodextrins on the material surface and thus imparts new functionality to the fabric (Mamba et al., 2007).

### 10.3.5 Gums

Gums are basically plant exudates. They are widely used in various food preparations and as thickening agents in various industrial applications. In printing of textiles, various types of gums such as gum karaya, gum Arabic, gum tragacanth, are used alone or in mixture with other thickeners such as starch. Similar to starches they do not make any permanent bonds with textile materials. Thus, they are applicable to give temporary finishing effects such as wrinkle-free, soil-free, weight gain, lustering and stiffening to textile materials. In the finishing of woollen and silk fabrics, gum Arabic is used for weighing or stiffening purpose instead of starch (Izydorczyk et al., 2005). Chemical structure of gum Arabic is shown in Fig. 10.6 (Shenai, 1995).

Guggul gum is another biopolymer from gum family but its use is less exploited in field of textiles. It is an exudate of Commiphora wightii and has many inherited medicinal properties. Guggul contains guggulsterones as shown in Fig. 10.7 (Rangi and Jajpura, 2017a,b).

Guggul gum has been used for thousands of years in the treatment of various diseases like arthritis, inflammation and lipids metabolism, in Indian traditional system of medicine (Urizar and Moore, 2003). It is reported that guggul gum has antioxidant property (Mester et al., 1979) and its ethanolic and methanolic extracts exhibit antibacterial activity (Rangi and Jajpura, 2017a,b; Romero et al., 2005).

![Fig. 10.6 Chemical structure of gum Arabic.](image_url)
10.3.6 **Cellulose and cellulose derivatives**

Cellulose is the most abundant material widespread in nature. It is renewable and may be obtained from many natural sources such as wood and vegetable biomass. Long cellulose polymeric molecules are insoluble in nature but hydrolyzed products of appropriate molecular length are soluble and produce viscous solution. Cellulose and its derivatives such as soda cellulose, carboxymethyl cellulose (CMC), methyl cellulose, hydroxyl ethyl cellulose, are used in printing paste preparation, coating and back filling, stiffening, and anticreasing applications to textile materials.

10.3.7 **Lignin**

Lignin is the main structural polymeric substance in the cell walls of higher plants with cellulose and hemicellulose. Researchers have proposed detailed models of lignin structure (Freudenberg and Neish, 1968); however, its exact structure still remains unknown. It is believed that structure of lignin changes according to the way of its isolation. It is a polymer synthesized from three monomers—p-coumaryl, coniferyl, and sinapyl alcohol, as shown in Fig. 10.8 (Maria, 1999).
Lignin is the second important component after cellulose in plant, which makes it abundantly available organic compound found in nature. Further, lignin-based hydrolyzed product with the help of enzymes gives new environmentally friendly products with potential functional properties. It is observed that treatment of textiles with a solution of lignin in nanostructure significantly improves the UV barrier properties of the fabric, imparts antibacterial property and maintains its antistatic property without hampering its physical and biophysical properties (Zimniewska et al., 2008).

Lignin shows high amount of char (around 35%–40%) when burnt. Therefore, it has received great attention as bio-based flame retardant additive (Li et al., 2002). Thus, it can also be used in flame retardant textiles as bio-based flame retardant (Cayla et al., 2016).

### 10.3.8 Melanin

One of the most interesting biomaterials is melanin, which is found in animal hair and skin, although one of the common sources is cuttlefish (*Sepia officinalis*) ink. Natural melanin is a structurally ill-defined polyphenolic material and its molecular structure is dependent on the conditions of polymerization, and therefore is tunable (Solano, 2017). Basic types of melanin are eumelanin and pheomelanin, which are shown in Fig. 10.9 below.

Melanin, being a biopolymer derived from natural sources shows good biocompatibility and biostability, no cytotoxicity, and antigenic response when it is added to cell culture. It also shows a series of important properties including capability of absorption for UV–Vis–IRs, free radical scavenging capacities, and redox reversibility (Kumar et al., 2016). Its easy and cheap availability with all the important properties opened gate for its use in various biotechnological and biomedical applications (Di Mauro et al., 2017) and it is suitable for use in medical textiles as well.

![Fig. 10.9 Chemical structures of: (a) eumelanin and (b) pheomelanin.](image-url)
Melanin is known to protect our skin by absorbing broadband UV radiation. Hence, it was recovered from the ink sac of the Indian squid, and its nanocoating was applied on cotton fabric to make it UV resistant. It was found that squid ink Eumelanin is an effective UV absorbent that can be nanofinished on to cotton fabric (Di Mauro et al., 2017; Solano, 2017).

10.3.9 Natural clay

Clay minerals are phyllosilicates of aluminum and may contain variable amount of metal ions like iron, magnesium and alkali metals. As most of the clays are made from minerals, they are highly biocompatible and have interesting biological properties. Some of the applications of the natural clays include drug delivery, tissue engineering and bioprinting (Blanchart et al., 2010; Kerr, 1952).

In textiles, clay rich in mineral can be used to dye the cotton fabric. It imparts good color fastness property to fabric as it has metal ion which forms coordinate bonds. Along with color it also gives antibacterial property to fabric because of the presence of metal ions. Another application of clay was explored by applying attapulgite clay on cotton and polyester cotton blended fabrics and this clay imparted good temporary flame retardancy to the fabrics (Chakrabarti and Shobhanashree, 2012).

10.3.10 Enzymes

Biofinishing is carried out on fabrics using enzymes and other biomaterials instead of applying chemical finishes. Enzymes are biocatalysts and have great potential in eco-friendly textile wet processing (Jajpura, 2019). Enzymes are biodegradable and capable to replace various toxic chemicals used in textile wet processing along with reduction in energy consumption (Shukla and Jajpura, 2004). Some of the enzymes such as amylase (Shukla et al., 2003), lipase, pectinase, cellulose (Khandual et al., 2011), catalase, sericinase, protease, and laccase (Jajpura, 2014b), alone or in mixture are extensively used in textiles, detergents and allied industries. Enzymes are applicable in preparatory textile wet processing operations such as desizing, bioscouring, biobleaching, as well as biofinishing operations such as biowashing, biopolishing, denim washing and bleaching, and defuzzing of wool. The aforesaid enzymatic applications play important role in making the textile wet processing and apparel production sustainable and toxin free (Jajpura, 2018). Thus, to protect the environment, there is a need to enhance enzyme application further in textile wet processing as well as in bioremediation.

10.3.11 Essential oils

Essential oils from plants have been used traditionally for aromatherapy. Some essential oils act as ointments, while some act as perfumes. Some essential oils such as pine, guggul, rosewood (Jajpura et al., 2016d), rosemary (Banupriya and Maheshwari, 2011), Eucalyptus grandis, turpentine, clove, cedar wood oil, have mosquito-
repellent, antioxidant, and antibacterial properties and are being used in natural healing agents (Jajpura et al., 2015).

Mosquito-borne diseases are rising at alarming rate all over the world. Therefore, control of mosquitoes has become important for all the health organizations. Commercially used chemical mosquito repellents have adverse health effects, so, demand of herbal products in market has reached to the peak. Essential oils having mosquito-repellent properties can be a good alternative to synthetic repellents as oils are renewable, eco-friendly and nontoxic in nature. Some of the oils which can be utilized in healing or producing mosquito-repellent textiles are as follows.

10.3.11.1 Pine (Pinus longifolia)

Pine is an aromatic plant which has good antimicrobial and healing properties. It is used in various products such as in disinfectants, insecticides, sanitizers, perfumes, cosmetics, and hospital products for treating headache, scurvy, fever, cold and wound healing (Jajpura et al., 2016d).

10.3.11.2 Guggul (Commiphora mukul)

Guggul is an important ancient medicinal plant which is used to cure various diseases such as leprosy, nervous diseases, muscle spasms, neuralgia, ophthalmia, pyorrhea, skin diseases, spongy gums, ulcerative pharyngitis, hypertension, high blood cholesterol, hemorrhoids, arthritis, and urinary tract. (Rangi and Jajpura, 2017a,b). Besides these, it is used extensively as thickening agents, adhesives, sizing agents, fixture for perfumes, incenses, gelling agents, emulsifying agents and stabilizers in the food industry.

10.3.11.3 Rosewood (Aniba rosaeodora)

Rosewood has rose-like fragrance, which makes its use possible in perfume industry and fragranced textiles. Various parts of rosewood tree are traditionally used in curing different diseases. Basically its seed oil, leaf extract and bark has wide application in curing itching, burning on the skin and scabies, improving irregular menstruation, in treating jaundice, to cure pimples, leprosy, blood diseases, burning sensations, and leukoderma. (Jajpura et al., 2016d). Thus, it can be used in perfumed textiles as fragrance with antibacterial as well as numerous healing properties.

10.3.11.4 Thyme

It is an integral part in recipes of Indian kitchen having numerous health-related benefits and medicinal properties such as heeling of ringworm and other fungal infections, as well as scabies and lice (Rey, 1990). Besides these, it prevents hardening of the arteries, treatment of toothache, urinary tract infection, and kills bacteria and parasite (Javed et al., 2013). Thus, these aforesaid properties can be utilized in producing sustainable antibacterial and repellent textiles.
10.3.11.5 Cedar (Cedar wood)

The oil from the cedar tree has many powerful healing applications such as in treating skin disorders due to its antiseptic and astringent properties. It has mesmerizing fragrance, which reaches the center of the emotional realm and has soothing and rejuvenating effect on the entire body (Barnard, 1999).

It is considered “Generally Recognized as Safe” as a food additive along with pesticide, which repels insects by a nontoxic mode of action. Hence, it can be applied safely on textiles for aforesaid purposes.

10.3.11.6 Cloves (Syzygium aromaticum)

It is a well-known natural antiseptic, analgesic antiinflammatory agent due to its high content of flavonoids (Milind and Deepa, 2011). It boosts the immune system by purifying the blood and helps to fight against various diseases and often added in cosmetic creams and lotions.

The aforesaid essential oils have versatile medicinal properties along with potential to develop effective, safer and eco-friendly mosquito repellent for textiles. Besides these, herbal plants have large repertoire of organic constituents that are renewable, less toxic and biodegradable. Essential oils as such cannot be applied to textiles as most of the essential oils are volatile in nature. Most frequently the used technique to apply essential oils is encapsulation for control release of the oils. Encapsulation can effectively control the release rate of fragrance compounds and essential oils as required, which ensures the storage life of volatile substances. Most popular is the microencapsulation technique, while nanoencapsulation also offers some advantages like more durability over microencapsulation. These application techniques require special apparatus for encapsulation of oils, which makes them expensive. Other method of application can be by using β-cyclodextrin, which has oleophilic moieties in the structure to entrap oil molecules.

10.3.12 Plant extracts as dyeing and finishing agents

Textile finishes are very important in improving aesthetic, handle, chemical and mechanical properties of textiles (Nayak et al., 2008). Natural plant extracts are important area of current and future aspects of textile finishing industry and therefore has greater market value (Ibrahim et al., 2017). Compounds, which are mostly extracted from plants, include phenolics and polyphenols, phenolic acids, quinines, flavonoids, flavones, flavonols, tannins and coumarins, terpenoids, essential oils, alkaloids, lactins, polypeptides and polyacetylenes (Holme, 2005; Sanz et al., 2008; Son et al., 2007; Villano et al., 2007). These components show not only antimicrobial but also antioxidant properties and UV protection properties. Healing power of many plants has been used since ancient times. Plant-based natural dyes and other bioactive natural extract in textile finish have gained significant momentum. For durability they need an anchor to attach themselves on the textile substrate.
Studies reveal that some specific species of plants such as neem, tea tree, azuki beans, aloe vera, tulsi leaves (Ocimum sanctum), clove oil, pomegranate rind, turmeric, eucalyptus oil, onion, and arjun bark, exhibit antimicrobial activity and are suitable for textile applications (Rangi and Jajpura, 2017a,b). Some of the extensively used natural extracts for dyeing along with natural finishing are as follows.

10.3.12.1 **Neem (Azadirachta indica)**

Its leaf extract is safer antimicrobial agent along with greener colorant for textiles (Abdel-Zaher et al., 2018).

10.3.12.2 **Aegle marmelos (Baelfruit or Golden apple)**

Its leaf extract in conjunction to various mordants gives different color shades in greenish tone along with functional properties (Unnati et al., 2017).

10.3.12.3 **Eucalyptus**

The dyed fabric with eucalyptus exhibits a wide range of brown shades in yellow-red color coordinates (Jajpura et al., 2018).

10.3.12.4 **Kalanchoe-pinnata**

Results show that dyed fabric has good UPF (Ultraviolet Protection Factor) and antibacterial properties (Rani et al., 2017a,b).

10.3.12.5 **Acacia catechu (Cutch)**

It gives significant antitoxicant and antimicrobial properties (Nagaraja et al., 2008).

10.3.12.6 **Acacia nilotica (Babul, Kikar chal)**

It consists of good functional properties along with colors from yellow to brown or black by the help of various mordants.

10.3.12.7 **Rheum emodi (Dolu, Rhubarb)**

Roots of this plant contain various anthraquinone derivatives such as rhein, emodin, aloe-emodin and chrysophanol (Das et al., 2008).

10.3.12.8 **Kerria lacca (Lac)**

It is anthraquinone-based natural colorant which exhibits yellow to red shades on textile materials (Teli et al., 2007).
10.3.12.9 *Bixa Orellana* (Annatto)

It is a carotenoid-based natural colorant consisting of bixin and norbixin chemical constituents and exhibits yellow to red shades on textile materials (Jajpura et al., 2016c).

10.3.12.10 *Terminalia chebula* (Harda, Kango)

It is the source of one of the most important vegetable tanning materials and has been used for a long time as natural tanning, mordanting, dyeing and finishing agent (Jajpura et al., 2017).

10.3.12.11 *Quercus Infectoria* (Majuphal, Gallnut)

This natural colorant is used as dyeing, tanning and finishing agent (Gupta and Laha, 2007).

10.3.12.12 *Punica granatum* (Pomegranate, Anar)

This natural extract has good antioxidant properties and gives yellowish brown to khaki color to textile materials (Jajpura et al., 2016b).

10.3.12.13 *Caesalpinia sappan* (Sappan Wood)

The natural coloring matter santalin present in sapan wood gives excellent red color to textiles with medicinal properties (Lee et al., 2008).

10.3.12.14 *Tagetes erecta* (Marigold)

Its flower extract is rich in xanthophyll, lutein, which gives good yellow color to dyed textiles with soothing healing properties (Rani et al., 2017c).

10.4 Application techniques

Most of the natural finishes are nonsubstantive towards textile substrates. Durability to dry cleaning, laundering and hot pressing processes is the greatest challenge for natural finishes as textiles are subjected to repeated washing during their life. For durability, they need an anchor to attach themselves on the textile substrate. Natural finishes can be fixed on textile surface by using either cross-linker or modifying the textile surface. Cross-linkers act as a bridge between natural finish and fiber but cross-linker must not affect the fabric quality (e.g., physical strength and handle) or appearance of the textiles (Shalini and Anitha, 2016). Modification of fiber can be done by irradiating the fiber surface (plasma treatment) or by chemical modification. Like other finishing treatments, natural finishes can also be applied using different techniques such as pad-dry-cure method, exhaust method, coating and spraying.
10.5 Recent developments in natural finishes

10.5.1 Developments in extraction of natural extracts

Plants, enzymes and other natural-based substances are temperature sensitive having constituents such as polyphenols, flavonoids and proteins. Thus, traditional used high temperature extraction and drying technology harm these beneficial components. It is observed that advanced heating technologies such as IR and microwave improve efficiency in extraction and drying (Souza da Silva et al., 2019). Besides these, ultrasonic-assisted extraction and drying in conjunction with conventional and advanced heating techniques also improve the process by efficient mass transfer (Kowalski and Rybicki, 2017). Anna Trojanowska et al. (2019) proposed ultrasound-assisted extraction and concentration of the biological active compounds by nanofiltration. Similarly, natural colorants were extracted from harda, beetroot, tamarind seed coat, turmeric and henna using ultrasound approaches for better efficiency (Sheikh et al., 2016; Sivakumar et al., 2009).

10.5.2 Green nanoparticles

The bigger molecular size limits penetration of natural finish into the fiber and only surface deposition takes place, which causes depletion in handle and aesthetics of the fabric. Reducing the particle size to nano level maintains inherent properties of fiber by increasing the extent of penetration into fiber structure and on the surface (Şahan and Demir, 2016). Integrating desirable properties such as enhanced durability of finish, antibacterial activity and UV protection by the application of nanoparticles is rapidly increasing in textile industry. Many of the natural materials contain compounds like alkaloids, flavonoids and phenolic compounds, which exhibit antimicrobial activity, UV protection property and antioxidant property. (Gupta, 2013). Natural materials are undoubtedly ecofriendly, nontoxic and nonallergic, but are less durable (Rajendran et al., 2014). Herbal nanomaterials are a solution to this problem. Therefore, the use of herbal nanoparticles for their enhanced properties is a value-added technology in textile finishing industry (Sivakumar et al., 2013, 2009).

Various forms of nanocellulose such as cellulose nanofibrils, cellulose nanocrystals, cellulose nanowhiskers, nanostarches and other gum derivatives have come into the spotlight nowadays as these can be used in very useful products. In many industries like pharmaceutical, food, ceramics, paint and textile, they have been applied and proved very useful (Salah, 2013). Cellulose nanofibers and other polysaccharide-based substances are biodegradable and also more absorbent than superabsorbent polymers and have been utilized in hygiene textile products. These sustainable substances can also be loaded with controlled slow release functionalities and used in various applications (Ataide et al., 2017). Similar to cellulose, nano and micro sized sericin and chitosan and their derivatives are available for textile finishes with uniform dispersion properties.
10.6 Conclusions

Most of the natural substances being ecofriendly and skin friendly are apposite alternative to toxic synthetic textile finishes. Thus, renewable and biodegradable natural finishing of textiles by industrial processes in large-scale units is an upcoming reality in the market of ecofriendly textiles. It can be concluded from the above cited text that fabric finished by natural finishes is safe for environment and human beings in comparison to synthetic finishes. Hence, application of natural finishes leads a path to greener and sustainable textile industry. However, the disadvantages of the natural finishes as discussed in this chapter need to be taken care to make the natural finishing the sustainable process for future clothing and textiles.

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Part Four

Sustainability in garment manufacturing
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Sustainable technologies and processes adapted by fashion brands

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11.1 Introduction

The term “sustainable fashion” is being given increasing attention by the global fashion brands due to stricter global regulations and increased consumer awareness (Nayak et al., 2019a; Henninger et al., 2016). Therefore, various fashion brands are ensuring that the materials and technologies used to manufacture their products comply with all the global sustainability standards. They are strictly monitoring the entire supply chain starting from sourcing of raw materials till the garment producers adapt sustainability in order to save the environment and present ethical practices (Barnes et al., 2006; Nayak and Padhye, 2015). Sustainable fashion and textile production by fashion brands involve the use of ecofriendly and biodegradable materials; environmentally friendly manufacturing processes; green supply chain, distribution, and retailing; and ethical consumers (Shen et al., 2014; Choudhury, 2014), which will be discussed in this chapter.

Various sustainable materials derived from natural and biodegradable resources adopted by fashion brands are discussed in this chapter. In addition, the use of recycled materials derived from natural as well as synthetic wastes are also discussed. Global fashion brands are using sustainable technologies (such as enzyme processing, natural dyeing, laser technology, and plasma technology) for sustainable fashion and textile manufacturing, which are also discussed in this chapter (Xing et al., 2007; Mahltig et al., 2004; Dubas et al., 2006; Gomes et al., 2013). The use of synthetic leather to replace animal leather for becoming ethical fashion brand is a global trend followed by many fashion brands now (Fletcher, 2013; Nayak et al., 2019b). This helps in reducing the animal cruelty and the environmental pollution involved in leather manufacturing process, which are also discussed in this chapter.

This chapter also includes the views expressed by three of the global fashion brands in materials and technologies to become sustainable. Qualitative interviews were organized with the managers of three of the global fashion brands dealing with apparel clothing and activewear are also included in this chapter. However, the statements received from each of the brands will be kept anonymous. The data were analyzed
by using the qualitative research software “N-Vivo.” Finally, the uses of various sustainable materials and technologies used by global fashion brands are also discussed in this chapter. The research work done by RMIT University students has also been included in this chapter.

11.2 Sustainable materials

This section deals with the use of various sustainable materials that the fashion brands are using to achieve sustainability. Materials derived from natural resources, recycled materials, and the new innovative material are discussed.

11.2.1 Natural materials

Many of the fashion brands are switching to use natural sustainable fibers such as organic cotton, BCI (Better cotton initiative)-certified cotton, hemp, and linen (Gwilt and Rissanen, 2012). They are targeting to use the materials derived from natural resources due to their biodegradability and recycled materials due to the closed loop approach. Some of the fashion brands are spending a large amount of their income to find innovative new materials derived from various wastes, wood, and other natural materials. Some of the examples include fibers such as soya, bamboo, milk, and polylactic acid (PLA), which are prepared from renewable biological sources and biodegraded after disposal (Mohanty et al., 2000). These fibers provide a solution to the recycling problems involved with synthetic fibers (Gross and Kalra, 2002). Some sustainable fibers can be derived from seaweed, lotus leaf, banana leaf, mushroom, or even wastes such as orange peels and ground coffee bean wastes. The detailed benefits of using various sustainable and biodegradable materials are already discussed in Chapters 1 and 2.

11.2.1.1 Mushroom and fungi fibers

Textile fibers have been successfully derived from mushroom and fungi. Due to diversified looks and characteristics, mushroom fiber can be made into different fashion products, including bags, caps, shoes, dresses, and jackets. In addition, the application of this material also can be found in architecture and furniture fields. The companies MycoWorks, ZVNDER, and Ecovative Design LLC put their effort into investigating and manufacturing vegan leather from fungus fiber. While MycoWorks uses Gano-derma lucidum, so-called Lingzhi or Reishi mushroom, for their product due to its safety status and benefits, ZVNDER choose tinder sponges in Transylvania to create a fabric that is akin to suede. This high absorbency material can help improve wearer’s foot and prevent skin irritation of people with eczema. Some of the products using the mushroom and fungi fibers are shown in Fig. 11.1.

Aniela Hoitink is the first person who made clothing from mushroom fiber. She has developed a flexible composite product called MycoTEX. She grew disc-shaped mycelium and placed them on a mannequin to shape the dress. The garment is thin like paper, but it is still comfortable to wear. Some of the garment designs are manufactured from fungi mycelium.
Another designer who inspired by this revolutionary material is Suzanne Lee, a British designer and director of Biocouture. She created fashionable jackets made of fungi mycelium.

In 2018, British luxury fashion brand Stella McCartney became the first brand collaborating with BOLT threads to produce the bags from vegan leather.

11.2.1.2 Lotus and banana fibers

Lotus fiber is a kind of natural fiber, which is extracted from the lotus stem and the lotus root. Lotus fibers nowadays are being used to manufacture luxury garments. In addition, lotus can be categorized as one of the finest and sustainable fabric in the word since its “waste” is transformed into a quality textile that does not use any polluting resources such as oil, electricity, gas, or any toxic chemicals during the entire production process.

Samatoa is recognized as an eco-friendly textile mill and design house, as it is providing Cambodian women with highly regarded textile crafting skills using lotus fibers. Although garments made from lotus fabric are not readily available on the current market, Italian company Loro Piana plans to sell products made from lotus fabric through Samatoa’s website. At Loro Piana, lotus flower fabric is available in light red, green, yellow, chocolate, and orange colors. Accessories such as light scarves and blazers made from the lotus fabric are sold at around $6000 apiece.

Banana fibers are in use in textiles since the early 13th century in Japan. In the past, the demand for banana fabric had declined due to the popularity of other fibers such as cotton and silk from China and India. But now banana fiber is making a comeback in the fashion industry. Guwahati-based designer Nandini Baruva presented her collection “Kirameki,” centered around sustainable fashion by using fabric made from banana fiber. She says, “Plant-based yarns have to be appropriately treated. They all have a unique texture, color and sheen, available in different thickness like other type of fabric, but most of all, they provide wearer the comfortable feel and with the beauty extracted from nature.” Some of the clothes produced were by Kirameki (Nandini Baruva).

Fig. 11.1 Fashion accessories manufactured from fungi fiber. Source: Bolt Threads.
11.2.1.3 Synthetic leather

One the most well-known fashion designers, Stella McCartney, has been guiding her own brand as a vegetarian brand, thus, there is no doubt that she prevents using animal leather in her products. For example, she had introduced an innovative “skin-free skin” leather fabric for Fall’17.

Another luxury brand, Dolce and Gabbana, is replacing animal leather with tree bark leather to create wonderful effects in their platform shoes and bags.

Some other brands such as KHOGY (a fish-leather based fashion business in Colombia) use fish and eel skins, which are typically thrown away as waste in the fishing industry. Concerning eco-friendly vegan leather shoes and accessories, brands such as Bourgeois Boheme, NAE Vegan, and Hugo Boss are using Pinatex, a textile type generated from pineapple industry waste. Matt and Nat and Corx is using Cork, a material from bark of the oak tree, that looks fabulous in wallets and bags. Meanwhile, Nat2 is a brand using coffee leather to make unisex sneakers, which are in high demand. Moreover, Happy Genie is a brand, which is totally sustainable as they use apple waste leather to produce fashionable handbags.

Turning to paper leather, some designers such as Ilvy Jacobs, Bottega Veneta, and Engage Green have also applied this material in their products. Regarding waxed cotton, it is a material that the brands such as Marc Jacobs and For All Mankind have long been used for bags and jeans, correspondingly due to its pliable, waterproof, and easily washable characteristics. In addition, the material could cut down on specialist textile cleaning bills and even save the environment against additional dry-cleaning substances. Interestingly, stated in Vegea Company’s website, a technology organization that collaborated with H&M Foundation in April 2017 in Vegeatex® innovation, a polymerization technology which is possible to transform grape peels and seeds into wine leather.

11.2.2 Recycling technologies

In addition to the new fibers used by various fashion brands, the use of recycled fibers of polyester and nylon are gaining increased popularity. This section describes the use of recycled fibers by global fashion brands.

11.2.2.1 Recycled polyester

Billion tons of polyester bottles and containers no longer in use end up in the garbage (Lou et al., 2005). Those are the pollutants that affect the environment so badly which is a major concern for people to resolve. In the 1940s, two scientists patented the PET based on the recycled polyester fiber from Terylene. This was the first step of recycling the plastic bottles and plastic containers in the fashion industry. The traditional recycling has some problems, but with the modern developments, scientists have found new technologies not only benefit to the industry but also preserve the environment. There are so many technologies with companies like BHET from Japan, HKRITA from Hong Kong, CARBIOS technology from France, and DEMETO from European Union (EU), a revolution which brings new period of sustainable recycling polyester in the fashion industry.
H&M is well known for fast-fashion clothing for men, women, teenagers, and children. Ever since 2013, H&M has been committed to sustainable products by collecting more than 34,000 tons of clothing to reuse and recycle. H&M always search for potential approaches to new technologies for effective recycling of polyester. In 2017, the H&M group participated in DEMETO with the aim to recycle polyester textiles into new fiber (H&M Sustainability) under the European Union’s Framework Program for Research and Innovation, Horizon 2020.

Patagonia is one of the leading global fashion brands adopting the sustainable materials. They recycle used polyester bottles, unusable manufacturing wastes, and worn-out polyester garments to manufacture new clothing following the circular economy concept. They manufacture various types of recycled garments such as shell jackets, board shorts, and fleece for both men and women. The use of recycled polyester reduces their dependence on virgin material derived from petroleum resources. This also helps to reduce the problems of landfill and emission of toxic emissions from incinerators. Some of the fashion products are manufactured by Patagonia.

11.2.2.2 Recycled nylon

Like polyester, nylon wastes can be recycled into new useable products. Nowadays, many global nonprofit organizations and fashion companies are finding ways in order to reduce the negative impacts of nylon wastes on the environment. There are some companies who are attempting to make products such as sunglasses, skateboards, and clothing from recycled nylon. Furthermore, there are some companies that collect abandoned fishing nets from ocean and give them a new life in the form of useable products. For example, a Norwegian company called Nofir Asset 7 (Nofir AS) had started to collect discarded fishing nets and gears since spring 2016, starting in Malta and converting them into new products. Since then they have collected 8000 kg of fishing nets from ocean in this area. The company tried its best to reduce the amount of fishing gears that were left in the sea by taking away useless materials from fishing industry. In addition, this company also helped the fishermen who wanted to get rid of the old equipment. Nofir AS takes care of all the transportation charges if necessary.

Nofir AS is just a small example of recycling company; there are many other companies such as Bureo Company, Net-Works, and Healthy Seas, who collect old fishing nets and recycle them with an attempt to save the environment. As the fishing nets are made from nylon and HDPE (high-density polyethylene), their material properties do not change even though they are exposed to salt water for a long time and are still suitable for recycling. Fishing nets are easy to recycle as they are thermoplastic, which can be melted to new products. In recycling process, the fishing nets are collected, cleaned, chopped into small pieces, palleted, and then melted to create new products such as bicycle seats, tool handles, chairs, plastic toys, and many other household products.

Aquadel, the fiber manufacturer in the United States, has developed a new product, ECONYL® (regenerated nylon) that can help to reduce the pollution caused by nylon waste. Aquadell starts with collecting not only the fishing nets, gears, and wastes in the sea, but also industrial plastic, fabric scraps, carpet flooring from all over the world. These wastes are then sorted and cleaned before they are converted in to new products. The nylon is then transported to Slovenia, using ECONYL® regenerated system to create ECONYL® regenerated nylon. After this, ECONYL® regenerated nylon is
processed into carpet yarns and textiles yarn that are used in fashion and interior industries.

As nylon can be recycled infinitely, without losing its quality, the company’s goal is that once their products are no longer useful for the customers, they can always go back to step one of the Regeneration System (Mihut et al., 2001). Products made from ECONYL® regenerated nylon is very familiar with fashion brands such as Adidas, Speedo, H&M, and Arena, and interior brands like Delos, Mercury, and Interface. The nylon recycling process is shown in Fig. 11.2.

Besides the conversion of old nylon materials into new products, there is a new program to “down-cycle” old fishing nets and gears into electricity by Hawaii’s multipartner marine debris group. First the nets are collected and sent to a scrap metal recycling facility where they are chopped into small pieces, and then the fragments are transported to another facility that is designed to convert these fragments to energy by incineration. This step will produce steam that drives a turbine from which electricity is generated. By this program, up to 832 tons of fishing nets are used that creates enough electricity for over 300 homes for a year.

11.2.3 Interview findings

During the preparation of this chapter, we also interviewed three global fashion brands to understand the concept of sustainable materials and processes adopted by them. Prior to the interview, the interviewees were communicated via email about the general description of the discussion and the interview questions. The interviews were organized in the manufacturing facilities to better understand the organization and ensure the credibility of the findings. The duration of each interview was about 1 hour. Data were collected in the form of audio recording, which were later transcribed for analysis.
All the three global fashion brands specified on their focus on the use of sustainable fibers such as organic cotton, low chemical cotton, bamboo, and lyocell. As per the standard requirements on sustainability, they source sustainable materials including fiber, yarn, and fabric to manufacture the garments. As per the statement of the sourcing manager of the fashion brand: “We focus to achieve environmental sustainability by using sustainable raw materials to make our clothes. We verify and confirm that our suppliers hold the certificates of their products, which meet the sustainability norms set for environmental sustainability. We are finding ways to include more sustainable raw materials in to all our product lines.”

The brands mentioned that they use various natural and synthetics fibers, which are organic and biodegradable. In the words of the country manager: “We use plant fibers such as organic cotton and linen, and animal-based fibers such as wool and cashmere. Our synthetic fibers including polyester and nylon are derived from recycled plastic bottles, fishing nets and old clothing materials. We are training our designers on the environmental impact of each type of product, which can help them to reduce the environmental impact during the design process. We are collecting information on the life-cycle assessment, with the help of an internal working group on the impact of recycled materials and other possibilities.”

One of the brands expressed the use of BCI certified cotton in the place of organic cotton. This is because the traceability of organic cotton is difficult, and the suppliers often fail to provide the necessary certification. In the words of a divisional merchandise manager with the global fashion brand: “We are trying to use more amount of BCI cotton rather than organic cotton, and we are a member of the BCI. This is because organic cotton involves complex process of certification and traceability of organic cotton is poor. BCI cotton not only reduces the use of toxic chemicals, but also promotes efficient water use, and fair working conditions. Our target in 2019 and subsequent years is to use 100% BCI certified cotton in our entire supply chain. The source of our BCI certified cotton involves countries such as Turkey, Brazil, Uzbekistan and India.”

All the brands are using recycled polyester and recycled nylon as a management policy. In the words of the country manager: “We are using recycled polyester rather than virgin polyester as the former has many advantages over the latter. The major advantage is the reduced carbon footprint of the recycled polyester as polyester is one of the major raw material in our product. Our focus is to replace all the virgin polyester with the recycled polyester by 2025. We use recycled nylon from consumer waste, industrial waste and waste collected from oceans (fishing nets). Use of recycled nylon helps us to reduce the problems associated with landfill and incineration”.

In the use of animal leather, all the three brands are following ethical practices. They are taking care of not to use the leather from endangered species and use the leather alternatives wherever possible. As per the interview with the divisional merchandise manager: “We are not using the leather from endangered species. We are also avoiding the leather from the animals subjected to cruelty and unethical practices. We also try to avoid the environmental impact of leather tanning by not using toxic chemicals and recycling the waste water within our supply chain network. We also verify the eco-certification with our suppliers. Our emphasis in recent years is to replace the animal leather with synthetic leather as much as possible.”
11.2.4 Academic research

Several academic institutions and research organizations are also working toward the concept of circular economy. The authors of this chapter were involved in some works by recycling the consumer waste and the industrial waste, which will be discussed in the following section.

11.2.4.1 Reuse of industrial waste

The waste management is crucial for many industries dealing with garments, fabrics, yarns, and fibers (Smith, 2003). There are diverse sorts of waste in the apparel industry starting from raw materials to the finished product. In fiber industries, there are fiber wastes; in spinning industries, there are wastes from dyed and undyed yarn, solid waste from the spinning process. Similarly, in the weaving process, mainly there are two kinds of waste: fabrics wastes and yarn waste. There are large quantities of waste from the cutting process, which is an important stage in garment production. Considering the apparel business, this is the most vital stage in garment manufacturing because it produces a massive amount of fabric waste, which is generated from the marker losses. Marker losses are the fabric losses produced because of the gap and the unused parts between the pattern pieces of the marker during the cutting process. Th other losses include ends of ply losses, ends of piece losses, edge losses, splicing losses, remnant losses, and ticket length losses.

There are several research studies in academic institutions to reduce the industrial waste. One such example is the students at RMIT University Vietnam working to reuse the industrial wastes collected from spinning, weaving, and garment industries. The students of fashion merchandise management collected fiber, yarn, fabric, and packaging wastes from various industries. Generally, these wastes are thrown by the industries into as a rubbish bin, which ends up in the landfill. The students applied innovative design concepts and converted the waste materials under the leadership of the principal author to different types of useable products. The yarn packaging wastes (cones and bobbins) were converted into products such as pen stand, home decorations, whereas the marker wastes were converted into garments. Some of the recycled products are shown in Fig. 11.3.

11.2.4.2 Upcycling of consumer waste

Upcycling is the process of converting the end-of-life clothing (EOL) to new products, which can be used again. Many of the fashion brands such as H&M and Zara are collecting consumer waste and converting them into new products. In an industrial project at RMIT University Vietnam, the students collected consumer donations and converted into various types of useable products. This work equipped the students with tools to solve global issues to achieve sustainable fashion from an industry perspective. This upcycling project can help to reduce the amount of waste EOL clothing ending up in the landfill and solve the problems associated with the incineration of clothing.
11.3 Sustainable technologies

There are many sustainable technologies used for garment dyeing, printing, and finishing. The contemporary technologies are replacing the traditional processes to achieve sustainability. The detailed principles of these technologies are discussed in earlier chapters. This chapter will discuss various contemporary technologies in dyeing, printing, and finishing the fashion brands are using.

11.3.1 Dyeing and printing

The traditional dyeing and printing technologies generate a large quantities of waste water or effluent, which are released to the eco-system (water or land). The effluent pollutes the water and the land leading to ecological imbalances. This section will discuss on various new dyeing and printing technologies, that are sustainable and used by fashion brands.

11.3.1.1 Natural dyeing

Natural dyeing uses the dyes derived from plant and animal resources, which are renewable and biodegradable. In addition, the amount of toxicity generated during...
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Fig. 11.4 Monsoon Blooms natural dyed clothes.
Source: https://www.monsoonblooms.com/.

natural dyeing is substantially lower than their synthetic counterparts (Mirjalili et al.,
2011). Therefore, many fashion brands are switching to natural dyeing from synthetic
dyeing. For example, Monsoon Blooms is a brand, which seeks Ayurvedicbased lifestyle. All the products from this brand are hand-dyed with medical plants. The dyehouse used for dyeing was set up by Central Government of India to protect Ayurvedic
medicine and ancient dyeing method called Ayurvastra. According to Eco Warrior
Princess, Ayurvastra utilizes mixture of plants, roots, and herbs and boils them with
fabric at controlled temperatures. When the fabrics are ready to be worn, these medicines are absorbed by the skin and into the body. Some of the natural dyed products are
shown in Fig. 11.4.
Scotland’s Harris Tweed, known for its warmth tweed jacket manufacturer in
Scotland, uses natural dyeing and eco-friendly dyeing processes. Sources such as
lichens (a type of fungus) and the plant woad (plant for indigo) are used to dye
deep reds, purples, and yellow checks of the brand.
Patagonia is known as a sustainable brand since it is marketing and selling outdoor
gears for skiing, climbing, surﬁng, snowboarding, ﬂy ﬁshing, and trail running. Patagonia is one of the ﬁrst brands that adopts natural dyes and manufacturing processes. In
2017, Patagonia had launched a new collection called Clean Colors, which included
ﬁve styles for womenswear and menswear that were applied with the natural dyes,
out of which 96% of dyes were made from renewable sources such as food waste,
pomegranate, carmine, citrus brown, palmetto green, and indigo. According to Sarah
Hayes, the Senior Material Research and Innovation Manager of Patagonia, dyeing is
the major key for their long-term business. Moreover, she is trying to develop some of
natural dyers in the world that allows her to achieve the goal that help natural dyes to
be more affordable for textile industry in the next ﬁve years (Laughlin, 2017).


11.3.1.2 Waterless dyeing

In dyeing process, dyes are applied to various textile substrates from a special solution containing dyes and other chemicals. The dye molecules are attached to the substrates by absorption, diffusion, or chemical bonding with parameters such as pH, temperature, and time as controlling factors. The affinity between the textile substrate and dye molecule depends on the dye class and the type of fiber in the textiles. Various dyeing methods are adopted to apply color to the textile material in different stages such as fiber dyeing, yarn dyeing, fabrics dyeing, and garment dyeing. In many of the dyeing methods, a large quantity of water is used to apply the dye into the textile substrate. For example, a simple cotton T-shirt can use up to 2700 L of water to apply the color.

Almost all the textile industries now use the traditional process of dyeing using water as a medium. After dyeing certain amount of textile materials, the dyeing exhaustion is reached, which indicates the dye is completely fixed and no more dye can be absorbed by the substrate. However, at this point there are still large quantities of chemicals and auxiliaries in the wastewater or effluent. In the textile substrate, the unfixed dyes and chemicals are released to the water after fixation and washing. The textile effluent in many instances is released to the surrounding land and water system, causing environmental problem. To avoid this problem, various waterless techniques such as dyeing with carbon dioxide or DyeCoo, air dyeing, and ultrasonic dyeing are used.

DyeCoo uses supercritical carbon dioxide (SCCO₂), which is formed when the pressure and temperature of CO₂ exceeds 73.8 bar and 31.1 °C, respectively. Supercritical
CO₂ possesses good solvency power, which is the key for dyeing with CO₂. Dyeing with SCCO₂ is free from chemical toxicity and effluent generation as it’s a waterless dyeing technology. DyeCoo follows almost a closed loop system as 95% of the CO₂ used can be recovered and reused. The energy consumption is reduced by 50%, and DyeCoo process is quicker than the traditional process. Therefore, DyeCoo is a sustainable technology. However, some of the disadvantages of DyeCoo are the use of high pressure, which requires a special design machinery and the initial investment is very high. Although the initial setup cost is higher, the cost of dyeing clothes is much cheaper. The setup used for DyeCoo process has been shown in Fig. 11.5.

Global fashion brands such as Nike, Adidas, GAP, and IKEA Green Tech AB use SCCO₂ dye technology. In 2017, Nike introduced DyeCoo technology in its manufacturing plants by opening a manufacturing facility in Taiwan based on SCCO₂ dyeing. Besides, Nike also have a range of products such as Nike Super Bowl 50 collection that use DyeCoo technology. Adidas is also using the SCCO₂ dyeing technology in its garment and footwear line by rolling out the traditional technology. Gap Inc. has already taken initiatives to manufacture denim using indigo dye and DyeCoo technology with a partnership between Banana Republic and Spanish denim mill, Tejidos Royo. IKEA, a venture capital division of Sweden-based retailer of IKEA Group has launched the waterless textile dyeing technology using CO₂ known as Green Tech AB. All these brands are leading toward sustainable fashion materials, processes, operations, and supply chains leading to a cleaner environment.

Like CO₂, dyeing with air or “Air-Dye” technology is also gaining popularity, which uses 95% less water and 86% less energy compared to traditional dyeing process. In addition, problems such as fabric damage, shade variation, and dyeing defects are reduced in Air-Dye technology. The feel as well as the fastness properties of the fabrics are also improved. In Air-Dye technology, the fabric is moved by the air in place of water, which as a big step in reducing toxic chemicals and water consumption. The flow of air is the key factor in the Air-Dye technology as air is used in transporting the fabric in jet-dyeing machines. Due to the use of air, there is no problem of effluent treatment and environmental pollution.
11.3.2 Garment finishing

Garment finishing by using laser and digital printing are also considered as sustainable technologies. These technologies are considered ecofriendly due to the elimination of wastewater and landfill problems, which are discussed in the following section.

11.3.2.1 Laser finishing

For the sake of a sustainable fashion, the famous denim brand Levi’s has successfully merged robotics with the manufacture of jeans by applying laser in a more environmentally friendly way. Fading denim and creating tears to look as authentic as possible needs several harsh ingredients along with grueling manual processes. Chemicals, multiple washes, and sandpaper are long-term factors on the traditional production line. Hence, it’s a tricky business to judge how bad a pair of jeans is for the environment, but to make it easier it can be considered that the more distressed they look, the more stressed the environment becomes. That is the reason why vintage feel comes with an environmental price tag.

Fortunately, Levi’s new laser finishing system (Levi’s arms robots with laser) is not only able to give its jeans that authentic look, but it also helps Levi’s to reduce both its carbon footprint and the number of hazardous materials used during the production process. This new technology is revolutionizing the way jeans are finished. With this new technology, as a replacement for hours of washing, intensive manual labor and scrubbing a robot is tasked with using infrared lasers to etch off thin layers of indigo and cotton. As a result, the same familiar faded finish and tears are created in as little as 90 seconds.

Compared with two or three pairs of jeans per hour utilizing the conventional process, the laser-equipped robots show a huge step forward. Head of Levi’s innovation center, Bar Sights said that the new system was not an incremental change, it was radical. Fig. 11.6 shows Levi’s new laser-finished denims with the use of robots.

11.3.2.2 Digital printing

Digital printing is also considered to be sustainable as it is free from the effluent problem (Nayak et al., 2007; Tyler, 2005). Digital printing allows the production of

Fig. 11.6 Levi’s new laser finishing robot for denim.
small quantities of fabrics without producing much waste. Digital printing reduces the usage of freshwater and energy consumption. It saves time as the print designs can be directly printed in the fabrics without much preparation of the dyeing and printing liquor. The sharpness and brilliancy of the images are improved in digital printing. Digital printing can also be used to print customized designs with precision both in fabrics as well as in the garments. Some of the clothes produced by Madhura creation using digital printing are shown in Fig. 11.7.

11.3.3 Interview findings

We also included the interview findings from three fashion brands mentioned above in the use of sustainable technologies. These global fashion brands expressed that they are using many of the sustainable technologies, which are discussed in the following section.

DyeCoo and Air-Dye are the technologies used by the global fashion brands to reduce the environmental impact. As per the sourcing manager’s statement: “We are using the new technologies for dyeing using carbon dioxide and air. These technologies are free from water pollution and save a large amount of energy, hence, they are eco-friendly. We are encouraging our suppliers to use the new technologies to reduce the environmental impact.”

There are several advantages of using laser over the conventional processes in cutting, engraving, embossing, denim fading, and other applications (Nayak and Padhye, 2016). In addition, product damage potential is reduced, no/less consumables are needed, and no problem of toxic by-product disposal as found in laser applications. In the response to our interview questions on the use of laser the country manager replied: “We are using the new technology such as laser in many of our manufacturing processes. We have replaced the traditional sand blasting technology for color fading denim with the laser application to achieve the same effect with little or no impact on the environment.”

However, the fashion brands included in our interview mentioned that they are not using the natural dyeing due to the associated difficulties in the processes. As natural dyeing cannot produce the brilliant shades, has poor fastness properties, and is limited
in the color range, they are not using natural dyeing. In the words of the country manager: “Although natural dyeing is ecofriendly and derived from renewable resources, we are not using natural dyeing due to the associated difficulties in the dyeing process. We cannot achieve the depth of the shade and they are poor in fastness properties. May be in the future we can use them, when these problems are resolved.”

11.4 Conclusions and future directions

This chapter has discussed the use of sustainable materials and technologies by various fashion brands during the manufacturing and supply chain process. Various sustainable materials such as organic cotton, BCI certified cotton, hemp, linen, wool, and silk are gaining impetus due to their biodegradability and natural source. New fibers derived from wastes such as orange peels and coffee beans are also discussed in this chapter. Innovative fibers from milk, seaweed, soybean, and lotus leaf are also being adopted by some fashion brands. Similarly, the use of recycled polyester and recycled nylon are also widely used as they are cheaper and reduce the dependency on virgin raw material.

The use of sustainable technologies such as natural dyeing, super critical carbon dioxide dyeing (DyeCoo), air dyeing, plasma technology, laser processing, and digital printing are also gaining popularity to become sustainable in the fashion manufacturing process. Fashion brands such as Adidas and Nike are using DyeCoo technology and air dye technology, which is helping to reduce the environmental problems of effluent treatment. Many of the fashion brands such as Monsoon Blooms and Scotland’s Harris Tweed are using naturel dyeing to achieve sustainability. Other technologies such as laser, plasma technology, and enzyme applications are replacing the traditional technologies to achieve sustainability by reducing the environmental impact.

The future of sustainable materials and technologies seems to be very bright. Due to increased consumer awareness and stricter global regulations, the fashion brands are trying to achieve sustainability. Many of the fashion brands are spending a large amount of their income to manufacture new sustainable products by research and development. The traditional fashion manufacturers need to adopt the sustainable approaches to survive in a global competitive environment. The industries that cannot follow the sustainable drive may need to close their business.

References


Ratnapandian, S., 2013. Application of Natural Dyes by Padding Technique on Textiles.
Part Five

Sustainable materials and recycling of textile wastes
Recycling of end-of-life clothes

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12.1 Introduction

Textile and apparel industry is one of the biggest industries in the world. It has been growing over time, along with the population growth as clothing is essential for humans (Sandin and Peters, 2018). The growth of the textile industry was around 9.7% per year over the last 5 years. The textile and apparel industry costs about 3 trillion dollars, which accounts for approximately 2% of the world’s Gross Domestic Product (GDP). The expansion of the textile market related to textile production technology can produce low price clothing and large quantity. The low-price products persuade the consumer to buy more and make an easier decision to dispose of them afterward. This consumer behavior is named “fast fashion.” The fast fashion trend is the key factor that drives the consumption in the clothing of the consumer. Not only the fast fashion trend but also the economic growth influence the textile waste generation. In the industrialized countries, the vendor company has excellent marketing of new products and the disposal of old ones because the stylistic norms promote their obsolescence (Claudio, 2007). The fashionable clothing contributes to consumption at a higher level than needed (Chavan, 2014). The massive amount of textile production and high clothing disposal rate have led the textile and apparel industry to the second largest polluting industry in the world. Processes involved in the fashion supply chain are contributing to a negative impact on the environment, for example, the pesticide usage in cotton cultivation, intensive water requirement during the textile production process, and the chemical usage in the textile production process. These pollute the environment. The textile industry sector contributes to 10% of the carbon footprint in the world. Textile waste management has emerged to reduce negative environmental impact and create global sustainability. Textile waste management, including recycling technology, is essentially required. It provides opportunities to reduce natural resources consumption and decrease carbon dioxide emission during the landfilling.

This chapter emphasizes the importance of textile recycling by focusing on the generation and quantity of textile waste, recent textile waste management technology, environmental issues of textile waste, textile waste management program, recycling technologies, and the application of recycled fiber and the challenges in this field.
12.2 Quantity of waste generated from the textile industry

The volume of clothes consumed globally has increased every year because of the increasing population growth, decreasing the price of textile and apparel, the faster fashion trend, and the planned obsolescence consumer. The increase in textile consumption has reflected in increased textile waste because the consumer tends to buy more clothes and disposes of it quickly. This behavior affects the depletion of natural resources (Chavan, 2014) and textile waste generation from indiscriminate disposal habits. There are three different sources of textile: (1) fiber, yarn, and fabric processing, (2) sewn products manufacture, and (3) discard at the end of its useful life (see Fig. 12.1). The waste from the fabric processing and manufacturing is categorized as preconsumer textile waste. The preconsumer textile waste recycling is not complicated because the composition and properties of textile waste are known. On the other hand, the postconsumer textile waste composition is complex, and it has a wide variance in quality and condition. The mixture of textile composition would make it more difficult to recycle.

As mention earlier, the textile and apparel products are complicated and varied in rational goods. It contains yarn from processed cotton fiber, which is woven or knitted into a fabric. It could also be woven together with other natural fiber or synthetic fiber such as nylon, polyester, polypropylene, and acrylic fiber. This mixture of fiber in fabric material and extra treatment make it hard to recycle or decompose. At the end of the clothes functional lifetime, the consumer disposes it as noncompostable waste. The accumulation of textile waste has resulted in an increasing environmental concern.

The textile wastes are categorized according to their source into two groups: the preconsumer and the postconsumer textile waste (Pensupa et al., 2017). Preconsumer textile waste is the manufacturing waste that happens before the product reaches the customer. This waste includes thread tails, fabric scraps, and quality control—rejected patches. The postconsumer textile waste is any clothes or household textiles that the consumer no longer needs and decides to discard. This section mainly focuses on postconsumer textile waste.

The textile waste reached 92 million tons in 2015 and has been predicted to increase to 148 million tons in 2030 (Echeverria et al., 2019). It usually discards as municipal solid waste for landfilling. The textile was accounted for 4% of municipal solid waste (Claudio, 2007). The pure cotton fiber is a decomposable material; it can be degradable.

![Fig. 12.1 Traditional sources of textile waste.](image)
during landfilling. However, some textile wastes contain synthetic fiber that takes a long period to be broken down in landfill and may never do so in that anaerobic environment. Therefore, textile waste management is an important key to reduce waste accumulation in a landfill.

Nowadays, the consumer decides the lifetime of clothes according to the fashion trend. They may discard it before its actual life span. The clothes lifetime is around 2–10 years based on the International Fabricare Institute data (see Fig. 12.2). The short lifetime of clothes increases the volume of textile waste in landfills.

About 75% of the world’s fashion market is within Europe, the United States, China, and Japan. European country, especially in the United Kingdom consumed 1.1 million tons of textiles in 2014 (1.7 million tons in 2014, including nonclothing textiles). There is a 5% increase compared with 1.0 million tons in 2010. The clothing bought in any year is likely to be disposed of in a couple of years later because of their lifetime. As a result, the discarded items are accumulated in the landfill as a municipal solid waste stream, and in the United Kingdom, it was accounted for 4%–5% of the municipal solid waste stream (Woolridge et al., 2006). The United Kingdom generated textile waste of around 1.13 million tons (Gracey and Moon, 2012). About 70% of those goes to the reuse and recycling process while the rest goes to incinerated (80,000 tons) or to landfill (350,000 tons) (Gracey and Moon, 2012). Besides, Spain alone generated 301,600 tons of textile waste in 2011 (Barbero-Barrera et al., 2016), while Nordic countries produced a similar amount as Spain. In Nordic countries such as Denmark, Finland, Iceland, Norway, and Sweden have a similar pattern of textile consumption and management. The Nordic residents consumed 13–22 kg of textile items per capita. Most of the textile waste in these countries are collected, and over half of the collected textile waste is exported for reusing/recycling propose or reusing domestically. The incineration unit can handle only a small amount of waste. In Denmark, approximately 89,000 tons of textiles are consumed every year. This amount of textile consumption generated 41,000 tons of textile waste. Around 15% of the waste is sent to incineration, while 23,000 tons are exported for reusing and recycling, and 12,000 tons are reused within Denmark (Palm et al., 2014). Like Finland, the amount of textile consumption is about 71,000 tons, which corresponds to 13.5 kg per capita. Only 25,000 tons of textile waste are collected for reuse/recycling and 3300 tons are put into incineration.

On the whole, European countries have discarded textiles approximately 5.8 million tons per year (Barbero-Barrera et al., 2016). The disposed textiles around 15%–20% are collected (the rest is landfilled or incinerated), whereas about 50% is downcycled, and 50% is reused, mainly through exporting to developing countries (Sandin and Peters, 2018). The Waste & Resource Action Program (WRAP, UK) reported that 95% of the landfilled textile waste is recyclable materials (Hu et al., 2018).

The United States is the top of the textile and apparel consumer, and it produces raw material to serve the business of other countries. The raw material for clothing like cotton is mostly provided in the United States and exported to developing countries for textile production (see Table 12.1).

The United States is the biggest textile consumer. The United States has also disposed approximately 15 million tons of textile per year. The volume of textile waste
Fig. 12.2 Average life expectancy of the textile item (year).
has gradually increased over the past 20 years, and it has reached 16 million tons in 2015 (EPA, 2015) (see Table 12.2), accounting for 32 kg of textile waste generated per capita.

The United States Environmental Protection Agency (EPA) reported that 16.2% of the textile waste volume (2.62 million tons) gets recycled while the remaining textile wastes go to landfill (10.46 million tons) and combust for energy recovery (3.14 million tons) (Hanoğlu et al., 2019). Charity organizations play an essential role in recycling most postconsumer textile waste. Approximately 500 recycling companies

Table 12.1 Cotton as input material by country (million tons).

<table>
<thead>
<tr>
<th>Country</th>
<th>Production Amount</th>
<th>Export Country</th>
<th>Export Amount</th>
<th>Import Country</th>
<th>Import Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>7</td>
<td>USA</td>
<td>2.4</td>
<td>China</td>
<td>4.0</td>
</tr>
<tr>
<td>India</td>
<td>6.3</td>
<td>India</td>
<td>1.7</td>
<td>Bangladesh</td>
<td>0.7</td>
</tr>
<tr>
<td>USA</td>
<td>2.8</td>
<td>Australia</td>
<td>0.9</td>
<td>Turkey</td>
<td>0.5</td>
</tr>
<tr>
<td>Pakistan</td>
<td>2.1</td>
<td>Brazil</td>
<td>0.8</td>
<td>Indonesia</td>
<td>0.4</td>
</tr>
<tr>
<td>Brazil</td>
<td>1.6</td>
<td>Africa</td>
<td>0.8</td>
<td>Vietnam</td>
<td>0.4</td>
</tr>
<tr>
<td>Australia</td>
<td>1</td>
<td>Uzbekistan</td>
<td>0.6</td>
<td>Thailand</td>
<td>0.3</td>
</tr>
<tr>
<td>Uzbekistan</td>
<td>0.9</td>
<td>Argentina</td>
<td>0.3</td>
<td>Korea</td>
<td>0.3</td>
</tr>
<tr>
<td>Others</td>
<td>3.3</td>
<td>Others</td>
<td>0.9</td>
<td>Others</td>
<td>1.8</td>
</tr>
<tr>
<td>Total</td>
<td>25.2</td>
<td>Total</td>
<td>8.4</td>
<td>Total</td>
<td>8.4</td>
</tr>
</tbody>
</table>

Source: Data from USDA, Bloomberg (Tot, 2010).

has gradually increased over the past 20 years, and it has reached 16 million tons in 2015 (EPA, 2015) (see Table 12.2), accounting for 32 kg of textile waste generated per capita.

The United States Environmental Protection Agency (EPA) reported that 16.2% of the textile waste volume (2.62 million tons) gets recycled while the remaining textile wastes go to landfill (10.46 million tons) and combust for energy recovery (3.14 million tons) (Hanoğlu et al., 2019). Charity organizations play an essential role in recycling most postconsumer textile waste. Approximately 500 recycling companies

Table 12.2 The textile waste management pathway (EPA, 2015).

<table>
<thead>
<tr>
<th>Year</th>
<th>Generation</th>
<th>Recycled</th>
<th>Combustion with energy recovery</th>
<th>Landfilling</th>
</tr>
</thead>
<tbody>
<tr>
<td>1960</td>
<td>1760</td>
<td>50</td>
<td>—</td>
<td>1710</td>
</tr>
<tr>
<td>1970</td>
<td>2040</td>
<td>60</td>
<td>10</td>
<td>1970</td>
</tr>
<tr>
<td>1980</td>
<td>2530</td>
<td>160</td>
<td>50</td>
<td>2320</td>
</tr>
<tr>
<td>1990</td>
<td>5810</td>
<td>660</td>
<td>880</td>
<td>4270</td>
</tr>
<tr>
<td>2000</td>
<td>9480</td>
<td>1320</td>
<td>1880</td>
<td>6280</td>
</tr>
<tr>
<td>2005</td>
<td>11,510</td>
<td>1830</td>
<td>2110</td>
<td>7570</td>
</tr>
<tr>
<td>2010</td>
<td>13,220</td>
<td>2050</td>
<td>2270</td>
<td>8900</td>
</tr>
<tr>
<td>2015</td>
<td>16,030</td>
<td>2450</td>
<td>3,050</td>
<td>10,530</td>
</tr>
</tbody>
</table>
in the United States export postconsumer textile waste to less developed countries. The United States is one of the top used textile exporters globally (see Fig. 12.3). Almost half (45%) of the collected textiles are recycled as secondhand clothes.

Asian countries are the most significant textile producers in the world. Almost 60% of textile products are manufactured in China, Bangladesh, India, Pakistan, Vietnam, and Indonesia. Therefore, the textile waste stream in Asian countries consists of pre-consumer and postconsumer textile waste. The Chinese population has gradually increased. The current population of China is 1.4 billion (excluding Hong Kong and Macau), which is equivalent to 18% of the total world population. The demand of textile and clothes is growing along with the population growth. China’s economy has also developed tremendously. The development of China has brought the fast fashion trend. The textile industry in China is the biggest in the world in both overall production and exports due to the low labor costs and plenteous resources.

Furthermore, China has employed modern technology to create a low-price and short-lived apparel for serving fast fashion trends. The trend could lead to a rise in the level of textile waste. Liang et al. (2018) reported that China alone had produced 26 million tons of textile waste (both preconsumer and postconsumer) per year, and only 1% of the waste goes to recycling process (Jianfang Liang and Xu, 2018). The low level of reuse and recycling clothes is related to the Chinese norm. Chinese consumers unwilling to use secondhand garments because of the available low-priced new apparel products in the Chinese market face saving concern because of the financial inferiority perception of the user of secondhand products and lack of a national system to facilitate the collection of used clothing items from consumers. Therefore, the textile waste is accumulated at a catastrophic level, causing clogged landfills and environmental pollution.

![Fig. 12.3 Top 10 exporters of used textiles in 2014 (share of total mass exported globally) (WRAP, 2016).]
Hong Kong is a leading production center and a global hub for clothing sourcing. Textile industry in Hong Kong is a significant export business accounting for 1.5% of the total export in 2017. Approximately 416 manufacturing units are in Hong Kong. The textile manufacturing in Hong Kong focuses on sophisticated and high value-added items, including quality ring-spun, open-end yarn, fine-gauge knitted fabrics, and complicated dyed and printed materials. The textile produced in Hong Kong around 48% were exported to Mainland China and the other major export markets, such as Vietnam, Bangladesh, Cambodia, Indonesia, Sri Lanka, Thailand, the United States, India, and the Philippines. In this circumstance, Hong Kong textile industry has created a strategic partnership with these countries; for example, Mainland China would supply the cotton for producing cotton textile and sending it to the Hong Kong companies’ offshore production of garments. In recent years, many Hong Kong textile manufacturers have relocated their production of lower-end and mass products to Southeast Asian countries such as Bangladesh, Cambodia, and Vietnam because these countries have low labor costs and nonrigorous environmental regulations.

Moreover, Hong Kong has developed textile technology to produce either a wide range of quality products in bulk or specialized items within a short lead time for varied applications. The technology will, of course, respond to fashion trends and drive market demand. With the considerable textile business growth, around 306 tons of textile waste was generated daily in 2015, and 93.2% of these ended up in landfills (Wang et al., 2018). The rest 6.8% of collected waste was locally recycled or exported as secondhand clothes, and a small number of textile waste was put into incineration (Ryu et al., 2007). Unlike any other place, Hong Kong is one of the most densely populated areas in the world. Reported population density of Hong Kong was 6732 people per square kilometer in 2017, according to the United Nations Department of Economic and Social Affairs data. Therefore, Hong Kong has limited landfill space, and the land is expensive and hard to find. The high level of accumulation of textile waste in landfill requires a quick solution.

In the developing countries that produce a massive amount of low-priced apparel, such as Bangladesh, Sri Lanka, and Vietnam, they have a similar pattern of waste production. The textile industry is one of the most critical sectors in the country’s economy. Most domestic textile products have been exported to achieve foreign exchange income. Bangladesh is the second biggest apparel exporter in the world after China. The textile and apparel sector contributes approximately 80% of the total export income, and it accounts for a 15% share of the country’s GDP (Islam et al., 2013). The massive production of the textile product is due to the plenty of resources of the country, opportunities, and beneficial government policies. Even the raw materials such as cotton and synthetic fiber were import from the United States or other countries, but natural gas, water resource, and labor play a dominant role in the production of ready-made garments. The Bangladesh garment manufacture is mostly located in Chittagong, Dhaka, Gazipur, and Narayanganj by the river consumes where it can easily reach the water supply. The abundant low labor costs and low energy costs are the main advantages of the Bangladesh textile industry. Bangladesh also has a trade
agreement on textile and clothing with American and European countries (Multi Fiber Arrangement, MFA).

Moreover, the textile business in Bangladesh is also supported by the country’s government policies to improve the exporter efficiency and promote the textile business for foreign investors. The plans support monetary advantages and institutional help. All these factors had led to the massive textile production, leading to a significant amount of preconsumer textile wastes (fabric or fiber cutting waste from the apparel industry). Figs. 12.4—12.6 show the types of waste occurring during textile

**Fig. 12.4** Type of solid waste generated during textile production (Bhuiya & Kuunal).

**Fig. 12.5** Waste production at each textile production stage (Bhuiya & Kuunal).
production, the amount of waste generated at each stage, and the textile waste type during textile production.

The textile waste is called “jhuta” or “jhoot” in Bangladesh. Bangladesh has produced 250 kg of textile waste daily (Bhuiya & Kuunal). The jhuta is collected and recycled to yarn. Approximately 550 tons of garment waste is being exported abroad from the port of Chittagong. The full container (40 cubic feet) of textile waste is worth of USD 15,000. These recycling businesses have the potential to reduce the accumulation of textile waste in landfills.

In Sri Lanka, the total export income of USD 4.6 billion is from the textile and apparel business. It represents 46% of the entire merchandise exports of the country (Dissanayake et al., 2018). Sri Lanka has approximately 300 textile manufacturers in the country. Most of textile and apparel produced in Sri Lanka was exported to the United States and European country. In 2014, Sri Lanka exported 294,000 tons of textile products, and approximately 44,100 tons of textile waste was generated accordingly (Dissanayake et al., 2018). Although there is a large amount of textile waste generated in Sri Lanka, there is still no effective waste management program to handle textile waste. The waste would be dumped into the open dump site and pollute the environment.

Vietnam is one of the biggest clothing exporters. The textile and apparel industry of Vietnam has a long history, and the business grows rapidly over the last decade. The industry growth has coincided with a rapid inflow of foreign direct investment. Vietnam has a trading agreement with many countries such as the European Union (EU), Japan, Korea, China, Hong Kong, Singapore, Taiwan, and the United States, which are the biggest textile market countries. With the preferential government’s policies and supportive solution, the compound annual growth rate of this business has increased by 19% per year (Ho and Watanabe, 2017). The textile industry plays a vital role in national social economy as 2.2–2.5 million people were employed in the industry to produce textile products contributing to 15% of national GDP (Ho and Watanabe, 2017; Luong et al., 2016). Currently, there are about 6000 textile and apparel
enterprises in the country and most are located in the Southeast and around the Red River Delta. Textiles and apparels are Vietnam’s second export products. Around 70% of Vietnamese textiles were export to the United States (42%), Japan (12.4%), South Korea (8.9%), Germany (3.8%), Spain (3.5%), the United Kingdom (2.8%), Canada (2.4%), China (2.2), the Netherlands (1.8%), and Taiwan (1.0%), and it costs USD 24 billion in 2014 (International Trade Administration, 2016). The high amount of clothing demand leads to a high volume of textile produced and textile wastes generated. The textile wastes from the manufacturer, such as the dust of cotton, fabric residues, waste accessories, metal, and plastic, are separated at the source for reusing and recycling. The dust of cotton and fabric residue are accounted for 22% of the total textile waste (Phuong, 2003), and some of the collected textile wastes were exported (see Table 12.3). The textile waste market in Vietnam is a competitive business. There are many professional collectors, preprocessors, and recyclers of textile wastes such as fiber, yarn/selvage, and clips located in Vietnam. These companies export textile waste to more than 20 countries in Asia for reprocessing purposes (see Fig. 12.7). This scenario could reduce the volume of textile waste and environmental pollution, but the recycling rates are considerably low compared to the waste generation. For the post-consumer textile waste of Vietnam, the wastes are disposed alongside with other organic wastes from household and sent to dumpsite station (see Fig. 12.8).

Turkey is another big textile and apparel manufacturing country. Turkey is the third-largest textile supplier of the EU (Alkaya and Demirer, 2014). Approximately 3.5 million tons of yarn and 3.6 million tons of knitting and weaving products are export to the EU countries (Ozturk et al., 2016). The textile and clothing industry has a significant contribution to the Turkish economy as there are 56,000 textile manufacturers in the country and over 2.0 million people employed to work the business in 2013. The turkey’s clothing business costs USD 15 billion for exporting product, therefore, contribute to 7% of national GDP. The clothing industry exported some 65% of its production.

In 2014, the total value of clothing exports in Turkey increased to USD 16.26 billion, and cotton clothing is the primary export textile product (80%). The knitted clothing and accessories, with an export value of US$ 10.02 billion, had a share of 61.66% in total clothing exports, and woven clothing had a share of 34% with a value of US$ 6.23 billion (Akhi Akter and Mir Abdullah, 2018).

<table>
<thead>
<tr>
<th>Material</th>
<th>2016 (million USD)</th>
<th>2015 (million USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber and yarn</td>
<td>2930</td>
<td>2540</td>
</tr>
<tr>
<td>Apparel</td>
<td>22,762</td>
<td>21,805</td>
</tr>
<tr>
<td>Fabric</td>
<td>1079</td>
<td>997</td>
</tr>
<tr>
<td>Geotechnique fabric</td>
<td>415</td>
<td>435</td>
</tr>
<tr>
<td>Accessory</td>
<td>1120</td>
<td>1187</td>
</tr>
</tbody>
</table>

Table 12.3 The overview of the export structure of Vietnam textile industry in 2016.
Fig. 12.7 The oversea textile company that has a free trade agreement with Vietnamese Textile Company (An, 2016).
Fig. 12.8 Municipal solid waste composition in percent of landfills in big cities in Vietnam (Truong, 2018).
High textile production leads to solid wastes generation in Turkey. Textile wastes were directly sent to the landfill sites of municipality instead of reusing in the mill. It accounts for 3%—4% of the total solid waste at the landfill station. Altun et al. reported that approximately 884,890 tons of textile waste generated in 2009. According to the manufacturer survey, the ratio of textile waste at landfill stations comprised 29% cotton and 24% polyester. There are 426,406 tons of household textile wastes generated and 73,357 tons of textile wastes in landfills. Therefore, it was estimated that 144,931 tonnes of cotton and 119,943 tonnes of polyester might have been wasted in 2009 together with other wasted textile raw materials (Altun, 2012).

According to the fast fashion trend spread all over the globe, the quantity of textile production has increased, and textile waste has subsequently generated. The amount of textile wastes generated daily is so enormous. Improper waste management has polluted the ecosystem and affected human health. This situation has raised the environmental concern about textile waste management system.

12.3 Textile waste management

The textile industry is known for a highly polluting activity in the world. It creates a high amount of pollution and consumes various natural resources. Air and water around the textile manufacture get polluted because of the excessive chemical use during the textile and apparel production. In almost every step of textile production, especially the dying and washing process in textile manufacturing leads to a high volume of water usage. Furthermore, the textile production also processes energy-intense activity. However, this section will focus on the management of textile waste, which includes pre- and postconsumer textile waste.

The textile waste composes of natural fiber, synthetic fiber, and accessories such as plastic and metal scrap. The natural fiber may take weeks or years to decompose depending on the source of fiber. For example, the product made of wool takes 15 weeks to break down (Hustvedt et al., 2016), and it almost completely degraded after a year in a landfill. Cotton is the world’s most widely used natural fiber in the textile market. The cotton fabric takes 5 months for decomposition.

On the other hand, the synthetic fiber in textile waste has hardly degraded the material. Synthetic fabrics such as polyester, spandex, and nylon take 30—40 years to break down, and it may take more than a hundred years to decompose fully. The fabric nowadays is made from fiber blend where two or more textile fibers are used. Cotton blend (cotton-polyester blend) is mostly used in the business. The ratio of cotton to polyester is varied. The complex fiber blend makes it difficult to break down even the cotton fiber that is compostable material. This leads to a pile of textile waste accumulated in the landfill.

The improper landfilling of textile wastes would contaminate groundwater and generate greenhouse gases upon decomposition. Methane is the dominant greenhouse gas formed during textile waste decomposition. It is a potent greenhouse gas contributing to global warming. Wool degradation generates ammonia, which is highly toxic in both terrestrial and aquatic fields (Dissanayake et al., 2018). According to the
pollution from accumulated textile waste, textile waste management is needed. The waste management of the textile product is different from other materials because the textile waste is a unique substance. The varied combination of the content requires a separate process of recycling. Therefore, the textile waste management has little attention from the manufacturer and consumer. This could be the reason for the small market share of textile waste management. Fig. 12.2 indicates that textile has contributed only 3% of global waste management market share (see Fig. 12.9).

Even the textile waste is unique, but the same principal waste management was applied (Meyer et al., 2016). The concept of textile waste management is shown in Fig. 12.10.

Waste management is considered to reduce the environmental problem from waste. The strategy to waste management gives priority to prevention and minimization first because the prevention and minimization of textile waste are processes to reduce the

![Fig. 12.9 Global waste management market share (%).](image)

![Fig. 12.10 Waste management hierarchy.](image)
waste stream generation. Prevention and minimization are profoundly affected by consumer behavior. The educating and rising environmental awareness are the keys to change consumer behavior toward increased prevention of textile waste. This could be applied to the manufacturing level by staff education and training. The rising concerns about the textile waste impact on the environment for all of the employees supported by existing practices and the procedure can reduce the textile waste generation.

Reusing is the next step after prevention and minimization in the waste management hierarchy. The textile reusing aims to prolong the useful life span of textile products by transferring them to new owners (Sandin and Peters, 2018). This step can be implemented in secondhand shops, flea markets, clothing charity stores, or even online market place. Salvation Army Trading Company Ltd. (SATCOL), SCOPE, and Oxfam are also secondhand clothing charity shops in the United Kingdom. Each shop collects between 5 and 7 tons of postconsumer textile waste per annum. The SATCOL alone has set up more than 200 shops for trading postconsumer textile waste. On the whole, there are approximately 6000 shops in the United Kingdom. The shop facilitates the reuse of clothing by collecting, sorting, baling, and transporting it to parts of the world where there is a demand for low-cost clothing. The SATCOL also reported that the disposed clothing has at least 70% of its useful life left (Woolridge et al., 2006). The destination of postconsumer textile waste is varied depending on the quality of textile and market conditions. In this state, the collector’s skill is essential for quality estimation. The good quality of postconsumer waste is sorted and is sent to East European and African countries for reselling. The remaining flow goes to recycling.

The textile recycling is a process to reuse the textile waste to produce a new product. The textile recycling can be categorized into two categories: upcycling and downcycling. Upcycling textile waste is a process to convert textile waste into high-value products. For example, the textile waste scrape was cut into pieces to decorating the new garment. On the other hand, downcycling textile waste is a process that converts the textile waste into low-value raw materials, for example, rags from textile waste, building composite from textile waste, and cleaning cloth from textile waste. Woolridge et al. (2006) reported that 43% of collected textile wastes were resold in secondhand shops in 2006. Approximately 7% of collected waste was used for fiber reclamation, in which the cotton fiber in the waste was extracted and reused to produce a new garment. This process has an environmental benefit of textile manufacturers because it can reduce demand for virgin resources and a reduction in pollution and energy burden as raw materials do not need to be imported.

The synthetic fiber is another relevant material in the textile industry. The synthetic fiber has improved the durable properties of the fabric such as stretching, waterproofing, and stain resistance. Since the introduction of synthetic fiber to the business in the early 1890s, the consumption trend increases drastically. The consumption of synthetic fiber increased by 4.3 million tons from 2007 to 2010, and nowadays, it is higher than natural’s (Gounni et al., 2019). For synthetic clothing and the high ratio of synthetic fiber in the fabric, are hardly decomposed materials. They take a hundred years to break down, but only 0.1% of recycled fiber is collected by charities for
reclamation (Leblanc, 2019). The textile waste recycling technologies for fiber reclamation will be emphasized in Section 12.5 Textile recycling technologies.

According to the waste management hierarchy, the landfilling for disposed textile is the least preferred option, but the majority of clothing and textile waste ends up in landfills as opposed to being recycled or reused (Kozlowski et al., 2012). It might be because landfilling is the easiest way to get rid of the waste through the waste collector’s perspective. In the EU, 5.8 million tons of textiles are disposed of annually. There are only 25% of these textiles recycled by charities and industrial enterprises, while the remaining 4.3 million tons goes to landfill or municipal waste incinerators (Barbero-Barrera et al., 2016). The proportion of textile waste for recycling is small, although these wastes have a high potential to be used as raw materials for valuable product production. It could be because different textile waste requires a specific technique for recycling. Therefore, the sorting process to separate different type of textile waste is important. Nowadays, waste collection is done through informal collection networks, which aimed to remove the wastes from a communal area and put them to the landfill. As the waste collector has less experience in recycling and environmental protection, resource recovery has been given less attention because of lack of investments and technical skills. This situation has slowed down the textile recycling market. In Hong Kong, there are 253 tons of textile wastes sent to landfills every day, and some of those were put into combustion, which is commonly used in industry for energy recovery from textile waste (Hanoglu et al., 2019). However, there have been many studies on the bioconversion of cotton textile wastes to biofuels, e.g., ethanol and biogas and other value-added products. The cotton fibers are rich in cellulose (more than 88%) (Hasanzadeh et al., 2018), but the main challenges in this field are the structure of cotton fiber because the cotton fiber is highly compact and crystalline in structure. Consequently, the cellulose conversion rate and production yield are shallow. Therefore, an appropriate pretreatment method is required to improve the digestibility of cotton-based textiles and achieve a high production yield.

12.3.1 Environmental impact of textile waste

The textile business is one of the most polluting industries. It produces approximately 1.2 billion tons of equivalent CO₂ (CO₂e) (Nature_Climate_Change, 2018). The production and use of textiles generated 3% of all greenhouse gas emissions worldwide (Norup et al., 2018). Typically, the carbon footprint can be divided into two layers: (1) primary footprint and (2) secondary footprint. The primary footprint is focusing on carbon emission directly through energy consumption—burning fossil fuels for electricity heating and transportation, while the secondary footprint is monitoring the indirect carbon emission, such as life cycle of product and sustainability. The majority of carbon emission of the textile industry is in the primary layer because the activities in the textile industry are related to energy consumption during the manufacturing process and transportation. The textile manufacturing is one of the key roles in the carbon emission. The type of fiber production shows different carbon emission (see Fig. 12.11).
When considering the carbon emission of the textile waste during landfill, a ton of textile waste generates 14.7 tons of CO₂ (Chavan, 2014) because of the decomposition of the cotton fiber in fabric by microbes. Nowadays, the demand for synthetic fiber is continuously increasing because the synthetic fiber is inexpensive material and it can improve fabric properties. Then the clothing produced by natural fibers such as cotton, wool, or silk is switched to natural fiber blended with synthetic fiber. The polyester fiber is one of the most popular fibers used in fashion today, and the consumption trend of polyester keeps increasing, considering that there was a 157% increase of polyester clothing consumption from 2000 to 2015. The polyester fiber is made from a chemical reaction of fossil fuel (coal and petroleum) and water. The coal and petroleum generates air pollutants, such as carbon dioxide, carbon monoxide, nitrous oxide, hydrogen sulfide, and sulfur dioxide. Consequently, polyester production causes pollution. It has been reported that the production of polyester for the textile industry creates more than 706 billion kg of CO₂e in 2015 as a single polyester t-shirt has emissions of 5.5 kg CO₂e, compared with 2.1 kg CO₂e for one made from cotton (Nature_Climate_Change, 2018). Nylon is another synthetic material that plays an essential role in the environmental issue as nylon emits a large amount of nitrous oxide during production. The nitrous oxide is one of the greenhouse gases that contribute to global warming. It has a Global Warming Potential (GWP) 265—298 times compared to CO₂. The time scale of nitrous oxide in the atmosphere is around 100 years. Besides the carbon emission from the textile material, the material and product flow in the textile business also plays a vital role in carbon emission. Transportation is the leading CO₂ generator (Bevilacqua et al., 2011). The transport in textile business (international flight and maritime shipping) starts from shipping raw materials from producer to the manufacturer. China is the

![Fig. 12.11 Comparative greenhouse gas emissions from fiber production (VS wool) (BSR, 2009).](image-url)
biggest cotton producer in the world, but most of the production volume is used
domestically. On the other hand, the United States is the biggest cotton exporter.
The raw cotton produced in the United States is shipped to textile producer countries,
such as Vietnam, China, Mexico, Indonesia, Pakistan, Bangladesh, etc. Then the
textile products are shipped around the world.

The textile industry is one of the significant consumers of water and fuel (energy
required for electric power, steam, and transportation). On average, 1 kg of textile re-
quires 200 L of water (Majumdar and Sinha, 2019). The natural fiber also contributes
to polluting the environment through the form of agriculture. Cotton production has
more significant impacts on land and water. The cotton production consumes a high
amount of water. On average, 1 kg of cotton requires 10,000 L of water. Besides water
consumption, consumption of pesticides is necessary for cotton production. Cotton
uses 16% of the world’s pesticides. The pesticides can cause a negative environmental
impact on the ecosystem. For example, the leakage of pesticide that contains nitrate
and phosphate contributes to the water eutrophication and surrounding cropland
(Guzzetti et al., 2018).

Then the natural fibers from other sources such as hemp, bamboo, and other fiber
crops that require fewer pesticides are interested. Organic cotton is another option for
an environmental-friendly fiber because it requires less pesticide. The organic cotton is
grown in 35 countries in the world (Radhakrishnan, 2017). However, organic cotton
represents only 0.03% of worldwide cotton production. Although organic cotton
production is insufficient for serving the whole textile market, the growth of organic
cotton production is significantly increased.

Nowadays, the polyester fibers are generally blended with natural fiber to create du-
rable fabric and take a long time to degrade. The nonbiodegradable material such as
polyester-blended fabric has contributed to the volume of municipal solid waste in
the landfill station. Furthermore, these polyester fabrics are shredded during washing
and release microplastics. The microplastics are harmful to the aquatic ecosystem. The
small size of micropollutants may enter fish and absorb them in their body fat. It is
toxic to the marine animal. Then the fish can be eaten by a human, and the microplas-
tics are transferred to the human body. This transferring process is called “bio-
magnification” (Guzzetti et al., 2018). The evidence of microplastics found in fish
and sea animal is shown in Table 12.4.

The transferring of microplastics happens not only in the animal, but also it accu-
ulates in microalgae. The microplastics accumulation is found in Chlorella and Sce-
nedesmus genus. They can gather and absorb nanoplastic beads (0.02 µm) with result
in photosynthesis inhibition and oxidative stress induction (Guzzetti et al., 2018). This
contamination of the aquatic environment may influence human health because the
microplastics are found in many food ingredients. For example, the microplastics
are found in canned sardines and sprats, salt, and sugar (Barboza et al., 2018). Recent
studies have documented the trophic transfer of microplastics in the lab scale and the
environment (Barboza et al., 2018; Nelms et al., 2018). The results showed that micro-
and nanosized plastics could be transferred to different food webs. These findings raise
concerns regarding the bioaccumulation and biomagnification of microplastics,
increasing the risks and toxic effects mainly to top predators.
Table 12.4  Summary of studies reporting the occurrence of microplastics in shellfish and fish of commercial interest as food (Barboza et al., 2018).

<table>
<thead>
<tr>
<th>Species name</th>
<th>Levels of mp</th>
<th>Size range</th>
<th>Parts</th>
<th>Types of debris</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shellfish</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Alectryonella plicatula</em></td>
<td>10.78 ± 4.07 particles/individual</td>
<td>5–5000 µm</td>
<td>Soft tissue</td>
<td>Fibers, fragments, pellets</td>
<td>From local fish market, China</td>
</tr>
<tr>
<td><em>Amiantis umbonella</em></td>
<td>6 particles/individual</td>
<td>10–5000 µm</td>
<td>Soft tissue</td>
<td>Fibers, fragments, pellets, film</td>
<td>Coastal water of the Persian Gulf, Iran, Asia</td>
</tr>
<tr>
<td><em>Amiantis purpuratus</em></td>
<td>6 particles/individual</td>
<td>10–5000 µm</td>
<td>Soft tissue</td>
<td>Fibers, fragments, pellets, film</td>
<td>Coastal water of the Persian Gulf, Iran, Asia</td>
</tr>
<tr>
<td><em>Cerithidea cingulata</em></td>
<td>12 particles/individual</td>
<td>10–5000 µm</td>
<td>Soft tissue</td>
<td>Fibers, fragments, pellets, film</td>
<td>Coastal water of the Persian Gulf, Iran, Asia</td>
</tr>
<tr>
<td><em>Crangon crangon</em></td>
<td>0.68 particles/g individual</td>
<td>200–1000 µm</td>
<td>Whole shrimp and peeled shrimp (abdominal muscle tissue)</td>
<td>Fibers</td>
<td>Belgium</td>
</tr>
<tr>
<td><em>Crassostrea gigas</em></td>
<td>0.6 particles/g individual</td>
<td>&gt;500 µm</td>
<td>Entire tissue</td>
<td>Fibers</td>
<td>From the local market, California, USA</td>
</tr>
<tr>
<td></td>
<td>0.47 particles/g individual</td>
<td>5–25 µm</td>
<td>Soft tissue</td>
<td>Not specified</td>
<td>Atlantic Ocean</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Market from Brittany, France</td>
</tr>
<tr>
<td><em>Cyclina sinensis</em></td>
<td>4.82 ± 2.17 particles/individual</td>
<td>5–5000 µm</td>
<td>Soft tissue</td>
<td>Fibers, fragments, pellets</td>
<td>From local fish market, China</td>
</tr>
</tbody>
</table>

Continued
<table>
<thead>
<tr>
<th>Species name</th>
<th>Levels of mp</th>
<th>Size range</th>
<th>Parts</th>
<th>Types of debris</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Eriocheir sinensis</em></td>
<td>13% ind. with MP</td>
<td>Not specified</td>
<td>Stomachs</td>
<td>Fragments, filaments</td>
<td>Baltic coastal</td>
</tr>
<tr>
<td><em>Meretrix lusoria</em></td>
<td>9.22 particles/individual</td>
<td>5–5000 μm</td>
<td>Soft tissue</td>
<td>Fibers, fragments, pellets</td>
<td>From local fish market, China</td>
</tr>
<tr>
<td><em>Mytilus edulis</em></td>
<td>0.36 ± 0.07 particles/g</td>
<td>5–25 μm</td>
<td>Soft tissue</td>
<td>Not specified</td>
<td>North Sea</td>
</tr>
<tr>
<td><em>Mytilus galloprovincialis</em></td>
<td>4.33 ± 2.62 particles/individual</td>
<td>5–5000 μm</td>
<td>Soft tissue</td>
<td>Fibers, fragments, pellets</td>
<td>From local fish market, China</td>
</tr>
<tr>
<td></td>
<td>6.2–7.2 particle/g</td>
<td>760–6000 μm</td>
<td>Valves, hepatopancreas, and gills</td>
<td>Filaments</td>
<td>From mariculture and natural stocks, Italy</td>
</tr>
<tr>
<td><em>Mytilus spp.</em></td>
<td>3.2 ± 0.52 particles/individual</td>
<td>200–&gt;2000 μm</td>
<td>Soft tissue</td>
<td>Fibers</td>
<td>Scottish coast</td>
</tr>
<tr>
<td><em>Modiolus modiolus</em></td>
<td>3.5 ± 1.29 particles/individual</td>
<td>200–&gt;2000 μm</td>
<td>Soft tissue</td>
<td>Fibers</td>
<td>Scottish coast</td>
</tr>
<tr>
<td><em>Nephrops norvegicus</em></td>
<td>83% ind. with MP</td>
<td>Not specified</td>
<td>Stomach</td>
<td>Filaments</td>
<td>Clyde, UK</td>
</tr>
<tr>
<td><em>Penaeus semisulcatus</em></td>
<td>7.8 particles/individual</td>
<td>&lt;100 -&gt;1000 μm</td>
<td>Muscle, skin</td>
<td>Fibers</td>
<td>Musa estuary, Persian Gulf</td>
</tr>
<tr>
<td><em>Patinopecten yessoensis</em></td>
<td>57.17 ± 17.34 particles/individual</td>
<td>5–5000 μm</td>
<td>Soft tissue</td>
<td>Fibers, fragments, pellets</td>
<td>From local fish market, China</td>
</tr>
<tr>
<td><strong>Perna perna</strong></td>
<td>26.7% ind. with MP</td>
<td>Not specified</td>
<td>Digestive tract and entire tissue</td>
<td>Fibers</td>
<td>Santos Estuary, Brazil</td>
</tr>
<tr>
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</tr>
<tr>
<td><strong>Pinctada radiata</strong></td>
<td>11 particles/individual</td>
<td>10–5000 μm</td>
<td>Soft tissue</td>
<td>Fibers, fragments, pellets</td>
<td>Coastal water of the Persian Gulf, Iran, Asia</td>
</tr>
<tr>
<td><strong>Ruditapes philippinarum</strong></td>
<td>5.72 ± 2.86 particles/individual</td>
<td>5–5000 μm</td>
<td>Soft tissue</td>
<td>Fibers, fragments, pellets</td>
<td>From local fish market, China</td>
</tr>
<tr>
<td><strong>Scapharca subcrenata</strong></td>
<td>45 ± 14.98 particles/individual</td>
<td>5–5000 μm</td>
<td>Soft tissue</td>
<td>Fibers, fragments, pellets</td>
<td>From local fish market, China</td>
</tr>
<tr>
<td><strong>Sinonovacula constricta</strong></td>
<td>14.33 ± 2.21 particles/individual</td>
<td>5–5000 μm</td>
<td>Soft tissue</td>
<td>Fibers, fragments</td>
<td>From local fish market, China</td>
</tr>
<tr>
<td><strong>Tegillarca granosa</strong></td>
<td>5.33 ± 2.21 particles/individual</td>
<td>5–5000 μm</td>
<td>Soft tissue</td>
<td>Fibers, fragments</td>
<td>From local fish market, China</td>
</tr>
<tr>
<td><strong>Thais mutabilis</strong></td>
<td>3 particles/individual</td>
<td>10–5000 μm</td>
<td>Soft tissue</td>
<td>Fibers, fragments, pellets, film</td>
<td>Coastal water of the Persian Gulf, Iran, Asia</td>
</tr>
</tbody>
</table>

**Fish**

<table>
<thead>
<tr>
<th><strong>Acanthurus gahhm</strong></th>
<th>10; 100%</th>
<th>2700 μm (mean)</th>
<th>Gastrointestinal tract</th>
<th>Fibers, film, fishing thread</th>
<th>Red Sea coast, Saudi Arabian</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Alepes djedaba</strong></td>
<td>20; 100% (8.00 ± 1.22 item/10 g fish muscle)</td>
<td>&lt;100–5000 μm</td>
<td>Muscle</td>
<td>Fibers, fragments, pellets</td>
<td>Gulf, Northeast of Persian Gulf</td>
</tr>
<tr>
<td>Species name</td>
<td>Levels of mp</td>
<td>Size range</td>
<td>Parts</td>
<td>Types of debris</td>
<td>Location</td>
</tr>
<tr>
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<td>-----------------------------------------------</td>
</tr>
<tr>
<td><em>Argyrosomus regius</em></td>
<td>5; 60%</td>
<td>217–4810 μm</td>
<td>Gastrointestinal tract</td>
<td>Fibers, fragments</td>
<td>From local market, Portuguese Coast</td>
</tr>
<tr>
<td></td>
<td>51; 75%</td>
<td>&gt;9.07 μm</td>
<td>Gastrointestinal tract</td>
<td>Fibers, hard plastic, nylon</td>
<td>Mediterranean Sea</td>
</tr>
<tr>
<td><em>Atherinopsis californiensis</em></td>
<td>7; 29%</td>
<td>&gt;500 μm</td>
<td>Gastrointestinal tract</td>
<td>Fibers, fragments</td>
<td>From local market, California, USA</td>
</tr>
<tr>
<td><em>Brama brama</em></td>
<td>3; 33%</td>
<td>217–4810 μm</td>
<td>Gastrointestinal tract</td>
<td>Fibers</td>
<td>From local market, Portuguese Coast</td>
</tr>
<tr>
<td><em>Cetengraulis mysticetus</em></td>
<td>30; 3.3%</td>
<td>≤1100 μm</td>
<td>Gut</td>
<td>Fragment</td>
<td>Southeast Pacific Ocean</td>
</tr>
<tr>
<td><em>Clupea harengus</em></td>
<td>566; 2%</td>
<td>&gt;1000 μm</td>
<td>Gastrointestinal tract</td>
<td>Fibers, fragments</td>
<td>North Sea</td>
</tr>
<tr>
<td></td>
<td>299, 21%</td>
<td>100–&gt;5000 μm</td>
<td>Gastrointestinal tract</td>
<td>Fibers, fragments</td>
<td>Baltic Sea</td>
</tr>
<tr>
<td><em>Cynoglossus abbreviatus</em></td>
<td>11; 12 (mean/individual)</td>
<td>&lt;100</td>
<td>Muscle, gut, gills, liver, skin</td>
<td>Fibers, fragments</td>
<td>Musa estuary, Persian Gulf</td>
</tr>
<tr>
<td><em>Cynoscion acoupa</em></td>
<td>552; 51%</td>
<td>&lt;500 μm</td>
<td>Gut</td>
<td>Filaments, hard microplastics</td>
<td>Goiana estuary, Brazil</td>
</tr>
<tr>
<td><em>Decapterus macrosoma</em>****</td>
<td>17; 29%</td>
<td>&gt;500 μm</td>
<td>Gastrointestinal tract</td>
<td>Fragments, styrofoam</td>
<td>From local market, Eastern Indonesia</td>
</tr>
<tr>
<td><em>Decapterus muroadsi</em>****</td>
<td>20; 80%</td>
<td>5000 μm</td>
<td>Gut</td>
<td>Fragments</td>
<td>South Pacific</td>
</tr>
<tr>
<td><em>Dentex macrophthalmus</em></td>
<td>1; 100%</td>
<td>217–4810 μm</td>
<td>Gastrointestinal tract</td>
<td>Fibers</td>
<td>From local market, Portuguese Coast</td>
</tr>
<tr>
<td><em>Dicentrarchus labrax</em></td>
<td>40; 23%</td>
<td>≤1000–5000 μm</td>
<td>Gastrointestinal tract</td>
<td>Fibers, fragments</td>
<td>Mondego estuary, Portugal</td>
</tr>
<tr>
<td><em>Diplodus vulgaris</em></td>
<td>40; 73%</td>
<td>≤1000–5000 μm</td>
<td>Gastrointestinal tract</td>
<td>Fibers, fragments</td>
<td>Mondego estuary, Portugal</td>
</tr>
<tr>
<td>Species</td>
<td>Percentage</td>
<td>Fiber Size</td>
<td>Organ(s)</td>
<td>Fibers, Fragments</td>
<td>Location</td>
</tr>
<tr>
<td>---------------------------------</td>
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<td>-----------------------------------------------</td>
</tr>
<tr>
<td><em>Engraulis encrasicolus</em></td>
<td>10; 80%</td>
<td>124–438 µm</td>
<td>Liver</td>
<td>Not specified</td>
<td>Mediterranean Sea</td>
</tr>
<tr>
<td><em>Engraulis japonicus</em>**</td>
<td>64; 77%</td>
<td>10–500 µm</td>
<td>Gastrointestinal tract</td>
<td>Fibers, fragments</td>
<td>Mediterranean Sea</td>
</tr>
<tr>
<td><em>Engraulis mordax</em></td>
<td>10; 30%</td>
<td>&gt;500 µm</td>
<td>Gastrointestinal tract</td>
<td>Fiber, film, monofilament</td>
<td>Tokyo Bay</td>
</tr>
<tr>
<td><em>Epinephelus areolatus</em></td>
<td>5; 20%</td>
<td>1800 µm (mean)</td>
<td>Gastrointestinal tract</td>
<td>Fibers, film, fishing thread</td>
<td>Red Sea coast, Saudi Arabian</td>
</tr>
<tr>
<td><em>Epinephelus chlorostigma</em></td>
<td>3; 33.33%</td>
<td>1900 µm (mean)</td>
<td>Gastrointestinal tract</td>
<td>Fibers, film, fishing thread</td>
<td>Red Sea coast, Saudi Arabian</td>
</tr>
<tr>
<td><em>Epinephelus coioides</em></td>
<td>20; 100%</td>
<td>&lt;100–5000 µm</td>
<td>Muscle</td>
<td>Fibers, fragments, pellets</td>
<td>Gulf, Northeast of Persian</td>
</tr>
<tr>
<td><em>Gadus morhua</em>**</td>
<td>80; 13%</td>
<td>&gt;1000 µm</td>
<td>Gastrointestinal tract</td>
<td>Fibers, fragments</td>
<td>North Sea</td>
</tr>
<tr>
<td></td>
<td>74; 1.4%</td>
<td>&lt;5000 µm</td>
<td>Gastrointestinal tract</td>
<td>Fibers, fragments, film</td>
<td>Baltic Sea</td>
</tr>
<tr>
<td></td>
<td>205; 2.4%</td>
<td>2800–4200 µm</td>
<td>Gastrointestinal tract</td>
<td>Fragments</td>
<td>Coast of Canada</td>
</tr>
<tr>
<td></td>
<td>302; 18.8%</td>
<td>&lt;5000–&gt;20,000 µm</td>
<td>Stomach</td>
<td>Fibers, fragments, granule, film</td>
<td>Norwegian coast</td>
</tr>
<tr>
<td><em>Lethrinus microdon</em></td>
<td>10; 20%</td>
<td>1480 µm (mean)</td>
<td>Gastrointestinal tract</td>
<td>Fibers, film, fishing thread</td>
<td>Red Sea coast, Saudi Arabian</td>
</tr>
<tr>
<td><em>Lipocheilus carnolabrum</em></td>
<td>7; 28.57%</td>
<td>1870 µm (mean)</td>
<td>Gastrointestinal tract</td>
<td>Fibers, film, fishing thread</td>
<td>Red Sea coast, Saudi Arabian</td>
</tr>
</tbody>
</table>

Continued
<table>
<thead>
<tr>
<th>Species name</th>
<th>Levels of mp</th>
<th>Size range</th>
<th>Parts</th>
<th>Types of debris</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Lutjanus kasmira</em></td>
<td>10; 16.67%</td>
<td>2160 μm (mean)</td>
<td>Gastrointestinal tract</td>
<td>Fibers, film, fishing thread</td>
<td>Red Sea coast, Saudi Arabian</td>
</tr>
<tr>
<td><em>Merlangius merlangus</em></td>
<td>50; 32%</td>
<td>1000–2000 μm</td>
<td>Gastrointestinal tract</td>
<td>Fibers, fragments, beads</td>
<td>English Channel</td>
</tr>
<tr>
<td><em>Merluccius merluccius</em></td>
<td>12; 29%</td>
<td>217–4810 μm</td>
<td>Gastrointestinal tract</td>
<td>Fibers</td>
<td>Portuguese Coast</td>
</tr>
<tr>
<td></td>
<td>3; 100%</td>
<td>10–5000 μm</td>
<td>Gastrointestinal tract</td>
<td>Fragments, line, film, pellet</td>
<td>Adriatic Sea</td>
</tr>
<tr>
<td></td>
<td>12; 16.7%</td>
<td>380–3100 μm</td>
<td>Stomach</td>
<td>Fragments, fibers, film, spheres</td>
<td>Spanish Atlantic</td>
</tr>
<tr>
<td><em>Micromesistius poutassou</em></td>
<td>27; 51.9%</td>
<td>1000–2000 μm</td>
<td>Gastrointestinal tract</td>
<td>Fibers, fragments, beads</td>
<td>English Channel</td>
</tr>
<tr>
<td><em>Morone saxatilis</em></td>
<td>7; 29%</td>
<td>&gt;500 μm</td>
<td>Gastrointestinal tract</td>
<td>Fibers, film, foam</td>
<td>From local market, California, USA</td>
</tr>
<tr>
<td><em>Mugil cephalus</em></td>
<td>30; 60% (wild)</td>
<td>&lt;2000–5000 μm</td>
<td>Gastrointestinal tract</td>
<td>Fibers, fragments, sheet</td>
<td>Hong Kong Coast</td>
</tr>
<tr>
<td></td>
<td>30; 16.7% (captive)</td>
<td>&lt;2000–5000 μm</td>
<td>Gastrointestinal tract</td>
<td>Fibers</td>
<td>From fish farms, Hong Kong</td>
</tr>
<tr>
<td><em>Mullus barbatus</em></td>
<td>11; 64%</td>
<td>10–5000 μm</td>
<td>Gastrointestinal tract</td>
<td>Fragments, line, film, pellet</td>
<td>Adriatic Sea</td>
</tr>
<tr>
<td></td>
<td>207; 66%</td>
<td>&gt;9.07 μm</td>
<td>Stomach and intestine</td>
<td>Fibers, hard plastic, nylon</td>
<td>Mediterranean Sea</td>
</tr>
<tr>
<td></td>
<td>128; 18.8%</td>
<td>380–3100 μm</td>
<td>Stomach</td>
<td>Fragments, fibers, film</td>
<td>Mediterranean coast</td>
</tr>
<tr>
<td>Species</td>
<td>Percentage</td>
<td>Fiber Size</td>
<td>Tissue</td>
<td>Description</td>
<td>Location</td>
</tr>
<tr>
<td>------------------------------</td>
<td>------------</td>
<td>------------------</td>
<td>-------------------------</td>
<td>---------------------------------------</td>
<td>------------------------------------</td>
</tr>
<tr>
<td>Mullus surmuletus</td>
<td>4; 100%</td>
<td>217–4810 μm</td>
<td>Gastrointestinal tract</td>
<td>Fibers</td>
<td>Portuguese Coast</td>
</tr>
<tr>
<td></td>
<td>51; 35 and 49%</td>
<td>&gt;9.07 μm</td>
<td>Gastrointestinal tract</td>
<td>Fibers, hard plastic, nylon</td>
<td>Mediterranean Sea</td>
</tr>
<tr>
<td>Odontesthes regia</td>
<td>9; 11.1%</td>
<td>Not specified</td>
<td>Gut</td>
<td>Fragments</td>
<td>Southeast Pacific Ocean</td>
</tr>
<tr>
<td>Oncorhynchus tshawytscha</td>
<td>4; 25%</td>
<td>&gt;500 μm</td>
<td>Gastrointestinal tract</td>
<td>Fibers</td>
<td>From local market, California, USA</td>
</tr>
<tr>
<td>Opisthonema libertate</td>
<td>40; 5%</td>
<td>≤3700 μm</td>
<td>Gut</td>
<td>Thread</td>
<td>Southeast Pacific Ocean</td>
</tr>
<tr>
<td>Parascolopsis erionna</td>
<td>5; 60%</td>
<td>1380 μm (mean)</td>
<td>Gastrointestinal tract</td>
<td>Fibers, film, fishing thread</td>
<td>Red Sea coast, Saudi Arabian</td>
</tr>
<tr>
<td>Platycephalus indicus</td>
<td>16; 100%</td>
<td>&lt;100–5000 μm</td>
<td>Muscle</td>
<td>Fibers, fragments, pellets</td>
<td>Northeast of Persian Gulf</td>
</tr>
</tbody>
</table>
|                              | 12; 21.8 (mean/individual) | <100  
->1000 μm | Muscle, gut, gills, liver, skin | Fibers                              | Musa estuary, Persian Gulf         |
| Platichthys flesus           | 40; 13%    | ≤1000–5000 μm    | Gastrointestinal tract  | Fibers, fragments                     | Mondego estuary, Portugal          |
| Plectorhinchus gaterinus     | 6; 33.33%  | 3310 μm (mean)   | Gastrointestinal tract  | Fibers, film, fishing thread          | Red Sea coast, Saudi Arabian        |
| Pristipomoides multidens     | 10; 20%    | 3800 μm (mean)   | Gastrointestinal tract  | Fibers, film, fishing thread          | Red Sea coast, Saudi Arabian        |
| Rastrelliger kanagurta       | 10; 56%    | >500 μm          | Gastrointestinal tract  | Fragments, film, monofilament         | From local market, Eastern Indonesia |

Continued
<table>
<thead>
<tr>
<th>Species name</th>
<th>Levels of mp</th>
<th>Size range</th>
<th>Parts</th>
<th>Types of debris</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rhizoprionodon lalandii</td>
<td>6; 33%</td>
<td>1000−5000 μm</td>
<td>Stomach</td>
<td>Pellets</td>
<td>Northeastern Brazil</td>
</tr>
<tr>
<td>Sardinella longiceps****</td>
<td>10; 60%</td>
<td>500−3000 μm</td>
<td>Gut</td>
<td>Fragments</td>
<td>Indian Coast</td>
</tr>
<tr>
<td>Sardina pilchardus****</td>
<td>99; 19%; 7%; 57%; 2%; 105%</td>
<td>10−5000 μm</td>
<td>Gastrointestinal tract</td>
<td>Fragments, line, film, pellet</td>
<td>Adriatic Sea</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt;9.07 μm</td>
<td>Gastrointestinal tract</td>
<td>Fibers, hard plastic, nylon</td>
<td>Mediterranean Sea</td>
</tr>
<tr>
<td>Saurida tumbil</td>
<td>4; 13.5 (mean/ individual)</td>
<td>&lt;100−1000 μm</td>
<td>Muscle, gut, gills, liver, skin</td>
<td>Fibers, fragments</td>
<td>Musa estuary, Persian Gulf</td>
</tr>
<tr>
<td>Sillago sihama</td>
<td>17; 14.1 (mean/ individual)</td>
<td>&lt;100−1000 μm</td>
<td>Muscle, gut, gills, liver, skin</td>
<td>Fibers, fragments</td>
<td>Musa estuary, Persian Gulf</td>
</tr>
<tr>
<td>Scyliorhinus canicula</td>
<td>20; 5%; 72%; 15.3%</td>
<td>1500 μm</td>
<td>Stomach</td>
<td>Micro-bead</td>
<td>North Sea</td>
</tr>
<tr>
<td></td>
<td></td>
<td>380−3100 μm</td>
<td>Stomach</td>
<td>Fragments, fibers, film</td>
<td>Mediterranean coasts</td>
</tr>
<tr>
<td>Scomberomorus cavalla****</td>
<td>8; 62.5%</td>
<td>1000−5000 μm</td>
<td>Stomach</td>
<td>Pellets</td>
<td>Northeastern Brazil</td>
</tr>
<tr>
<td>Scomber japonicus****</td>
<td>7; 71%; 35%; 31%; 30%; 3.3%</td>
<td>&gt;9.07 μm</td>
<td>Gastrointestinal tract</td>
<td>Fibers, hard plastic, nylon</td>
<td>Mediterranean Sea</td>
</tr>
<tr>
<td></td>
<td></td>
<td>217−4810 μm</td>
<td>Gastrointestinal tract</td>
<td>Fragments, fibers</td>
<td>Portuguese Coast</td>
</tr>
<tr>
<td></td>
<td></td>
<td>≤2100 μm</td>
<td>Gut</td>
<td>Fragment</td>
<td>Southeast Pacific Ocean</td>
</tr>
<tr>
<td>Species</td>
<td>Percentage</td>
<td>Length (μm)</td>
<td>Tissue Type</td>
<td>Description</td>
<td>Location</td>
</tr>
<tr>
<td>------------------------------</td>
<td>------------</td>
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<td>--------------------------------------------------</td>
<td>------------------------------</td>
</tr>
<tr>
<td><em>Scomber scombrus</em>**</td>
<td>13; 31%</td>
<td>217–4810 μm</td>
<td>Gastrointestinal tract</td>
<td>Fragments, fibers</td>
<td>Portuguese Coast</td>
</tr>
<tr>
<td></td>
<td>13; 30.8%</td>
<td>&lt;5000 μm</td>
<td>Gastrointestinal tract</td>
<td>Fibers, fragments, film</td>
<td>Baltic Sea</td>
</tr>
<tr>
<td><em>Siganus canaliculatus</em></td>
<td>3; 29%</td>
<td>&gt;500 μm</td>
<td>Gastrointestinal tract</td>
<td>Monofilament</td>
<td>From local market, Eastern Indonesia</td>
</tr>
<tr>
<td><em>Solea solea</em></td>
<td>533; 95%</td>
<td>&lt;100–500 μm</td>
<td>Gastrointestinal tract</td>
<td>Fibers, fragments</td>
<td>Adriatic Sea</td>
</tr>
<tr>
<td><em>Sparus aurata</em></td>
<td>110; 44%</td>
<td>&gt;9.07 μm</td>
<td>Gastrointestinal tract</td>
<td>Fibers, hard plastic, nylon</td>
<td>Mediterranean Sea</td>
</tr>
<tr>
<td><em>Spratelloides gracilis</em>**</td>
<td>4; 40%</td>
<td>&gt;500 μm</td>
<td>Gastrointestinal tract</td>
<td>Fragments</td>
<td>Baltic Sea</td>
</tr>
<tr>
<td><em>Sprattus sprattus</em>**</td>
<td>515; 18.8%</td>
<td>100 – &gt;5000 μm</td>
<td>Gastrointestinal tract</td>
<td>Fibers, fragments</td>
<td>From local market, Eastern Indonesia</td>
</tr>
<tr>
<td><em>Sphyraena jello</em>**</td>
<td>15; 100%</td>
<td>&lt;100–500 μm</td>
<td>Muscle</td>
<td>Fibers, fragments</td>
<td>Northeast of Persian Gulf</td>
</tr>
<tr>
<td><em>Thalassoma rueppellii</em></td>
<td>12; 8.33%</td>
<td>1930 μm (mean)</td>
<td>Gastrointestinal tract</td>
<td>Fibers, film, fishing thread</td>
<td>Red Sea coast, Saudi Arabian</td>
</tr>
<tr>
<td><em>Thunnus alalunga</em></td>
<td>131; 12.9%</td>
<td>&lt;5000 μm</td>
<td>Stomach</td>
<td>Fragments</td>
<td>Mediterranean Sea</td>
</tr>
<tr>
<td><em>Thunnus thynnus</em></td>
<td>34; 34.4%</td>
<td>&lt;5000 μm</td>
<td>Stomach</td>
<td>Fragments</td>
<td>Mediterranean Sea</td>
</tr>
<tr>
<td><em>Trachurus trachurus</em></td>
<td>56; 28.6%</td>
<td>1000–2000 μm</td>
<td>Gastrointestinal tract</td>
<td>Fibers, fragments, beads</td>
<td>English Channel</td>
</tr>
<tr>
<td><em>Trigla lyra</em></td>
<td>31; 19%</td>
<td>217–4810 μm</td>
<td>Gastrointestinal tract</td>
<td>Fragments, fibers</td>
<td>Portuguese Coast</td>
</tr>
<tr>
<td><em>Xiphias gladius</em>**</td>
<td>56; 12.5%</td>
<td>&lt;5000 μm</td>
<td>Stomach</td>
<td>Fragments</td>
<td>Mediterranean Sea</td>
</tr>
<tr>
<td>Species name</td>
<td>Levels of mp</td>
<td>Size range</td>
<td>Parts</td>
<td>Types of debris</td>
<td>Location</td>
</tr>
<tr>
<td>------------------------------</td>
<td>--------------</td>
<td>---------------------</td>
<td>--------------------------------</td>
<td>----------------------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>Zeus faber</td>
<td>1; 100%</td>
<td>217–4810 μm</td>
<td>Gastrointestinal tract</td>
<td>Fibers</td>
<td>Portuguese Coast</td>
</tr>
<tr>
<td></td>
<td>42; 47.6%</td>
<td>1000–2000 μm</td>
<td>Gastrointestinal tract</td>
<td>Fibers, fragments, beads</td>
<td>English Channel</td>
</tr>
<tr>
<td>Clupea harengus</td>
<td>400; 0.25%</td>
<td>&gt;20 μm</td>
<td>Gastrointestinal tract</td>
<td>Spherical particles</td>
<td>North Sea</td>
</tr>
<tr>
<td>Limanda limanda</td>
<td>Two plastic particles were found in only 1 (Sprattus sprattus) out of 400 individuals</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Merlangius merlangus</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sprattus sprattus</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chelon subviridis</td>
<td>30; between 0 and 3 pigments and MP particles were isolated from each fish.</td>
<td>1–1000 μm</td>
<td>Eviscerated flesh (whole fish excluding the viscera and gills) and excised organs (viscera and gills)</td>
<td>Fragments, filaments, films</td>
<td>*From local market, Malaysia</td>
</tr>
<tr>
<td>Johnius belangerii</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rastrelliger kanagurta</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stolephorus waitei</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: [****indicates that this species is included in the list of the most commonly caught marine species worldwide according to FAO, 2016].
Besides the synthetic microfiber, the dyestuffs and chemicals used during the textile process are toxic to the environment. These substances are highly toxic and mutagenic and decrease light penetration; photosynthetic activity leads to oxygen deficiency in water (Chequer et al., 2013). There are around 200,000 tons of dyes lost to effluents every year during the textile production because of the inefficiency of the dying process. Most of these dyes are leaked out from conventional wastewater treatment processes and persist in the environment. In China, there are around 1.84 billion tons of wastewater contaminated with dyestuffs. These wastewaters contain many substances, such as detergent solvents, surfactants, dyes, and other recalcitrant organic matter (Jieying Liang et al., 2018). Azo dyes are commonly used in coloring textile material. The dyes offer an extensive range of colors and better colorfastness, making them invaluable to the textile industry. However, the azo dyes can be degraded to aromatic amines, which are toxic to animals and humans. Some of the aromatic amines have been implicated to be carcinogenic in humans, and as many as 5% of azo dyes can cleave to form these dangerous compounds (see Table 12.5).

Another substance that has an impact on the environment is an antimicrobial agent. The antibacterial agents have been used in the textile market for a long time, especially medical textile. This substance is frequently used in textile manufacturing for two primary purposes: (1) protection of the textile user against pathogenic or odor-causing microorganisms and (2) protection of the textile itself from damage caused by mold, mildew, or rot-producing microorganisms (Shahidi and Wiener, 2012). The antimicrobial agent has been applied at the surface of the fiber or within the fiber depending on the purpose. The antimicrobe that coats on the surface will act as the microorganism touches the textile surface, but the antimicrobial agent that diffuses in the fiber will migrate from the textile to the external medium to attack the microbes (Morais et al., 2016). The antimicrobe typically used in the textile industry is “biocides.” The biocides are substances that harm microbial cells. They will act as follows.

1. Damage or inhibit cell wall synthesis
2. Inhibition of cell membrane function
3. Inhibition of protein synthesis
4. Inhibition of nucleic acid synthesis (DNA and RNA)
5. Inhibition of other metabolic processes

The action mode of biocides is shown in Table 13. The quaternary ammonium compounds and polybiguanides are active against a wide range of microorganisms, such as Gram-positive and Gram-negative bacteria, fungi, and certain types of viruses (Simoncic and Tomsic, 2010; Yao et al., 2008). These biocides can prevent the Gram-positive (Staphylococcus aureus) and the Gram-negative (Escherichia coli) bacteria by interrupting the cell membrane (Yao et al., 2008). The interaction between the cationic group of the biocide and the negatively charged cell membrane of microbe leads to cell membrane damage. Similar to the quaternary ammonium compound, triclosan has an action against both Gram-negative and Gram-positive bacteria. It also presents antifungal and antiviral properties (Morais et al., 2016). Silver particle is a famous biocide. It has bactericidal activity against a wide range of bacteria, namely Pseudomonas aeruginosa, S. aureus, Staphylococcus epidermidis, E. coli, and Klebsiella
pneumonia (Hasan et al., 2013). The release of the silver to the environment, especially in aquatic system, creates a potential health hazard to the aquatic organism. Nanosilver is lethal to small fish.

Furthermore, the nanosilver particle was binding/crossing an egg membrane and entering into the fish embryos. These antimicrobial agents inhibit the growth or lead to the death of microorganism in the ecosystem when they leak out from the finishing textile production process or the landfilling. This may be harmful to other living species including human beings (see Table 12.6).

### Table 12.5 Detail of azo dyes.

<table>
<thead>
<tr>
<th>No.</th>
<th>Substance</th>
<th>CAS number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4-Aminodiphenyl/xenylamine/biphenyl-4-ylamine</td>
<td>92-67-1</td>
</tr>
<tr>
<td>2</td>
<td>Benzidine</td>
<td>92-87-5</td>
</tr>
<tr>
<td>3</td>
<td>4-Chloro-o-toluidine</td>
<td>95-69-2</td>
</tr>
<tr>
<td>4</td>
<td>2-Naphthylamine</td>
<td>91-59-8</td>
</tr>
<tr>
<td>5</td>
<td>o-aminoazotoluene/4-o-tolylazo-o-toluidine/4-amino-2', 3-dimethylazobenzene</td>
<td>97-56-3</td>
</tr>
<tr>
<td>6</td>
<td>2-Amino-4-nitrotoluol/5-nitro-o-toluidine</td>
<td>99-55-8</td>
</tr>
<tr>
<td>7</td>
<td>p-chloranilin/4-chloroaniline</td>
<td>106-47-8</td>
</tr>
<tr>
<td>8</td>
<td>2,4-Diaminoanisole/4-methoxy-m-phenylenediamine</td>
<td>615-05-4</td>
</tr>
<tr>
<td>9</td>
<td>4,4' Diaminodiphenylmethane/4,4-methylenediamine</td>
<td>101-77-9</td>
</tr>
<tr>
<td>10</td>
<td>3,3'-Dichlorobenzidine/3,3'dichlorobiphenyl-4,4'-ylenediamine</td>
<td>91-94-1</td>
</tr>
<tr>
<td>11</td>
<td>3,3'-Dimethoxybenzidine/o-dianisidine</td>
<td>119-90-4</td>
</tr>
<tr>
<td>12</td>
<td>3,3'-Dimethybenzidine/4,4'-bi-o-toluidine</td>
<td>119-93-7</td>
</tr>
<tr>
<td>13</td>
<td>3,3'-Dimethyl-4,4'-diaminodiphenylmethane/4,4'-methylenedi-o-toluidine</td>
<td>838-88-0</td>
</tr>
<tr>
<td>14</td>
<td>p-cresidin/6-methoxy-m-toluidine</td>
<td>120-71-8</td>
</tr>
<tr>
<td>15</td>
<td>4,4'-Methylene-bis-(2-chloro-aniline)/2,2'-dichloro-4,4'-methylenedianiline</td>
<td>101-14-4</td>
</tr>
<tr>
<td>16</td>
<td>2,4-Xyldine</td>
<td>95-68-1</td>
</tr>
<tr>
<td>17</td>
<td>2,6-Xyldine</td>
<td>87-62-7</td>
</tr>
<tr>
<td>18</td>
<td>4,4'-Oxydianiline</td>
<td>101-80-4</td>
</tr>
<tr>
<td>19</td>
<td>4,4'-Thiodianiline</td>
<td>139-65-1</td>
</tr>
<tr>
<td>20</td>
<td>o-Toluidine/2-aminotoluene</td>
<td>95-53-4</td>
</tr>
<tr>
<td>21</td>
<td>2,4-Toluylenediamine/4-methyl-m-phenylened</td>
<td>95-80-7</td>
</tr>
</tbody>
</table>
As almost every process in textile production makes intensive use of chemicals and natural resources and generates a high environmental impact (Caniato et al., 2012), the ecological concern about textile waste was raised. Consequently, several producers try to replace toxic compounds in fabric by eco-friendly substances, such as natural dyestuffs and natural antimicrobial substances. The organic fiber is also applied to the industry, but the proportion of organic fiber in the market is still less than 1% of the world’s total annual cotton crop. The famous companies, such as H&M and Inditex, the parent company of Zara, have used organic cotton on their product. Furthermore, reusing existing fabrics and fiber for the recycled or upcycled process can minimize the textile waste and extend the life span of the material and preventing it

<table>
<thead>
<tr>
<th>Biocide</th>
<th>Action mode</th>
<th>Fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quaternary ammonium compound</td>
<td>Damage cell membranes, denature proteins, inhibit DNA production, avoiding multiplication</td>
<td>Cotton, Polyester, Nylon, Wool</td>
</tr>
<tr>
<td>Triclosan</td>
<td>Blocks lipid biosynthesis, affecting the integrity of cell membrane</td>
<td>Polyester, Nylon, Polypropylene, Cellulose acetate, Acrylic</td>
</tr>
<tr>
<td>Metals and metallic salts (e.g., TiO2 and ZnO)</td>
<td>Generate reactive oxygen species, damaging cellular proteins, lipids, and DNA</td>
<td>Cotton, Wool, Polyester, Nylon</td>
</tr>
<tr>
<td>Chitosan</td>
<td>• Low molecular weight: inhibits the synthesis of mRNA, preventing protein synthesis</td>
<td>Cotton, Polyester, Wool</td>
</tr>
<tr>
<td></td>
<td>• High molecular weight: causes leakage of intracellular substances or blocks the transport of essential solutes into the cell</td>
<td></td>
</tr>
<tr>
<td>Poly(hexamethylene biguanide)</td>
<td>Interacts with membrane phospholipids, resulting in its disruption and the lethal leakage of cytoplasmic materials</td>
<td>Cotton, Polyester, Nylon</td>
</tr>
<tr>
<td>N-halamines (e.g., N-chloro-2,2,6,6-tetramethyl-4-piperidinyl methacrylate)</td>
<td>Precludes the cell enzymatic and metabolic processes, causing the consequent microorganism destruction</td>
<td>Cotton, Polyester, Nylon, Wool</td>
</tr>
</tbody>
</table>

Table 12.6 The action modes of the main antimicrobial agents, as well as the primary fibers in which they are used (Morais et al., 2016).
from going into landfills. This could reduce the demand of raw materials and reduce energy consumption and pollution caused during manufacturing processes.

### 12.4 Current situation of textile recycling (global scenario)

The recycling process is a recovery operation that reprocesses waste materials or substances into products for original or other purposes. This recovery operation includes the reprocessing of organic material but does not include energy recovery and the reprocessing of waste into fuel materials. It has benefits for an environment. The manufacturing process that uses recycled materials required considerably less energy than that required for producing new products from raw materials. The recycling process reduces waste landfilling, which generates greenhouse gasses. It decreases the waste incineration that requires fuels to operate. Therefore, it could claim that recycling process saves resources and energy. The recycling process has been proposed in many industries, including textile industry. Textile recycling is suitable for both environmental and economic benefits.

**Fig. 12.12** shows that the trend of utilizing textile waste continuously increased over time. Textiles have been recycled since the 18th century. Wool fiber is the first recycled fiber in history. The virgin wool was depleted during the Napoleonic War and then the wool product was reprocessed into the new yarn. The recycled wool product was produced by blending old wool with new wool to create unique textile products. The textile product from recycled wool shows a little harder than the original product. The discarded pure cotton fiber has the potential to be reused and recycled to produce a value-added product. For example, it could convert into superabsorbent polymers and composite material while polyester/cotton fiber blends could be used as a thermal and acoustic insulation material in the automobile and construction sectors. The discarded sportswear usually contains polypropylene fiber. These fibers can be used as a raw material for composite material by reprocessing and blending the fiber.
with other polymers. Besides clothing, other items such as mattresses can be recycled too. There are around 169,000 tons of mattresses purchased in 2010, but only 25,000 tons of mattresses were recovered. The recovered mattresses were put into the process to separate the steel because mattresses contain steel around 50%. Although the textile industry has been utilizing used fibers for at least 200 years, the markets for recycled textile fiber continue to evolve.

Several clothing retailers have started the upcycling process by announcing “take-back programs” that collect the used textiles from customers to be recycled into other clothing. Since 2013, the H&M Company started a recycling program that aims to have zero garment going to landfill. The program allows customers to leave the post-consumer textile waste at the retail shop and then the wastes will be transformed into recycled textile fibers for new products. The Trash-2-Cash is a cross-sectoral EU project that pools together designers, researchers, materials suppliers, and textile producers from all over Europe to create recycled fibers and design high-quality industrial materials from textile waste (like old jeans). Some companies start an alternative idea to reduce textile waste generation by launched clothes rental service. The fashion rental companies, such as Rent the Runway, Le Tote, Fly Robe, and Swishlist, allow customers to rent out branded clothes by paying a monthly fee. The clothes rental company can reduce the textile waste by decreasing the waste generation because the customer can return the outfit when they do not want it rather than throw it away. The clothes rental service creates a circular pattern of resource use, reducing waste, and reusing resources more.

The organic cotton has also grabbed consumer attention. Then the most prominent American retailer, Walmart, has started an organic cotton apparel market since 2004. Nowadays, Walmart is the leader of the organic textile retailer, and the company offers several lines of products, including apparel and bedding products.

In the mid-1990s, the era of innovative eco-fashion has immersed. Patagonia is another company that plays an essential role in recycling textile waste. In 1993, the company set up an eco-fashion line by producing the fleece clothing from post-consumer plastic soda bottles. The post-consumer plastic soda contains polyethylene terephthalate (PET), which was melted to form fiber that can be woven into a fabric. During 1993–2006, the Patagonia Company recycled 86 million soda bottles from the municipal solid waste.

Furthermore, Patagonia and the Italian company name “Calamai” started the recycling program from the post-consumer T-shirt. The recycling cotton program saves 20,000 L of water per kilogram of cotton, a water-intensive crop. Another approach creates a plant-based biopolymer. Cargill Company is one of the biggest American agricultural and biomaterial providers producing biopolymer, namely “Ingeo fiber” in 2000. The Ingeo fiber is polylactic acid polymer made from corn by-product, and it has been used in Versace (one of the haute couture designer clothing) collection (Claudio, 2007). Econyl is a type of nylon-like material produced from recycled fishnet and carpet. The econyl can be used in swimwear to replace caprolactam (a derivative of oil). As textile recycling has a significant impact on society and the environment, the regulation to control the textile waste management and value chain of textile waste is needed.
12.4.1 Global scenario

Textile waste management has high-level attention in many countries because of the textile waste effects on social economy, human health, and environment. Almost half a portion of textile wastes are continuing their life as clothing, just not domestically. The global trade of secondhand clothing and textiles has become one of the enormous worldwide businesses. Based on volume, the United States is the largest exporter of secondhand clothing in the world (Hawley, 2006). The used textile and apparel are shipped to developing nations in which the item can be resold.

On the other hand, unwanted secondhand clothing would end up in developing countries where the facilities of waste management are inadequate. Then global trade of worn clothing and textiles has a detrimental impact on the local textile industry and environment. Therefore, the government and local communities had launched legislation of textile waste management. The collaboration between local communities and the private sector for creating a textile recycling plan is mandatory.

12.4.2 America textile recycling program

The US EPA does not have specific federal regulations to control the textile recycling process and textile production. According to the textile production process release hazardous water, therefore, it was regulated under the Resource Conservation and Recovery Act (RCRA). The RCRA helps the EPA to inspect any activities that involved with the hazardous waste. The generation, storage, transportation of dangerous waste, and especially the treatment and disposal of hazardous waste are rigorously controlled. The other acts that may be related to the textile waste are the Clean Water Act (CWA), the Oil Pollution Prevention and Regulation, the Clean Air Act, and the Toxic Substance Control Act. Even the United States does not have textile waste regulations, but the United States was concerned about the textile waste issue. Therefore, the Secondary Materials and Recycled Textiles (SMART) Association was established since 1932. The SMART association composed of many companies around the world involved in the textile industry. The SMART aims to solve the textile waste issue by reuse and recycling both pre- and postconsumer textile wastes. For the preconsumer textile waste, the SMART member will collect the clothes and process it to produce wiping clothes or home furniture. In the case of postconsumer textile waste, the SMART member will export it to the developing countries (Hawley, 2006). The organization and private textile recycling companies have to put a considerable effort into textile waste management. The council for textile recycling (CTR), a nonprofit, tax exempt organization incorporated in the State of Maryland drives almost half of the textile waste generated to charities. Then the charities will resell the useable clothes with low prices in the flee market/secondhand store and get shipped to foreign countries. The CTR also announced the bold goal for the United States to produce zero landfill-bound textile waste by 2037. There are more than 2000 companies that work on textile recycling and postconsumer textile waste stream in the United States. The waste management system in the United States is similar to Europe. The textile wastes are collected by the collecting agency (door-to-door pickup), and textile wastes
are sold to textile recyclers, including used clothing dealers and exporters, wiping rag graders, and fiber recyclers. The workers in the recycling company separate overly worn or stained clothing into many categories. The low-quality fiber might end up as polishing cloths, rags or high-quality paper, insulation, or seat stuffing in the automobile industry. Phoenix Fibers, a textile recycling company in Arizona, produces housing insulation, sound dampening, and even prison mattresses from worn-out denim. Goodwill, a prominent textile recycling company in the United States, reported that less than 20% of clothing donations are resold in the United States, and more than 45% of clothing donations are shipped to foreign countries. In 2013, the United States exported about 860,000 tons of secondhand apparel to developing countries, and in a year later, the United States exported approximately 18% of total mass globally. Although this scenario promotes the circular economy in textile waste, it also harms the final destination country such as toxic substances exposed to the environment without proper treatment; the workers in the recycling plant have physical contact to the poisonous substance without appropriate protective measures. The textile waste destinations like China and sub-Saharan African countries start to ban the import of textile waste. In 2017, the Chinese government announced a plan to prohibit the import of particular wastes (Qu et al., 2019). On the other hand, African countries have banned the import of secondhand clothing due to the political issue, and they want to protect local textile industries (Newell, 2015).

Although the US textile export rate is high, there is still a massive amount of waste in the country. Increase in public awareness about the textile waste issue is very important for the whole textile management system. The new technologies for reuse and recycle products are mandatory. Many companies in the United States use recycled textile as a raw material for their product, for example, Patagonia, The North Face, and American Eagle Outfitters. Furthermore, the consumer is increasingly demanding circular practices that can promote the product. This could create a closed-loop textile market.

The recycling system in Brazil is similar to America; it includes collection, sorting, transport, and recycling. Local government supports the textile waste recycling activities because all activities create employment and offer opportunities to the businesses. There are several textile recycling projects for upcycling purposes in Brazil, such as Reuse Fabric Bank, Retail Fashion, Brandili Textile, Insecta Shoes, Ecosimple, Bank of Clothing from Caxias-do-Sul. These projects aim to prolong the life of clothing and empower consumers, suppliers, and involved workers, as well as to reduce waste by reusing and recycling (Filho et al., 2019). These scenarios lead to closed-loop textile recycling.

### 12.4.3 European textile recycling program

management (Bukhari et al., 2018). The European Commission launched the new targets of the waste framework directive by a circular economy package. The package aims to recover 70% of the waste from landfills to 10% by 2030. It requires the collaboration of the government and private companies to achieve the goal.

The European countries have launched WRAP (Waste & Resources Action Program) to tackle the number of waste generated, including clothing and textile waste. The WRAP has focused on consumer behavior and fashion trend. However, the clothing supply chain consumes a massive amount of resources. The water, chemicals, and energy used before and during manufacturing and transportation create many carbon footprints even before reaching the consumer. The consumer behavior needs to be changed by reducing the purchase volume of clothing and increases recycled clothing preference to minimize natural resource consumption. The WRAP also reports that extending the active life of clothes by 9 months could save consumers around £5 billion per year and reduce the carbon, water, and waste footprints by about 20%—30% each. The WRAP has created the Sustainable Clothing Action Plan (SCAP) 2020 Commitment, which is a voluntary agreement targeting every stage of the clothing supply chain. The SCAP requires the collaboration of industry, government, and retailer to improve the sustainability of textile. The development of textile sustainability can be done by improving separation waste system and set priority to reuse over recycling as the various fibers that comprise clothing is the main challenge of reprocessing and recycling. Therefore, well-categorized textile waste is a benefit of the recycling process. In the United Kingdom, WRAP works with hundreds of businesses and local authorities, trade associations, and charities.

For example, a Textile Recycling Association (TRA) has collectors, sorters, processors, and exporters of used clothing and textiles. TRA collects the textile wastes and manually sorts and grades according to their condition and the types of fibers used. Unwearable textiles are sold to the “flocking” industry for shredding and respinning. Wool is usually recycled by blending the fiber with new wool to produce new textile products. The final product may be little harder, but surely longer lasting. In some case, the textile is resorted by type and color for avoiding the redying process. Then the shredded materials are pulled into fiber and spinning to produce the recycled yarn without redyeing process. In case of polyester, the shredded polyesters are compressed into polyester chips. The polyester chip is melted and spun into new filament fibers used to make new polyester fabrics. The recycled yarn can be used in a wide range of textile industries such as car insulation, loudspeaker cones, furniture padding, or even building materials.

The WRAP will also extend the work with international partners to deliver improvements in sustainability. The European Clothing Action Plan (ECAP) is based on the WRAP scheme. The European countries such as Denmark, Finland, Germany, Italy, Netherlands, Norway, Poland, Romania, Spain, and Sweden have also signed up to Sustainable Clothing Action Plan (SCAP). It aims to divert textiles waste away from landfills. The European Commission LIFE program has funded the WRAP (€3.6 million) for commencing the ECAP. ECAP aims to reduce textile waste stream across Europe and embed a circular economy approach. The specific aims of the ECAP are diverting over 90,000 tons of clothing waste from landfill and incineration by 2019.
and reduce the waste footprints of clothing (including carbon and water) in Europe. The ECAP also prevents waste generation throughout the clothing supply chain. The ECAP has to encourage the textile producer to apply technology into the business, for example, using recycling fiber for new fabric production and creating a resource-efficient design. Besides the textile recycling technology, the ECAP also introduces customers to buy smarter and use clothing for longer via the “Love Your Clothes consumer” campaign.

There are numerous of textile recycling companies run in Europe (i.e., SOEX and I: Collect) and some pilot/demonstration projects for fiber recycling, for example, Relooping Fashion in Finland, Re:newcell in Sweden and Pure Waste Textile in Nordic country that uses textile waste as a raw material for their products. There are also several projects related to sorting textile waste for recycling propose, such as SITex and Textile back to Textiles (Sweden), Textiles4Textiles (Netherlands) and FIBRESORT (Belgium). A SOEX group is one of the top textile recycling in German. The SOEX also provides service throughout Germany, Europe, and the world. The service includes clothes sorting, domestic sales, and export of second-hand clothing, trading end-of-line goods, surplus goods, new goods, returned products and goods with manufacturing flaws, recycling used textiles. In 2013, the SOEX group collaborated with the most important Swedish fashion retailer names Hennes & Mauritz AB (H&M) to find a solution to textile recycling. The H&M will collect all second-hand clothes at its shop and will give a discount for new clothes to customers. All second-hand gathered clothes will be sent to the SOEX Group for recycling and making new products. Clothing from textile waste and insulation material that is used in the automobile industry are made in Germany, and some of the content is sent to the USA for redesign and other purposes (Muhammad, 2013). This scenario also implements to other countries in Europe, South America, and the Middle East. The post-consumer textile wastes in the UK usually are export to sub-Saharan Africa, the EU (mainly Poland and Hungary), Asia (mostly Pakistan) and non-EU Eastern European countries (primarily Ukraine). The textile waste exporting business has instantly grown from around 75,000 tons in the mid-1990s to 350,000 in 2014 (WRAP, 2016). Approximately 40% of this volume is exported to Poland and Hungary due to the free trade conditions and the operating cost of the recycling plant. However, the global textile waste trade to and from EU countries are regulated under the EU’s Transfrontier shipment of waste regulation. The textile wastes are categorized by their hazardousness. Some of the textiles contain hazardous substance; therefore; it needs to go to the procedure and ultimate requirement in case it will be sent to non-OECD countries (Tojo, 2012).

France was interested in recycling textile waste. France has started an Extended Producer Responsibility (EPR) policy for end-of-use clothing, linen, and shoes (Filho et al., 2019). The policy points out that textile producers are “considered responsible by law for providing or managing the recycling of their products at the end of their usage”. In 2007, the EPR declared a legal framework for managing textiles waste, and the launching framework improves the recovery rate of postconsumer textile waste up to 90% and 50% of this amount can be reused (Bukhari et al., 2018). The EPR policy for textile waste helps the textile recycling industry to overcome challenges, and it
also creates jobs for social. The sorting of textile waste has provided 1400 full-time jobs in France as of 2017. The EPR policy also drives societies to financial support innovation and research to provide feasible solutions for the textile producer. To respond to the circular economy, VTT Technical Research Center of Finland has launched the project name “Tekstilien kierrätyslautakunta (TEKI)” or “The Relooop Fashion” for emphasize the important of textile recycling. The Relooop Fashion creates the model of close circulation ecosystem from lab scale to pilots. It also creates a foundation for a new kind of industrial utilization of textile waste that is unsuitable for reuse.

The new EU circular economy package that includes a waste management policy entered to force on 4 July 2018. The new rules focus on improving waste management to minimize waste volume. It also mentions the new separate collection rule and new technology to recover the fiber from textile waste, which can boost the recycling rate. The EU governments will push the directives included in the package into national law before 2020.

### 12.4.4 Asian textile recycling program

China is the world’s largest textile fiber producer, with the processing volume of the textile fiber of 53 million tons in 2015 (S. Wang, 2018). Even China generates more than 20 million of textile wastes domestically every year, but the country also imports the secondhand clothing and textile waste. In 2016, around 0.13 million tons of discarded textile materials ended up in China (Qu et al., 2019). With the high volume of textile waste accumulation and the negative effect of textile waste on the environment, the textile waste policies and legislation are mandatory. The policies and regulations of the textile industry in China are rigid. The central government of China has announced 118 textile environmental policies from 1989 to 2016 (Xu et al., 2018). The majority of the policies enforce the textile manufacturer to control their production, but the regulations are not implied at the consumer stage. The regulatory instrument includes the enforcement of laws and regulations, setting objectives, standards, and technologies that the producer must meet. A person who contravenes a regulation order shall get economic and/or penal sanctions. However, there is no standardization and regulation of textile waste collection and recycling in China. The lacking of standards on the safety and quality of recycled products, management of recycling processes, could lead to personal health and environmental problem. Recently, the Ministry of Industry and Information Technology has announced industry standards on recycled polyester chips and fibers, which serve as recommended practices for businesses.

The textile recycling business in China contributes both open- and closed-loop system. The open-loop recycling uses waste to create a new product. It postpones waste from being generated but does not ultimately keep the product from the waste stream. Some recycling companies in China use textile waste as a raw material such as Changshu Automobile Interior Parts Factory. The company has developed a technology to convert fine cotton and polypropylene fibers into automobile interior parts, such as the inner surfaces of doors (Mo et al., 2009). For closed-loop recycling, the discarded textiles are used as a raw material for making the same product over and over again.
The Zhejiang Jiabao New Fiber Group Co. Ltd. (China) recycles the old uniform to polyester fiber/polyester chip and sell it or even use it for making new uniforms.

Even China has both an open- and closed-loop recycling system, but the volume of textile waste is hard to manage. In 2017, the Chinese government announced a plan to ban the import of textile waste. This policy could be a benefit for China in terms of they are giving more time to well-establish the standardized waste management systems (Qu et al., 2019).

In Hong Kong, the textile waste issue has grabbed great attention, as the growth of the textile industry has caused severe environmental impact. The Hong Kong government has delivered “Hong Kong Blueprint for Sustainable Use of Resources (2013—2022)” in May 2013. The purpose of this plan was waste reduction, which includes textile waste from the community. The Hong Kong Housing Affairs Department (HAD) has launched the Community Used Clothes Recycling Bank scheme (CUCRB). The CUCRB aims to facilitate textile recycling in the community to support environmental protection. To achieve the scheme’s objective, it requires the collaboration of the government, district councils (DCs), and nongovernmental organizations (NGOs). The government acts as the coordinator, promoter, and funder of the scheme. The government will adopt a green procurement policy to promote waste reduction and recycling. DCs are responsible for designing the area for placing the textile recycling banks; appointed NGOs will act as scheme managers to manage the recycling banks and the textiles collected. The current appointed NGOs are Friends of the Earth (Hong Kong), Christian Action, Salvation Army, and Conservancy Association (Lee, 2015). There are some other programs for promoting textile reuse and recycling in Hong Kong apart from CUCRB. For example, the Christian Action and Conservancy Association creates recycling activities to raise children’s awareness about the textile waste issue.

The Hong Kong Conservancy Association manages the textile waste collection and exports to a foreign country. The Redress sets up a circular economic concept of fashion shows, namely “Redress Design Award” to educate the designer about sustainable design theories and techniques. This has persuaded several clothing brands to work at different stages along the supply chain to reduce textile waste. The H&M Foundation, a nonprofit funded by the family, founders, and main owners of H&M Group, has cooperated with the Hong Kong Research Institute of Textiles and Apparel (HKRITA) to develop an upcycling program of textile waste. This program includes a take-back campaign for the customer to drop off unwanted clothes in store and then the collected textile waste will put into a fiber-to-fiber recycling program to form a closed loop for textiles. HKRITA also works with the Novetex Upcycling Factory to set up new technology for separating textile waste to produce yarn and reuse fabric made of mixed fibers. Once the production can perform on a big scale, it will solve the textile waste problem.

A developed country like Japan has fewer problems with municipal solid waste accumulation than other countries in Asia. It could be because the recycling policies, innovative recycling technology, and high standard of waste management in Japan facilitate waste management system. The Basic Act for Promotion of the Recycling-Oriented Society was enacted in 2000, followed by laws for recycling containers.
and packaging, home appliances, food, construction materials, and automobiles. Even there is no specific policy about textile recycling, but the textile recycling businesses in Japan has continuously grown. Japan environment planning (JEPLAN) is a commercial recycler in Japan. The JEPLAN works on managing the collection points and logistic networks to provide recycling services to meet the demand of the customers and consumers.

Moreover, the JAPLAN also develops new recycling technology that helps to build Japan into a sustainable recycling-oriented society. The “FUKU-FUKU” project is one of the textile recycling projects launched by JEPLAN. The project aims to provide convenient channels for the consumers to return unwanted clothing and deliver them to the recycling plant of JEPLAN. Unlike any other textile recycling plants that use textile waste to produce recycled yarn or automobile part, the JEPLAN developed a new recycling technology that turns textile waste into fuel. The cotton fiber in the textile waste was hydrolyzed into glucose and then the glucose generated will be used to produce bioethanol. Similar to “FUKU-FUKU” project, Teijin Group is a chemical technology company that aims to create a closed-loop recycling system for recycling polyester products. The company collects unwanted clothes from the consumer in a retail shop. Then the company uses a chemical technique to extract polyester fiber from the textile wastes to form a polyester chip. The polyester chip would turn into polyester fiber and polyester fabric. These recycled polyester materials can be used as raw material to produce uniform (office wear), furniture, household goods, and construction materials. In 2009, the Teijin group set up a closed-loop polyester recycling system in China with textile fiber producer Zhejiang Jiabao New Fiber Group Co. Ltd. The partnership will use technology based on Teijin’s “Eco Circle” garment take-back system that involves the complete depolymerization of polyester textiles. Teijin also works with textile and apparel brands such as Henri Lloyd, Li Ning, Quiksilver, and Patagonia on the garment for take-back programs. The company takes and reprocesses the unwanted clothing and then returns the recycled fabric to their partnership retailer. This showed that textile recycling could provide financial benefits and reduce environmental impact (Newell, 2015). Therefore, social awareness of textile waste has been heightened to reduce waste generation and motivate people to use the resource adequately.

12.5 Textile recycling technologies

The textile recycling plays a vital role in textile waste management. It is a potential method to reduce the waste proportion before it goes to the dumpsite. The textile recycling process requires incorporative technology to handle a bunch of textile material. The variety and complexity of textile wastes are the main obstacles to the recycling process. Therefore, ongoing research and development focus on the problem of processing used and mixed fibers. The textile recycling processes can be categorized into three main categories, including (1) mechanical process/physical process, (2) chemical process, and (3) biological process. In most of the cases, the recycling process consists of a mix of physical and chemical processes. The detail about each process will be explained in the following subsection.
12.5.1 Physical process

The physical recycling process can be divided into two main methods: (1) the mechanical process and (2) thermal process. The mechanical recycling process is a process that converts textile waste materials into new materials without changing the basic structure of the material. The mechanical means include crushing, grinding, shredding, or pulling, which are often applied for size reduction. Even the cutting process cannot change the basic chemical structure of the material, but it can cause disaggregation and deliberation of fiber bundles, shortening the fiber length, and loss of a degree of polymerization. The processed fiber may be respun with virgin cotton fiber to have comparable properties to the cotton fiber. Therefore, the mechanical process is mostly applied in the downcycling sector; the textile wastes were degraded into different kinds of products such as decoration materials, construction materials, and agricultural and gardening use products. For these kinds of products, textile waste is cut and shred into fibers which can then be respun into yarn or made into nonwoven textiles. Then the nonwovens can be used to produce disposal products such as diapers, sanitary wipes and napkins, and durable products such as materials for apparel, home building packaging, and industrial applications. The mechanical process often combines with other technologies such as thermal processes or chemical processes to create the desired recycling product. Another option for the physical recycling process is the thermal process. The thermal process is usually used for recycling synthetic fiber. The process begins with size reduction by a mechanical process. Then the small size of polyester fibers is heated and remelting and extrusion into resin pellets. The resin pellet is melt extrusion again to form a fiber. This fiber-to-fiber recycling creates an entirely closed-loop fashion. However, the characteristic of reextruded polyester fiber has changed during the decolorization and recycling process.

12.5.2 Chemical process

The chemical recycling processes use chemicals to break down or depolymerize fibers into their monomers, which can be polymerized back into new materials. This process has attracted attention from the textile recycling business because of its advantages. The chemical recycling benefits are as follows.

- The monomers obtained from the chemical recycling process can be used to make a variety of new materials.
- Contaminants such as dyes, pigments, and metals can be removed during the chemical recycling process.
- The new catalyst used in the polymerization process can create a character for new material.

Typically, the fabric wastes are composed of cotton/polyester blend. Separation of cotton and polyester requires several approaches and methods, as presented in Fig. 12.13. Cellulose fiber in cotton waste is hard to dissolve naturally. Specific and expensive solvents such as NMMO (N-methylmorpholine N-oxide) (Tojo, 2012) or ionic liquids (organic salts in liquid state with a low melting point) are used in the chemical recycling process. The NMMO solubilizes the cellulose in textile waste.
The dissolved cellulose and polyester are separated by filtration. The polyester residues in solid phase are melted and respun to recycled fiber. The NMMO process is considered to be the most environmentally friendly method of producing regenerated cellulose fibers on a commercial scale. As the chemical is nontoxic and reusable and the working temperature is around 60°C, the process is industrial favor. The regenerated cellulose fibers by this method are called “lyocell” and also available in trade names such as “New Cell” and “Tencel” (Courtaulds). The properties of lyocell, such as crystallinity and fibrillar structure, are slightly different from the original fiber. However, the properties of lyocell can be controlled by monitoring the postfiber treatments. On the other hand, depolymerization of cellulose fiber by acid hydrolysis generates sugar monomer. The glucose monomer cannot be polymerized into cellulose polymer, but it can be used for other purposes such as fermentation into biofuels (Jeihanipour et al., 2010).

Extraction of polyester can be divided into two main methods, which are depolymerization and polyester dissolution. To dissolve the polyester, specific solvents are
required. Then the dissolved polyester can be respun into new polyester fiber. For example, dimethylterephthalate, methyl-p-toluate, or dimethylisophthalate are chemicals that use for dissolving polyester fiber and separating the polyester from nonpolyester components. The product of chemical recycling can be used as a feedstock for methanolysis to form dimethylterephthalate and alkylene glycol. The dimethylterephthalate is further hydrolyzed to form terephthalic acid (Tukker, 2002).

There are many ways to depolymerize the polyester fiber (see Fig. 12.13), for example, glycolysis, methanolysis, hydrolysis, and alcoholysis. The product from different depolymerization technique is varied. For instance, the alcoholysis or alkali hydrolysis of cotton/polyester blend generates terephthalic acid, ethylene glycol, and cotton monomers. After alkali hydrolysis, the terephthalic acid is precipitated in a solid form while ethylene glycol is present as an organic component in the liquid phase. These recovered products can be used as a feedstock for new polyester polymerization. The depolymerization of polyester via hydrolysis reaction produces a mixture of polyols such as unsaturated polyesters, polyurethanes, and polyisocyanurates. These polyols could turn into polyurethane by polycondensation. Then the recovered polyurethane can be used to produce polyurethane resin composites. Methanolytic depolymerization of polyester usually performs in harsh condition (250–270 °C/8.5–14.0 MPa). The depolymerization products are dimethylterephthalate, methyl-(2-hydroxyethyl)terephthalate, bis(hydroxyethyl)terephthalate, dimers, and oligomers, which found in the solid phase (Yang et al., 2002). Even the single step of the chemical process shows potential for textile recycling, but a combination of the methods for textile waste pretreatment is recommended. Therefore, the recycled material is most often mechanically pretreated before the depolymerization or dissolution (Sandin and Peters, 2018).

12.5.3 Biological process

The biological process or enzymatic treatments have attracted much interest because of their effectiveness under mild treatment conditions. The textile fiber consists of two main types of fiber, including natural fiber and synthetic fiber. The natural fibers are categorized into three groups: plant fiber, animal fiber, and mineral fiber. The plant-based natural fibers, such as cotton and linen, are mostly used in textile manufacturing. The plant-based fiber has a lignocellulose structure, which is composed of cellulose, hemicellulose, and lignin. These natural polymers can be degraded by microbial hydrolase enzymes such as cellulase, hemicellulase, and ligninase. The cellulase and hemicellulose enzymes break down cellulose into a small molecule of sugar that can serve the biorefinery unit. As the cellulose is a high crystallinity polymer, it results in low conversion rate and yield. The biological process would typically begin with a pretreatment step. The pretreatment step is used to modify the textile waste and break the macrostructure of the fiber. Therefore, the pretreatment process is necessary for decreasing crystallinity of cellulose and enhancing its susceptibility to subsequent hydrolysis. The enzymatic hydrolysis is the bioprocess to break down the cellulosic material into a small molecule of sugar. The textile waste hydrolysis provides soluble sugar and solid residues, which are synthetic fiber. The synthetic fiber is easily
removed by filtration, and it can be respun to produce synthetic fiber. Commercially, cellulase enzymes, such as Novozymes CelliC Ctec3 from Novozymes, show the highest catalytic activity at pH 5, 50°C. Similar hydrolysis result obtained from the chemical acid hydrolysis of cellulose operated at temperatures of up to 200°C.

Therefore, the enzymatic hydrolysis conditions are more economical for industrial application (Jeihanipour, 2011). The energy consumption of textile recycling by biological process attracts the textile recycling investor as if the cheaply available cellulases are developed. Recently, there are only a few studies investigated for the biological method of textile degradation (Hu et al., 2018a; Hu et al., 2018b; Li et al., 2019; H. Wang et al., 2018). Hu et al. (2018a,b) studied the feasibility of cotton textile waste for cellulase production by fungi, namely Aspergillus niger CKB. Then the extracted enzyme is used to hydrolyze the cotton. The result showed that the fungi could grow on the surface of textile with hydrolysis yield of 70% (Hu et al., 2018). This result has supported the recycling of textile waste by the biological process, which is a feasible process.

The animal-based fibers such as silk and wool have proteins polymer structure. Silk is natural protein fiber from Bombyx mori silkworms. The structure of silk comprised of fibroin (72%–81%) and sericin (19%–58%). The fibroin is the main structural component in silk, and sericin is the glue-like outer layer that coats fibroin during fiber spinning and formation of cocoons (Brown et al., 2015). These proteins both contain the same 18 amino acids such as glycine, alanine, and serine in different amounts. The fibroin contains repetitive amino acids (-Gly-Ala-Gly-Ala-Gly-Ser-), which form a crystalline structure. The crystalline structure of fibroin is difficult to degrade because it has high hydrophobic property.

On the other hand, the sericin protein in silk has an amorphous structure and hydrophilic property, so it is easy to degrade. However, the enzymatic degradation of silk requires a two-step process. The first step is enzyme adsorption to the silk surface, and the second step is the hydrolysis of the ester bond in silk protein structure.

Silk can be hydrolyzed into collagen and albumin by using bacterial proteinase (Forlani et al., 2000). The proteinase enzymes, including protease XIV, protease XXI, protease E, α-chymotrypsin, and collagenase, are required to degrade the fiber biologically (Srihanam and Simchuer, 2009). The proteinase K from Engyodontium album, protease XIV from Streptomyces griseus, α-chymotrypsin from bovine pancreas, and collagenase from Clostridium histolyticum were studied for biodegradation of silk (Brown et al., 2015). The result showed that each enzyme has targeted at the different cleavage site (see as Table 12.7), which led to a variation in mass loss during silk fibroin degradation.

Wool is another protein fiber that generally used in the textile industry. The wool fiber is a polymer of keratin protein that typically contains alanine, leucine, arginine, and cysteine. The keratin protein has folded to form a repeating secondary protein structure. Then the secondary structure of keratin has twisted to form a coil structure. All protein coil structures are linked together with hydrogen and disulfide bond. The disulfide bond linked content in the wool structure contributes to protease-resistant ability. The common proteolytic enzymes, such as pepsin, trypsin, or papain alone,
cannot degrade wool fiber (Brandelli et al., 2010). It requires specific protease enzyme to hydrolyze wool fiber into a small protein molecule.

Furthermore, the cuticle that coats wool fiber decreases the hydrophilic property of wool, which makes it difficult for biodegradation. The keratin biodegradation enzyme production was studied since 1950. The keratinolytic enzyme production from fungus Bacillus and thermophilic actinomycetes were investigated (Stahl et al., 1950). The characteristic of keratinase from different sources was also studied (Brandelli et al., 2010; Gupta and Ramnani, 2006). Gupta and Ramnani (2006) reported that keratinase enzyme from most bacteria, actinomycetes, and fungi has optimum pH range from neutral to alkaline and the optimal temperature range from 30 to 80°C (Gupta and Ramnani, 2006). Therefore, keratin degradation enzymes for different purposes have further developed for the past 60 years (Gupta and Ramnani, 2006). However, the application of keratinolytic enzyme to utilizing wool waste was studied in 2010 (Brandelli et al., 2010). Fang et al. (2013) investigated the degradation of keratin waste (wool) by keratinolytic enzymes from Stenotrophomonas maltophilia BBE11-1 (Fang et al., 2013). The results showed that S. maltophilia keratinases have great utilization ability for wool treatment in the textile industry. Also, the protease-like proteins, KrtA, and KrtC from Fusarium oxysporum 26-1 have wool degradation ability. The protein has partially degraded the wool fiber by removing the cuticle of wool fibers (Chaya et al., 2014). The other protease enzyme that can hydrolyze wool fiber is an esperase enzyme. This enzyme can break down disulfide bond that linked between protein fibers, which caused about 25% weight loss in wool. The wool degradation by modified esperase (L-cysteine—assisted esperase) showed about 90% weight loss (Zhang et al., 2018). This could implement that esperase potentially be applied to better utilize the keratinous resources such as wool/polyester-blended fabrics.

Besides the natural fibers degrading enzyme, some enzymes can hydrolyze synthetic fibers, such as polyester, polyamides, and polyacrylonitriles (Mueller, 2006). Enzymatic recycling of polyester has been investigated for more than 20 years (Kawai et al., 2019). Degradation of the polyester fiber requires two types of enzymes: cutinases and lipases. The cutinase enzyme hydrolyzes the ester binding of cutin. The lipases are enzymes that hydrolyze lipids into a small molecule of glycerides. Although

<table>
<thead>
<tr>
<th>Protease</th>
<th>Source</th>
<th>Cleavage site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proteinase K</td>
<td>Engyodontium album</td>
<td>Adjacent to His, Phe, Trp, Tyr, Ala, Ile, Leu, Pro, Val, Met</td>
</tr>
<tr>
<td>Protease XIV</td>
<td>Streptomyces griseus</td>
<td>Adjacent to His, Phe, Trp, Tyr, Lys, Arg</td>
</tr>
<tr>
<td>α-Chymotrypsin</td>
<td>Bovine pancreas</td>
<td>Adjacent to Tyr, Phe, Trp, Val, Ile, Leu</td>
</tr>
<tr>
<td>Collagenase A</td>
<td>Clostridium histolyticum</td>
<td>X-Gly-Pro</td>
</tr>
</tbody>
</table>

Note: X can represent any amino acid.
these enzymes can potentially hydrolyze polyester, their hydrolysis yields are currently low. In 2016, Yoshida et al. (2016) discovered a microbial strain, namely *Ideonella sakaiensis* 201-F6 that converts polyester into terephthalic acid and ethylene glycol. This novel bacterium could boost the polyester hydrolysis yield up to 50% in 50 days (Yoshida et al., 2016). However, the polyester hydrolytic enzyme from *I. sakaiensis* 201-F6 cannot penetrate the polyester material; therefore, the hydrolysis reaction only happens on the surface of the material. The biological recycling of polyamide and polyacrylonitrile fibers has a similar challenge to polyester recycling. The polyamide and polycrylonitrile fiber—degrading enzymes are available, but the protein cannot penetrate the material. This has led to the conclusion that recycling of polyester with enzymatic hydrolysis is currently not feasible. Then vermin composting concept has occurred. The vermin composting uses the living organisms to produce enzymes that degrade the textile waste. Similar to the normal composting process, the vermin composting process also requires different kinds of microbes to convert organic waste into nutrient-rich soil. The living organism such as earthworms was added in the vermin composting process to speed up the composting process. This process may not create closed-loop recycling, but it has introduced favorable environmental treatment into textile waste management (Piribauer and Bartl, 2019).

12.6 Factors influencing fabric waste recycling process

The textile recycling process is a very challenging process. The main barrier of textile recycling is the complexity of textile wastes. The content of fibers is very complex, including cotton, silk, various synthetic fibers, and mixed materials. These materials are used together, and the wastes generated are mixed. It has been reported that the composition of textile wastes have affected the properties and quality of recycled fiber. Ütebay et al. (2019) also supported that the recycled fiber quality and recycled yarn properties are associated with the textile waste properties and shredding parameters (Ütebay et al., 2019). Then the sorting process of textile waste is needed before recycling. The sorting process is labor-intensive classification work. The used textile wastes are classified into specific groupings according to their materials, colors, and average piece size and recycled. The cotton waste is collected by small recovery enterprises, which convert them into cotton fibers and then produce nonwoven fabrics. The polyester blend fabric is classified according to color by individual collection businesses and then is sent to small recovery enterprises and recovered into granular polypropylene through washing and smelting (Mo et al., 2009). Automated sorting technology has been developed to address the labor cost and the purity of materials in this step. Textiles for Textiles (T4T) project funded by the European Commission’s eco-innovation initiative has created an automated sorting technology for textiles and clothing. The automated sorting machine uses near-infrared spectroscopy technology to separate the waste by its color and composition. Then the grouping textile wastes will be recycled by a suitable recycling technique. This automated sorting machine has saved 53% of energy usage during fiber recycling. It has reduced water and chemical usage in the recycling process around 80%—90% in a pilot project of the jean manufacturer.
The strength of textile fiber also influences the recycling process. The textile waste needs to be shredded into small pieces before recycling. Moreover, unique textile characteristics such as flame retardant and water-resistant fabric contain many chemicals, including organophosphate compound, organohalogen compound, and organic compounds. These chemicals have contaminated the fiber, and they need another process to remove them from recycled fiber. The dyestuff and other chemicals that embed in the waste fiber also halt the recycling. The dyes in recycled fiber are unwanted material for the textile manufacturer, so the price of contaminated fiber is lower than the clean recycled fiber. Furthermore, some chemicals are toxic and carcinogen.

Cost of the recovery process and recycling technology is a significant concern for the recycling operation. Nowadays, the price of technology for converting textile waste into recycled fiber is high.

Besides, the price of virgin fiber in the market is not high, so the manufacturer has tended to use virgin fiber rather than apply the recycled fiber into the textile production process. The logistics cost for collection and transfer of the textile wastes to recycling station is also considered as a part of production cost. The shoddy or waste scrapes are generally shipped to the recycling plant that has sufficient technology and infrastructure. In some cases, the waste stream has internationally transferred to the recycling station to create a new product, which affects the increase in production cost. The cost of recycled fiber may not directly influence recycling production, but it affects the end designate manufacturer. The textile manufacturers tend to use lower price fiber.

12.7 Fabric wastes valorization

The utilization of textile wastes is one of the most crucial parts of waste management. The valorization of textile waste helps in reducing the accumulated textile waste in the landfill or dumpsite station by turning into value-added products. However, a lack of recycling technology and infrastructure for recycling textile waste results in the impurity of recycled fiber. Then this recycled fiber is typically used in the downcycling process. The textile waste that goes to the upcycling process has been adopted in limited groups. The application of the fiber in upcycling fashion needs specific designing and special advertisement to make the product commercialized. In terms of the utilization of textile waste building block, the textile wastes have the potential to be used as a feedstock to produce various products. Several companies have launched a textile waste utilization project that aims to create a circular system for textile waste. Some of them have demonstrated the platform of textile waste recycling in small industrial scale. The fabric waste valorization in this subsection will be divided into two groups, including (1) application of recycled fiber in the textile industry and (2) application of recycled fiber of the textile industry. The details are as follows.

12.7.1 Application of recycled fiber in the textile industry

 Both of natural fiber and synthetic fiber can be extracted from the textile waste for producing recycled fiber. Although the extraction technologies are available, the operating
cost of the process is pricey. Therefore, only 0.1% of recycled fiber is converted into a new textile product in the United States (Leblanc, 2019). The application of recycled fiber in the textile industry can be categorized into two routes. Firstly, textile waste is utilized to produce new textile product via the creativity of the designer. A few fashion agency has foreseen the rapidly accelerated pace of textile consumption globally. They tried to present a sustainable fashion way of clothing by efficient resource design. ReBlend (a Dutch circular fashion and textile agency) has made an effort on new fashion design by using postconsumer waste. On this wise, the textile wastes are used in an eco-friendly process (minimize water, chemical dying) to make yarn for new clothes. The life cycle analysis of this process shows that it reduces the energy use by 33%, and it decreases the water consumption by 62% compared with clothes production from virgin fiber (Koszewska, 2018). Tonlé company is another company that also used preconsumer textile waste to produce fashionable clothing. The company has utilized more than 97% of its textile scrap into new design clothing (Koszewska, 2018). Secondly, the application of recycled fiber via novel technologies is another route to utilize the extracted fiber. The natural fiber is dissolved and respun to form a recycled fiber. The recycled fiber that has been used in the textile market is shown in Table 12.8. Even the benefit of the recycling process is shortening the textile production process, but the quality of recovered fiber is usually lower than the virgin fiber. Therefore, the recycled fibers are respun with virgin fiber to improve their properties. Liu et al. (2019) have demonstrated the utilization of postconsumer cotton waste for recycled fiber production. The postconsumer fiber was shredded into small pieces. Then they were hydrolyzed by sulfuric acid to reduce the molecular weight of the cotton fibers. The alkaline/urea solvent systems were used for regenerating the cellulose in cotton fiber (Liu et al., 2019). This technique can remove dyestuff from textile waste. Furthermore, this technique creates a smooth surface on recycled fiber, unlike the ionic liquid (NMMO), which gives a hairy surface structure on the fiber. Lv et al. (2015) also reported another ionic liquid technique to separate natural fiber and synthetic fiber for textile manufacturing purpose. The nylon/cotton-blended fabric was treated with a sodium hydroxide solution (2 wt%) at 80°C for 2 h for pretreating the fabric. Then 1-allyl-3-methylimidazolium chloride ([AMIM]...)

### Table 12.8 The application of recycled textile waste in the textile industry.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Product</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton waste</td>
<td>Recycled cotton fiber</td>
<td>Liu et al. (2019)</td>
</tr>
<tr>
<td>Nylon/cotton fabrics</td>
<td>Recycled nylon and regenerated cellulose</td>
<td>Lv et al. (2015)</td>
</tr>
<tr>
<td>Waste jeans (cotton/polyester blend)</td>
<td>Recycled cotton fiber</td>
<td>Yousef et al. (2019)</td>
</tr>
<tr>
<td>Cotton fiber</td>
<td>Cellulose carbamate fiber</td>
<td>Paunonen et al. (2019)</td>
</tr>
</tbody>
</table>
(Cl) was applied to dissolve cellulose fiber before the filtration process. The filtration process is used to separate the nylon fiber (solid phase) and dissolved cellulose. The dissolved cellulose was regenerated. The regeneration of cellulose/[AMIM]Cl solution was performed in water as ionic liquid was completely miscible with water in any ratios. The regenerated cellulose was cast into fiber again for respinning with new virgin fiber (Lv et al., 2015). Yousef et al. (2019) have demonstrated the ionic liquid technique on a pilot scale. The waste jeans composed of cotton and polyester at different proportion were used as a raw material. The result showed that the recycling rate of this technique was approximately 93% and the profitability was 1466 dollar/ton of waste. This result supported that the developed strategy can be seen as a potential approach for recovery of cotton (Yousef et al., 2019). Another method for regenerating cellulose fiber from textile waste is cellulose carbamate technology. The cellulose carbamate fiber production used less than 2% and 25% of the water consumed by cotton and viscose fiber production, respectively. The textile waste contains cellulose mixed with urea at an elevated temperature, which then degraded urea into isocyanic acid and ammonia. The isocyanic acid bonded with the hydroxyl group of cellulose to create carbamate. The carbamate group in the cellulose improves cellulose dissolution in alkali property, and the carbamate cellulose regenerated into textile fibers in an acidic coagulation bath (Paunonen et al., 2019).

The application of recycled fibers has pilot-scale demonstrated in several projects. The VTT Technical Research Center of Finland’s Tekstiilien kiertotalous has started a Circular Economy of Textiles project, which targets the textile waste as a raw material for new fiber production. The project begins with collecting old cotton clothes from consumers and then applies the technologies to dissolve and process them into recycled fiber and new garments. H&M collaborated with I:CO is also keen to produce a new product from postconsumer waste, which consumers donate their clothing at H&M store. ReShare (a division of Salvation Army) has launched a uniform recycling project. The project has transformed the army uniform into new yarn and new products. The fibers of army uniform comprised of cotton and polyester in a ratio of 50:50 were blended with virgin fiber to produce blanket.

Besides fiber, other compounds trapped in textile waste can be extracted for further use in the textile process. Vecchiato et al. (2017) demonstrated the pigment recovery from the flame-retardant fiber. The viscose fiber was hydrolyzed at 50°C for 4 h by enzyme hydrolysis. The viscose fiber was decomposed entirely, and the pigment was separated to be reused (Vecchiato et al., 2017).

The product from recycling technology requires a further investigation of the characteristic of recycled fiber compared to virgin cotton. The water and carbon footprint of recycled fiber production are considered. The chemical recycling can be promoted to commercial scale if the suitable textile waste sorting technologies are ready.

### 12.7.2 Application of recycled fiber of the textile industry

Research work had been developed to apply the textile wastes into the building materials and increase their life cycle. For the textile fiber properties (natural and synthetic fiber), such as mechanical strength, moisture resistance, and thermal performance,
these properties are essential for material reinforcement. The reinforcing material is usually made from agro-waste. Several research groups developed a method to turn the textile waste into building materials, such as cement, fire bricks, and concrete block (see Table 12.9). The agro-wastes in the building material are replaced by textile waste because of many advantages. The cotton fiber structure is a linear polymer of

Table 12.9 The application of textile recycling of textile industry.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Product</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton waste</td>
<td>Concrete blocks</td>
<td>Algin &amp; Turgut (2008)</td>
</tr>
<tr>
<td>Textile wastes</td>
<td>Reinforce material</td>
<td>Echeverria et al. (2019)</td>
</tr>
<tr>
<td>Viscose yarn waste</td>
<td>Nanocellulose (applications of nanocellulose are in the fields of nanocomposites, food packaging, drug delivery, tissue scaffolds for cell culture and oil treatment technologies)</td>
<td>Prado et al. (2019)</td>
</tr>
<tr>
<td>Textile waste (mix synthetic fiber: 15% polyamide [nylon], 40% polyacryl, and 45% modal)</td>
<td>Reinforce material (absorb sound)</td>
<td>Tiuc et al. (2016)</td>
</tr>
<tr>
<td>Mix synthetic fiber (nylon/spandex and polyurethane)</td>
<td>Thermal insulation panels</td>
<td>Dissanayake et al. (2018)</td>
</tr>
<tr>
<td>Textile fibers (cotton, viscose, polyester, acrylic) and their blends (cotton/polyester, acrylic/wool, acrylic/polyester, acrylic/viscose)</td>
<td>Biochars</td>
<td>Hanoğlu et al. (2019)</td>
</tr>
<tr>
<td>Cotton textile waste</td>
<td>Briquette</td>
<td>Avelar et al. (2016)</td>
</tr>
<tr>
<td>Textile cotton waste</td>
<td>Biogas</td>
<td>Raj et al. (2009)</td>
</tr>
<tr>
<td>Textile waste (70% cotton, 15% wool and acrylic)</td>
<td>Insulation material</td>
<td>Tilioua et al. (2018)</td>
</tr>
<tr>
<td>Cotton-based waste textiles</td>
<td>Ethanol</td>
<td>Jeihanipour &amp; Taherzadeh (2009)</td>
</tr>
<tr>
<td>Cellulose in blended fibers waste textiles</td>
<td>Biogas and ethanol</td>
<td>Jeihanipour et al. (2010)</td>
</tr>
<tr>
<td>Postconsumer carpet</td>
<td>Reinforce concrete</td>
<td>Pakravan et al. (2019)</td>
</tr>
</tbody>
</table>
α-cellulose. It has a 65%–70% crystalline structure and 35%–30% of amorphous regions. This structure shows high strength and stiffness when it dries, while tenacity and elastic behavior increased by 5% when it is wet (Echeverria et al., 2019). The properties of textile have a benefit over the agro-waste based on their strength, physical performance, lightweight (only 1/30 of the brick, steel, or concrete), and less thermal conductivity (Barbero-Barrera et al., 2016). So less agro-waste can be used and also the production cost of building block can be decreased.

The wool fiber is an α-keratin polymer. It has a helical structure of the polypeptide. The wool has highly elastic behavior because it contains 25%–30% crystalline structure. For synthetic fiber such as polyester fiber, it is hydrophobic and has high stiffness and strength behavior because of its chemical composition. The polyester fiber is composed of PET. It has 65%–85% crystalline structure and the benzene ring structure in polyester gives stability to the polymer against ultraviolet radiation (Echeverria et al., 2019).

Besides the building materials, the products from textile recycling are used as a feedstock in the biochemical platform. Jeihanipour and Taherzadeh (2009) investigated the possibility of using jeans as a feedstock for ethanol production (Jeihanipour and Taherzadeh, 2009). The jeans were pretreated with alkali pretreatment (12% NaOH at 0°C for 3 h) and hydrolyzed to produce glucose. The glucose was then fermented by *Saccharomyces cerevisiae* to produce bioethanol. The result showed that the pretreatment improved the conversion yield to 99% in 4 days and produced 0.48 g ethanol/g pretreated textiles used.

### Table 12.9 Continued

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Product</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lyocell (recycled cellulose fiber from textile waste)</td>
<td>Heavy metal adsorbents</td>
<td>Bediako et al. (2016)</td>
</tr>
<tr>
<td>Nylon fiber</td>
<td>Cement mortar reinforcement</td>
<td>Spada et al. (2015)</td>
</tr>
<tr>
<td>Recycled jeans mixed with wood fiber and alginate</td>
<td>Composite material</td>
<td>Lacoste et al. (2018)</td>
</tr>
<tr>
<td>Polyester–cotton textile</td>
<td>Ethanol</td>
<td>Gholamzad et al. (2014)</td>
</tr>
<tr>
<td>Polyester–cotton textile</td>
<td>Cellulase</td>
<td>(Hu et al., 2018; Hu et al., 2018)</td>
</tr>
<tr>
<td>Polypropylene fiber</td>
<td>Concrete</td>
<td>Yin et al. (2016)</td>
</tr>
<tr>
<td>Textile waste</td>
<td>Microbial fuel cells</td>
<td>Sivaram et al. (2019)</td>
</tr>
</tbody>
</table>
Hasanzadeh et al. (2018) also investigated the bioethanol and biogas production from denim jeans. The denim jeans are cotton/polyester blend fibers. The denim jeans were treated with a low concentration (0.5 M) of sodium carbonate to reduce the cellulose crystallinity in cotton before enzyme hydrolysis. The glucose recovered from hydrolysis was higher than 80%. The bioethanol yield was 59.5%. Alternatively, they also tried anaerobic digestion of the pretreated cotton to produce biogas. It was found that the highest methane yields of 361.1 mL/g VS were achieved from jeans after pretreatment with 0.5 M Na2CO3 at 150°C for 120 min (Hasanzadeh et al., 2018). Hu et al. (2018a,b) step forward to apply textile scrap for cellulase enzyme production. The textile scrape was treated with NaOH and used as a carbon source for growing cellulase producing fungi. The maximum cellulase activity was 1.56 FPU/g (Hu et al., 2018). The cellulase enzyme can be circulated in the textile recycling model for hydrolyzing cotton fiber, or it can be applied in other industry fields.

Furthermore, the RESYNTEX project is a research project funded by the EU’s Horizon 2020 innovation program, aimed to utilize textile waste to produce value-added products. The project involves biochemical processing for converting cotton to glucose and wool into protein hydrolysate and hydrolyzes synthetic fiber into its building block. The recovered glucose is then used for other biochemical production; the protein hydrolysate from wool is useful as a resin or adhesive material while the monomer of synthetic fiber can be applied into various products (Filho, 2018). HKRITA has developed a novel bioprocess for utilizing textile waste. The textile wastes are converted into a value-added product, such as glucose, biosurfactant, or bioplastics. These materials could be used in a range of industries. This promising potential of textile utilization has been observed. The development of textile recycling process for providing value-added textile materials and other biochemical in commercial scale is required to create a sustainable society.

12.8 Challenge of textile recycling

The textile recycling has attracted attention recently owing to the closed-loop recycling of textile wastes emerged. The ideal closed-loop recycling creates circle economy and reduces the environmental problem. The water and carbon footprint in the textile industry is minimized because the recycling has shortened the fiber production process. However, textile recycling has no commercially feasible process yet, as there are many challenges to overcome. Firstly, textile wastes are complex materials. It is composed of different fiber blends to obtain the desired properties of fabric. The dyestuffs and chemicals are added for coloring. The textiles are treated with chemicals to induce properties to obtain desired textile properties such as fireproofing, water resistance, or self-cleaning. Therefore, the textile production process is chemical intense, and residues from processes might stay in the textile. The sorting is a crucial step to separate the fiber blend into a pure fraction. Then the specific technique chosen to accomplish recycling of textile materials into high-value textiles has to be optimized to each fiber type (Bukhari et al., 2018). Previously, the sorting process is done by skilled workers. This process is a time-consuming and labor-intensive process. Moreover, the sorted
textile may not be accurate in terms of textile composition; therefore, the automated textile sorting technology has been developed. The automatic sorting machine has been installed for operating in pilot scale, but the technology is not ready for commercial scale.

Secondly, the impurity of recycled textile has reduced the fiber value. As the chemicals and dyestuffs are bonded into the fiber, it is difficult to clear the dye and other contaminants off the fiber without breaking fiber structure. The long fiber from textile waste would be used as a material to produce clothing and home textiles due to the coloring problem. On the other hand, shorter fibers and fewer contaminants are directed toward nonwoven applications in insulation, personal hygiene, and automotive. The dimethyl sulfoxide (DMSO) is used as a decolorant agent for polyester fiber. The colored polyester fiber and DMSO are heated to 140°C, and the polyesters are dissolved in the liquid mixture. Then insoluble materials are faded by DMSO. Although DMSO is a nontoxic substance, it could carry other compounds into a biological system. The toxin substance that dissolved in DMSO can penetrate through human skin, which may cause a severe side effect. Therefore, the decolorant in the process must be handled with caution or an alternative decolorant should be applied.

The cost of virgin fibers is cheaper than recycled fiber—one of the main reasons that the recycled fibers are not engaged in commerce. Because the recycled fibers need to go through many treatment processes to obtain the desired property, the cost of recycling technology, transportation is added to the recycled fiber cost. Therefore, this fiber has a higher price than the virgin one. Besides the production cost, the recycled cotton fiber properties are incomparable to the virgin cotton, so the recycled fiber may not be preferable to the production plant and investor.

Lastly, customer attitude about recycling product is inadequate. This leads to less demand in the recycled material market. The unawareness of consumer in fast fashion has caused a tremendous amount of textile waste. Moreover, the consumers do not know that the textile should be recycled and they have no idea about how to dispose of the textile waste properly. Its situation has increased the textile waste that accumulated in the landfill. Therefore, the communicative about a suitable way to reduce the waste stream by changing consumer behavior is mandatory. The government and private sectors should take part to create a closed-loop textile recycling. This collaboration should be adopted in every sector.

12.9 Conclusions

The growth of textile waste is increasing globally and it causes direct and indirect pollution to the environment. To encounter the textile waste problem requires the collaboration between the central government, regional government, private sector, society, and other. Waste regulations and standards should firmly be enforced. The raised consumer awareness about sustainability fashion, the impact of textile waste, and the recycling program for postconsumer waste should be broadcasted and translate that awareness into action. The utilization of textile waste should be adopted to reduce the waste volume and create a closed-loop and opened-loop recycling system.
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Recycling of plastics into textile raw materials and products

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13.1 Introduction

The ever-increase in the number of unused plastics, also known as plastic solid waste (PSW), is a concern in developed and developing countries. Plastic waste started to exist with the manufacturing of synthetic polymers in the year 1940 (Ghaemy and Mossaddegh, 2005; Al-Salem et al., 2009; Bartolome et al., 2012). Plastics form part of synthetic polymers where they are categorized into thermoplastic and thermostet plastics. Thermoplastics are plastics that can be hardened during cooling process and softened at higher temperature. Mostly, thermoplastics are produced using injection and compression molding processes. Molecules and atoms made up thermoplastic by joining each other forming a long carbon chain. The presence of carbon atoms results in nonbiodegradable thermoplastics, therefore, plastic waste (Al-Sabagh et al., 2016).

Plastic waste is mostly influenced by man-made (synthetic) fibers that are not biodegradable. Polyethylene terephthalate (PET), polystyrene (PS), high-density polyethylene (HDPE), and polypropylene (PP) are examples of man-made fibers (Thorneycroft et al., 2016; Sulyman et al., 2016; Sandin and Peters, 2018; Jankauskaite et al., 2008). These man-made fibers are used in the production of thermoplastics. Thermoplastics were dominating municipal solid waste in the United States (Sulyman et al., 2016). Apart from plastic waste, clothes produced from fibers, namely, cotton, polyester, nylon, elastane, and viscose, are gradually promoting waste. Statistically, utilization of both cotton and polyester fibers in the global market is at 24% and 51%, respectively (Lenzing, 2017; Sandin and Peters, 2018).

Textile waste occurs due to human beings disposing unused textile raw materials during manufacturing or clothes when their service life is finished (Dahlbo et al., 2017; Lenzing, 2017; Sandin and Peters, 2018). Hence, textile waste is divided into two groups that are: waste before product utilization and waste after end of life (pre- and post-consumer waste). Wastes before product utilization are mostly generated in the production process and it is also known as industrial waste (Bartl et al., 2005; Muthu et al., 2012b). Wastes generated during production process include
fibers, spinning, knitting, and weaving wastes. Generally, these wastes are collected and sold at lower prices to waste spinners or end up in landfill sites. Industrial wastes are easy to recycle in comparison to post-consumer wastes as they are composed of different fiber blends and materials such as pieces of metals, buttons, buckles, etc. (Bartl et al., 2005).

Textile waste is also influenced by properties of the textile fabric and yarn thickness (Dahlbo et al., 2017). In addition, textile waste is influenced by the availability of clothes in the European countries at lower cost in comparison to other consumer goods. Households in European countries were spending 4.2% in clothes. The increase in the consumption of clothes and sales results in increased textile waste (Dahlbo et al., 2017). Textile waste is also influenced by the utilization of clothes, that is, depending on a season (cold or warm), special occasions, and functions (birthdays and marriages). These result in clothes being used for shorter time, even once and thrown away (Al-Salem et al., 2009). Clothes were previously disposed by handing them to friends and family as well as donation to charity organizations. However, about 1,136,363 tons of textile waste generated from unused clothes are being recycled each year, which is less than 25% of the total generated waste (Domina and Koch, 1999).

In India alone, researchers have found that municipal solid waste generated is almost 62 million tons every year (Swaminathan, 2018). The quantity of waste is expected to increase at a rate of (1 – 2) % annually. Al-Salem et al. (2009) have reported that an avalanche of plastic waste of around $250 \times 10^6$ ton are produced annually in European countries with a possibility of 3% growth. Plastics waste comprises of 12.3% weight of the total municipal solid waste and mostly bottles produced using PET dominating this sector. This was attributed by the nonbiodegradability of plastics as well as lower rate of recycling waste (Al-Salem et al., 2009; Thorneycroft et al., 2016; Sulyman et al., 2016). Lower rate of recycling is also influenced by unavailability of methods and technologies that are able to separate and sort waste especially polymers and monomers efficiently (Östlund et al., 2015). Worldwide fund for nature (WWF) has reported that over 300 million tons of plastic are produced each year and they end up in offshore and landfill. This results in an increase in recycling plants operating illegally and without following environmental standards.

In order to minimize environmental pollution caused by plastic waste as well as monetary issues, the new legislative regulations are encouraging countries to recycle waste (Paszun and Spychaj, 1997; Bartl et al., 2005; Thorneycroft et al., 2016; Sandin and Peters, 2018). Apart from environmental pollution, recycling is also influenced by the availability of raw materials and synthetic fibers at cheaper prices as well as uncertainty in cotton production (Larney and van Aardt, 2004). While mostly metals, glass, and newspapers were traditionally recycled, this resulted in a decline in waste caused by these commodities (Domina and Koch, 1999). Statistics have shown that European countries have already established companies that are collecting and recycling almost 20% of plastic waste. In Germany, above 70% of plastic waste is collected and recycled; however, smaller amount of waste is incinerated (Textile Recycling Association, 2005; Sandin and Peters, 2018). Palm and his co-workers have reported that plastic waste in Denmark is either collected, recycled, and used locally or exported.
to other countries for recycling (Palm et al., 2014). PET waste bottles were first recycled in 1977 (Miller, 2002).

Recycling is defined as a process where a material or product is reprocessed so that it can be reused to produce new raw material (Sandin and Peters, 2018). It is also defined as a way of reprocessing and reusing product to achieve different goals, which includes lowering water and energy usage and minimizing waste and environmental impacts. Human health issues, landflling, and carbon footprints are examples of environmental impacts (Muthu et al., 2012a). Recycling processes are more advantageous in comparison to incineration and landfilling. Advantages of recycling wastes include minimizing municipal solid waste, manufacturing of new raw products, availability of feedstock in abundance and creation of new job as well as development of new markets (Thorneycroft et al., 2016; Dahlbo et al., 2017; Park and Kim, 2014).

Al-Salem and his co-workers have found that recycling plastics will prevent utilization of fossil fuel–based products. This is attributed by the production of plastic that is almost 8% of world’s oil production. In addition, plastic recycling will lower emissions of nitrogen oxides, carbon dioxide, and sulfur dioxide (Al-Salem et al., 2009; Park and Kim, 2014). Greenhouse gases such as carbon dioxide, methane, water vapor, and chlorofluorocarbons will also be reduced when higher percentages of plastic waste are recycled. Furthermore, as mentioned earlier, recycling will lower energy, water, and amount of chemicals utilized in plastic manufacturing process. Energy can be recovered by recycling plastic waste, which can be used as thermal insulator (Safinia and Alkalbani, 2016). Patterson (2000) has reported that recycled PET wastes have higher economic values followed by aluminum.

Drawbacks of recycling plastic waste include negative impact on the environment and climate change. Climate change is influenced by some recycling processes powered by fossil energy. Costly life cycles as well as movement from one geographical area to the other are some other drawbacks of recycling waste. Malaysia is an example, where waste was moved from developed countries such as Canada, Japan, and United States by ocean transportation, which was then left in Malaysia (Yoshioka et al., 1994; Shen et al., 2012; Sandin and Peters, 2018). In addition, drawback of waste recycling is the sorting and separation processes, that is time-consuming and tedious. It is difficult to separate blended or mixture of different waste materials efficiently. For example, recycling waste material produced from a blend of natural and synthetic fibers (Muthu et al., 2012b). Furthermore, individuals and companies are not interested to participate in waste recycling due to unstable economy; therefore, they end up dumping plastic waste in the landfill as it is cheaper (Wang, 2006). Fewer markets designed for recycled products, shortage of equipment and higher recycling cost are some of the reasons companies are not interested in recycling (Larney and Van Aardt, 2004; Jankauskaite et al., 2008). It is also difficult to recycle motor vehicle tires with wire cord inserted due to metals and rubber impurities present in the end product produced (Shukla et al., 2009).

This chapter discusses various sources of plastic waste and problems caused by it. Methods of separating and sorting plastic waste are also discussed. Various recycling methods and their pros and cons are also discussed in this chapter. Finally, the life cycle analysis and recent developments in plastic waste recycling are included in this chapter.
13.1.1 Main sources of plastic waste

Continuous production of materials or end products using PP, PET, PS, and HDPE fibers is the main reason of plastic waste. It is attributed to plastic or synthetic fibers being available at lower cost, better tensile strength, and physical and chemical properties. Polyolefin fibers are being increasingly used in the manufacturing of fashion and textiles. The properties of polyolefin fibers include better thermal and electrical properties, lower density, and ease of processing than some other plastics. Plastics produced from polyolefin fibers are utilized in sporting goods, X-ray and photographic films, automotive industries, and packaging applications (Bartolome et al., 2012; Shukla et al., 2009; Sulyman et al., 2016). In packaging applications, plastics are used in sacks, bags, wraps, water containers, and soft drink containers. Plastics of polyolefin are also being used in the manufacturing of imperishable products such as appliances, battery casings, and furniture (Ghaemy and Mossaddegh, 2005; Al-Salem et al., 2009). In addition, polyolefin plastics are utilized in electrical goods, construction, and building industries (Jankauskaite et al., 2008).

Large quantity of plastic waste is also caused by end products produced from thermoplastic polymers, mainly PET (Sulyman et al., 2016). PET is produced using a polycondensation reaction of ethylene glycol (EG) and terephthalic acid (TPA); however, water is used as a byproduct. Two reactions with disparity are used to synthesize PET. The first one is the esterification reaction where TPA interact (react) with EG and this results in a pre-polymer known as bis(hydroxyethyl) terephthalate (BHET). Dimethyl terephthalate (DMT) is interacted with ethylene glycol; methanol is utilized as a byproduct in the second reaction; this process is called transesterification reaction. Previously, transesterification method was mostly used in the production of PET due to easy purification of DMT without difficulties using distillation.

In the 1960, production of PET has been shifted to TPA due to its availability in abundance without impurities at the industrial scale using recrystallization (Jankauskaite et al., 2008; Park and Kim, 2014). The production of PET is influenced by its demand in the packaging application (bottles) and clothing industry (fibers). After the commercial production of PET, 60% has been converted into fibers while 30% has been remolded into bottles and 10% for other products. The appearance of bottles produced using PET, which is like a glass, and the ability to retain carbon dioxide are the main reason PET is used in the food packaging. Currently, bottles produced from PET are replacing those from traditionally utilized glass fibers and they were firstly utilized in the year 1980 (Patterson, 2000; Shukla et al., 2009; Bartolome et al., 2012). Bottles were produced by stretching PET into dimensional structures using blow-molding process (Park and Kim, 2014). They are used as storage for wine, water, beer and milk (Patterson, 2000).

Properties of PET include better stiffness, creep resistance, flexibility, and toughness. In addition, PET possesses better tensile strength, impact strength, crystal appearance, and nontoxic. These properties can be attributed to higher molecular weight of PET, which results in excellent mechanical properties. Furthermore, end products produced using PET are lightweight and difficult to break due to better fiber properties (Shukla et al., 2009; Al-Sabagh et al., 2016; Park and Kim, 2014). There is a shift in...
the production of PET fibers from developed to developing countries, which also increase production of PET (Bartolome et al., 2012).

Disadvantages of PET fibers include increasing use of petroleum-based products and nonbiodegradability. Excluding other synthetic fibers resulting in plastic waste, about 8% by weight and 12% by volume of solid waste is caused by PET (Shukla et al., 2009). A forecasting in 2019 showed that the utilization of PET is expected to increase by almost 4.5%. However, the increase in the utilization of products produced from PET and other synthetic fibers will definitely result in plastic waste and smaller space for landfilling, therefore pollute environment due to their nonbiodegradability (Park and Kim, 2014).

### 13.1.2 Separation and sorting of plastic waste

Separation as well as sorting process are important in waste recycling. Incorrect separation might result in the presence of contaminants in the end product produced from recycled waste, therefore influences product quality. Separation is performed in two ways, namely, automated or manual. Manual separation is used to differentiate glass and plastic bottles. Even though manual separation is done by human beings, textile waste is transported to the recycling process using conveyor belt which consumes 1.27 kWh/t of electricity. Consumption of electricity in manual sorting is lower in comparison to automated sorting. Near infrared (NIR) automatic sorting machine consumes 55 kWh/t of electricity. The infrared radiation present in the NIR-sorting machine analyzes materials based on electromagnetic spectrum. However, this machine is utilized in small-scale operation (Dahlbo et al., 2017).

Automated sorting machines are also utilized to separate plastic bottles. However, it is not recommended as bottles differ in size, shape, coatings, and color; therefore, the machine takes longer time to analyze. Plastic bottles can also be separated using density sorting method. Drawback of density sorting is that the majority of plastics have almost same density. For example, the density of plastics such as HDPE, medium-density polyethylene (MDPE), lower density polyethylene (LDPE), linear lower density polyethylene (LLDPE), and PP is between 0.94 and 0.96 g/cc. Density sorting can be improved by using hydro-cyclones. Wettability of materials is occurred due to the centrifugal force from hydro-cyclones. Disadvantage of separating waste using liquid is wettability and size of the particles. Stiff plastic waste from electronic scraps can be sorted using water combined with tetrabromoethane (TBE). However, the process is not cheap and it might influence contamination in the recycled products (Al-Salem et al., 2009).

### 13.2 Plastic recycling methods

Different methods are used to recycle plastic waste, namely: primary, mechanical, chemical, and quaternary recycling. Each method has its own pros and cons that are suitable for specific environment (Al-Salem et al., 2009; Bartolome et al., 2012).
Synthetic fibers differ in their properties depending on the polymer and method used during production process, accordingly fiber strength, length, and diameter varies. Due to these properties, the methods used to recycle plastic waste are going to differ. The routes used for reuse and recycling of textile wastes are shown in Fig. 13.1 (Sandin and Peters, 2018).

Methods used to recycle waste are combined in order to achieve a recycling route. Recycling route is grouped into fiber, polymer, monomer, downcycling, and upcycling. Almost above 57% of fabric wastes are recycled into fibers. This is attributed to recycled fibers that are used for insulation and spinning of new yarns (Sandin and Peters, 2018). Materials produced by recycling process sometimes have lower qualities and properties, which is called downcycling. Downcycling is mostly applied to clothing and home textiles such as blankets, kitchen rags, and upholstery (Schmidt, 2016). Downcycling in clothing is influenced by wearing and laundry machines that break and damage fibers.

Upcycling is a recycling process where the endproduct produced possesses better qualities in comparison to the original one. Mostly recycled polymers have better or similar qualities than the virgin fibers (Palm et al., 2014; Sandin and Peters, 2018). The quality of the product produced from recycling process is influenced by additives, pigments, and stabilizers used in the manufacturing of plastics; however, additives increase thermal resistance of plastics.

![Diagram of recycling process](image-url)

**Figure 13.1** The routes used for reuse and recycling of textile wastes (Sandin and Peters, 2018).
Open-loop recycling and closed-loop recycling are paramount in the early stages of plastic solid waste (PSW) when recycling of plastics is considered. Open-loop recycling is defined as the recycling of various waste materials of poor qualities that are converted into other original materials and waste products (Al-Salem et al., 2009; Sulyman et al., 2016). Closed-loop recycling is a process where a waste or a byproduct is utilized in the manufacturing of a new product. The new product possesses similar characteristics as compared to the original one. Both energy and raw materials are important in the manufacturing of products from virgin polymer. Energy is used when raw material is converted into a new product. However, energy required for converting waste materials into new product is higher in some polymers when compared to that for virgin raw material only. Due to this, closed-loop recycling is not feasible for some plastic waste (Wang, 2010).

13.2.1 Primary recycling

Before different methods for recycling PET waste were developed, primary recycling was the only method used to recycle PET waste (Bartolome et al., 2012). A product is recycled to its authentic form (Muthu et al., 2012b). In a primary recycling (re-extrusion) process, cleaned and pure fragments (scrap) from waste are collected and recycled. Fragments might be combined with virgin raw materials to produce a quality product (Jankauskaite et al., 2008; Al-Sabagh et al., 2016). Both fragments and virgin materials must possess similar properties. Advantages of primary recycling are that the process is simple and cheap. However, the scraps must not be contaminated and obtained from single waste, i.e., PET, PA waste only (Bartolome et al., 2012). Disadvantages of the primary process include difficulties in recycling different polymers and materials (metals, paper, adhesives, and papers) (Park and Kim, 2014).

13.2.2 Mechanical recycling

Mechanical recycling, also known as secondary recycling process, can also be utilized to recycle textile waste by mechanical means. Even though the process existed long time ago, it started to be profit-oriented in the year 1970 (Al-Salem et al., 2009). Mechanical recycling PET waste was firstly carried out in countries such as Canada, United States, and Western Europe (Paszun and Spychay, 1997). Mechanical recycling is carried out only on one polymer, i.e., PP and PE. Contaminations that include dust, glue, ethylene vinyl acetate (EVA), and paper are removed from plastic waste in a cyclone.

It is difficult to recycle waste when it is contaminated and complex. After contaminants have been removed, plastic scraps are separated based on their density in a tank and washed. Scraps are washed using water; however, surfactants and caustic soda can also be used if there is glue in the waste. Before the process starts, plastic wastes are reduced into either pellet or powder form. Grinding, milling, and shredding are some of the processes used to reduce waste into smaller size. Almost all recycling companies start by milling waste before recycling. However, the process of crushing and tearing waste, i.e., clothes, requires higher amount of energy, therefore, costly. Cleaned plastic
wastes are crushed into smaller pellets and extruded into strands (Al-Salem et al., 2009; Muthu et al., 2012b; Park and Kim, 2014). Strands can be carded and needle-punched to produce a mat with good absorbent properties (Korhonen and Dahlbo, 2007).

Drawbacks of mechanical recycling process are presence of impurities and complexity of the PET waste, poor quality of the recycled waste, and mechanical stress. The complexity is influenced by irregular shapes and sizes of PET waste, different colors, and waste deterioration. The quality of the product produced from recycled waste is influenced by waste preparation, washing as well as separation process (Al-Salem et al., 2009; Park and Kim, 2014). However, the quality of the product produced from waste is also influenced by the life cycle of the polymer being recycled. For example, thermal and environmental impacts alter characteristics of PET waste. In addition, circulation of liquid and product stored in bottles produced from PET expedites deterioration and contamination (Upasani et al., 2012). Windows, pipes, and grocery bags are examples of products produced using mechanical recycling process (Al-Salem et al., 2009).

13.2.3 Chemical recycling

Chemical recycling, also known as tertiary recycling, is a well-established method which meets sustainable development principles. This means the method can be used currently by present and future researchers without difficulties even in more years to come (Achilias and Karayannidis, 2004; Wang, 2010). The main aim of chemical recycling process is to obtain higher percentages of the monomer with shorter reaction time (Bartolome et al., 2012; Al-Sabagh et al., 2016). The compound of PET is formed using reversible polycondensation where a condensation substance is added to the polymer to force the reaction to change direction (reverse direction). This results in monomers and oligomers with lower molecular weight.

There exist three reversible reactions in the process of PET depolymerization: firstly, carbonyl oxygen is transformed into hydroxyl group when the carbonyl carbon (proton) is swiftly transferred into molecules in the polymer chain. Secondly, addition of the hydroxyl-bearing molecule, which results in hydroxyl oxygen. The third one is the quick removal of proton and carbonyl oxygen to produce either alcohol or water (Patterson, 2000).

Advantage of chemical recycling method is the monomers or raw materials produced which made up the original polymer. In addition, availability of depolymerizing agents, resin synthesis, and monomers are other advantages of chemical recycling. Depolymerizing agents used in chemical recycling include ethylene glycol, water, and methanol (Yoshioka et al., 1994; Paszun and Spychaj, 1997; Achilias and Karayannidis, 2004; Bartolome et al., 2012). Chemical recycling of PET is grouped into glycolysis, hydrolysis, and methanolysis; however, the methods are influenced by the hydroxyl-bearing molecule added. The methods are shown in Fig. 13.2 (Bartolome et al., 2012). However, ethylene and methanol glycol as well as water are used as condensation products (Patterson, 2000). Plastic wastes to be recycled are mechanically treated before being depolymerized (Sandin and Peters, 2018).
In a glycolysis process, plastic bottle wastes are crushed into flakes and washed to remove contaminants. After the flakes are dried, they are extruded to produce a new desired product; however, virgin PET can be blended with the flakes before extrusion process to improve qualities of the end-use product. Washed smaller pieces of PET waste are depolymerized using glycolysis and monoethylene glycol (MEG). The end product produced can also be repolymerized after depolymerization to improve its properties (Jankauskaite et al., 2008; Upasani et al., 2012).

This process can also be done in a polymerization plant using cleaned flakes, MEG and TPA; however, flakes are partially fed. Both MEG and TPA in a powder form are blended together to produce stiff slurry which is suctioned into esterification vessels. Due to the higher pressure inside esterification vessel, molten oligomer is produced. Polymer is formed when molten oligomer is converted into liquid using polycondensation process (Upasani et al., 2012). Lower molecular products of PET produced are purified and ready to be used again as raw materials. The raw materials can be utilized in the production of chemical end products (Bartolome et al., 2012).

Wang (2010) have reported that waste plastics are converted into fuels, monomers, and chemicals using hydrolysis and pyrolysis processes. Shen et al. (2012) have reported that above 70% PET waste is recycled into fibers, 10% to bottles, and 20% into sheets. The properties of the produced raw materials from recycled PET waste using MEG and PTA are influenced by speed of the agitator, height of slurry, and solid concentration in the slurry (Upasani et al., 2012).

Glycolysis process can also be used to recycle waste caused by bottles produced using PET. The process is carried out at a pressurized reactor maintained between 238 and 242 °C, which is the fluids critical point, organic solvent, and metal acetates acting as catalyst. The new raw material produced from recycled PET bottles using glycolysis process is mostly BHET monomer. Temperature, pressure, and concentration of both the catalyst and EG influence the rate of reaction (Ghaemy and Mossaddegh, 2005). Chemical recycling process is paramount if the product produced is going to be utilized as food packaging applications (Patterson, 2000).
13.2.3.2 Methanolysis

Methanolysis is a chemical recycling process utilized by PET producers such as DuPont and Hoechst (Paszun and Spychaj, 1997). In this process, PET is degraded using methanol at higher temperature and pressure. DMT and EG are the principal products in the methanolysis of PET and they are also used in the polymer production as raw materials (Paszun and Spychaj, 1997; Bartolome et al., 2012). Methanolysis process is carried out at a pressure that is between 2 and 4 MPa and temperature between 180 and 280 °C (Paszun and Spychaj, 1997). Breakdown of polymer occurs when EG is released. Transesterification catalysts such as cobalt, zinc, and magnesium acetates are used to expedite chemical reaction. However, zinc acetate is mostly utilized (Paszun and Spychaj, 1997). Drawbacks of the methanolysis method are that the process is costly, and it is carried out at higher pressure and temperature (Shukla et al., 2009). Higher cost is due to the refining and separation of the products produced after reaction. Water needs to be monitored as it can distract the process by breaking catalyst and result in azeotropes (Bartolome et al., 2012). Methanolysis method is no longer utilized in the production of PET due to poor recovery of DMT (Patterson, 2007).

13.2.3.3 Hydrolysis

Hydrolysis constitutes family of the chemical recycling process. In this process, both EG and TPA are produced at higher temperature and pressure by depolymerization process, which is tedious. Hydrolysis process is not preferred for producing virgin PET for food packaging application due to excessive cost related to recycled TPA, which requires further purification. PET hydrolysis can be performed in alkaline, acid, and neutral conditions. Hydrolysis in water is performed at temperatures between 50 and 180 °C.

Acid hydrolysis process is costly due to the presence of sulfuric acid in the EG, which requires purification and recycling as higher amount of concentrated sulfuric acid is detrimental. Nitric acid can also be used in the PET depolymerization into TPA and EG to produce either new raw material or oxalic acid; however, the process is also expensive (Yoshioka et al., 1994, 2003; Park and Kim, 2014).

In an alkaline hydrolysis process, smaller pieces of PET waste and sodium hydroxide (NaOH) are weighed as well as measured amount of water and they are poured into a beaker. The beaker is placed on the top of a stainless steel vessel heated to a temperature between 160 and 260 °C using electric stove for 3 min. Nitrogen (N$_2$) is used to replace air before the heating process starts. As soon as it reaches the specified temperature, oxygen is pressurized between 0 and 10 MPa using oxygen oxidation process. This process is considered as the initiation, the time in which the reaction started, while the time in which the beaker is removed from the electric stove is considered as end of reaction. This is followed by cooling process at room temperature. Water is used to wash the product inside the beaker and filtered. The solution in the beaker was sodium terephthalate which was precipitated to TPA using sulfuric acid.
Some amount of oxalate ion can be obtained after sodium ions have been removed from the solution using ion chromatography (Yoshioka et al., 2003). Disadvantages of the hydrolysis recycling process are pollution problems and corrosion (mostly in TPA) (Gaemy and Mossaddegh, 2005). In addition, hydrolysis process is very slow when compared to glycolysis and methanolysis. This is attributed to the poor nucleophile of water in comparison to other depolymerizing agents such as ethylene glycol and methanol. Apart from the higher pressure and temperature required in this process, it is not also not easy to recover TPA monomer using hydrolysis process (Bartolome et al., 2012).

13.2.4 Quaternary recycling

Quaternary recycling is a recycling process used to minimizing plastic waste by burning and it is also called incineration (Al-Sabagh et al., 2016). Bartolome and his co-workers (Bartolome et al., 2012) reported that chemical energy present in plastic waste is recovered during incineration. However, the energy recovered by burning waste is lower in comparison to that required in the manufacturing process. Quaternary recycling is mostly used when it is complex to collect and separate waste. In addition, when the waste is toxic and harmful, quaternary recycling is utilized. Drawback of quaternary recycling is the poisonous air that might be harmful to human health (Bartl et al., 2005; Bartolome et al., 2012; Park and Kim, 2014). In addition, burning plastic waste results in organic compounds that are inflammable (Al-Salem et al., 2009). There is disagreement among researchers about quaternary recycling process where the recovered energy is classified as recycling. Recycling is defined as material recycling or reuse unlike in quaternary recycling where materials are burned and no longer utilized (Sandin and Peters, 2018). Hence, quaternary recycling is not fully agreeing with the definition of recycling.

13.2.5 Disadvantages of plastic recycling

Disadvantages of the new product manufactured from recycled plastic waste are lower melting viscosity and poor mechanical and thermal properties. The properties are influenced by hydrolytic chain scission and polymer deterioration during recycling process. However, additives and antioxidants can be used to improve product quality (Jankauskaite et al., 2008). In addition, disadvantages of materials produced from recycled waste are the presence of contaminants and decrease in molecular weight. Contaminants are influenced by the degeneration of both physical and mechanical properties of the plastic during recycling process. Acid, water, acetaldehyde, and particles of different colors result in contamination, which influences final properties. Color contaminants are mostly influenced by smaller particles of bottles with different colors. They can be minimized by separating and washing bottles before recycling (Jankauskaite et al., 2008; Al-Sabagh et al., 2016). Upasani et al. (2012) have reported that polyvinyl chloride is one of the contaminants present in PET recycling.
13.3 Life cycle analysis

Life cycle analysis (LCA) is used to analyze various recycling methods used in municipal solid waste (MSW) and impacts they have on the environment (Al-Salem et al., 2009). Dahlbo et al. (2017) have defined LCA as a method used to analyze a product from waste collection, processing and recycling; the new material produced; and impact on the environment. LCA is useful for choosing techniques to be used for recycling and achieving end product with desired properties from the recycled waste. It depends on the life cycle inventory (LCI) data used and assumptions. Mostly, environmental impacts and gas emissions occur in the production process. LCA has shown that recycling and collection of waste might result in a friendly environment if waste is always separated before recycling process efficiently (Al-Salem et al., 2009; Wang, 2010; Dahlbo et al., 2017).

As a majority of plastics are produced from petroleum-based products, waste management programs are combined with production cycle and treatment process. Addition of waste management program in the recycling process results in energy being used efficiently and it is shown in Fig. 13.3 (Kirkby et al., 2004), which is known as integrated waste management (IWM). The main aim of waste management program is to monitor and manage waste processing without affecting environment. In addition, the objective of waste management is to find new ways to prevent waste and improving already existing methods for recycling. Waste management cycle is categorized into generation and handling of waste, classification and processing, collection, separation and manufacturing, and transportation of waste (Al-Salem et al., 2009). The above stages are useful in developing new ideas on the various applications where solid waste is utilized (Al-Jayyousi, 2001).

LCA is also being used to analyze all the environmental impacts based on ISO standards 14040 and 14044. ISO standard 14067 is being prepared and is going to be utilized to analyze carbon footprint. LCA based on ISO standards is categorized into life cycle description, analyzing impact on the environment, interpretation, and scope (Muthu et al., 2012b). Apart from LCA, cost, flow of material, and grave analysis as well as contingent valuation method can be done before taking the recycling approach (Bartl et al., 2005; Wang, 2010).

13.4 Recent developments

Currently, recycled PET wastes have replaced the traditionally utilized fibers such as glass and steel in concrete reinforcement. PET bottles are collected from the seashores and crushed into smaller pellets. Monofilaments are manufactured when the pellets are melted, drawn, and cut into staple fibers. Staple fibers obtained by this process are utilized for concrete reinforcement. Concrete reinforced using recycled PET waste fibers are used in road pavement and mine gateway (Ochi et al., 2007; Sulyman et al., 2016).

Instead of using sand, waste plastic is mixed with cement in India. This is attributed to the shortage of cement, depletion of sand in quarry and rivers caused by an increase
Advantages of replacing sand with waste plastics include eco-friendly environment, sustainability, utilization of waste, and lower transport cost. However, the compressive tensile strength as well as the density of a matrix of plastic and cement decreases with an increase in the amount of plastic waste. The decrease is caused by lower compactness between cement and plastic. The decrease in the compressive tensile strength is lower when fewer amount of plastics waste is utilized. However, higher values in the decrease of compressive tensile strength were obtained when large quantities of plastics waste were utilized (Wang, 2010; Thorneycroft et al., 2016).

It was reported that the compressive tensile strength of a matrix of plastic and cement is mostly influenced by the method used in the mixing process, properties, and amount and size of plastic waste. The mixing process is important as it might result in irregular dispersion of waste fibers in the concrete, therefore, forming fiber balls. A matrix of fibers and concrete can be mixed using either machine or hand. In addition, compressive tensile strength is influenced by inability of water to flow freely due to the hydrophobic properties of plastic (Frigione, 2010; Thorneycroft et al., 2016; Ochi et al., 2007).

Safinia and Alkalbani (2016) have reported that plastic bottle waste was used to reinforce blocks of concrete also known as masonry brick. Masonry brick differs from other bricks as it has holes. Plastic bottles were encased inside concrete blocks by surrounding each bottle with a mixture of cement and crushed stones. Results
obtained showed that the compressive tensile strength of the concrete blocks with plastic bottle waste was higher in comparison to the ordinary one. Safinia and Alkalbani (2016) were also agreeing with other researchers that the mixing process influences tensile strength of the composite of plastic waste and concrete block.

Ochi et al. (2007) have reported that concrete reinforced using plastic waste has to be tested for emission of poisonous gases. This is carried out to prevent escalation of fire (Ochi et al., 2007). In addition, textile wastes are currently recycled into carpets and nonwovens. Nonwovens produced from recycled waste include waddings, rags, and absorbing and covering blankets. Carpets produced from recycled waste are utilized for soil and concrete reinforcement (Bartl et al., 2005; Wang, 2010; Dahlbo et al., 2017). North Carolina State University has partnered with Burlington industries to produce a denim composed from a blend of 50/50 % raw cotton yarn and denim waste (Bhatia et al., 2014).

BHET is produced when PET waste is recycled using glycolytic depolymerization. It is used for dyeing polyester fabric; however, after it has been modified into disperse dye. Recycled PET wastes using glycolysis process are also used as polyurethane foam and coatings, resins (UV curable and alkyd), and unsaturated polyester (Jankauskaite et al., 2008; Shukla et al., 2009). Furthermore, recycled waste is also used as oil filters, gowns and drapes in hospitals (Bhatia et al., 2014). Asphalts are utilized as binders in the construction of road pavements. The cons of asphalt are that it is unable to withstand both higher and lower temperatures. Therefore, recycled plastic waste are used to modify asphalt to improve its properties (Shukla et al., 2009).

13.5 Conclusions

Based on the available information, it was found that new raw materials can be produced from recycled plastic waste. However, the properties of the produced raw materials are influenced by the method utilized during recycling process. Properties of the recycled end product can be improved by washing the raw materials with bleach and caustic soda depending on their end-use applications. In addition, the properties of the end product can be improved by blending both virgin and flakes of plastic together before recycling process. Methods that are currently used in waste recycling produce lower yield when environment-friendly catalysts are utilized. Higher yields are obtained when harmful catalysts are utilized. Therefore, new methods that can encourage companies and individual to recycle plastic waste are required. Longer reaction time, higher energy consumption, and pollution problems caused by the current methods utilized in a chemical recycling are another concern; therefore, there is a need to explore new technologies that can minimize these drawbacks. Lastly, different methods currently used in the recycling process are not sustainable but promising to be the solution of plastic waste.
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Sustainable approaches in effluent treatment: Recent developments in the fashion manufacturing

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Chandigarh College of Technology, CGC Landran, Mohali, Punjab, India

14.1 Introduction

Textile and clothing sector is one of the biggest and oldest industries present globally. Textile industry deals with the conversion of fibers into yarns and yarns into clothes. The industry deals with the synthesis, enhancement, and trade of both synthetic and natural fibers. The global textile market is forecasted to reach $842.6 billion in value in 2020. After China, India is the second largest producer of textiles and garments in the world. The Indian textiles and apparel industry is expected to grow to a size of US$ 223 billion by 2021 according to a report by Technopak Advisors. Thus, this industry has potential to generate employment for many people.

The major impediment for the growth of textile industry is the bulk effluent water generated by the industry. The industry uses large amount of water for dyeing of fabrics and ranks among top 10 users of water. Different kinds of dyes including azo dyes, synthetic dyes, acid dyes, basic dyes, and sulfur dyes are used in textile industries. 70% of the dyes used for dyeing fabrics are not absorbed by the fabric and discarded in effluent. Besides the leftover dyes, the effluent wastewater also contains chemicals such as acids, alkalis, dyes, hydrogen peroxide, starch, surfactants dispersing agents, and soaps of metals (Yaseen and Scholz, 2019). This highly polluted wastewater is a major harm to the flora and fauna. Furthermore, many small-scale industries discard their waste directly to river stream.

This water when used for irrigation purposes causes diseases such as cancer in the surrounding area. Therefore, because of deep concern of environmentalist, the textile industry is classified into Red category because of the amount of pollution it causes. Government has posed a strict environmental regulation on the discharge of effluent water from industries directly into the river. It is mandatory for every industry to have effluent treatment plant established in the company’s premises so as to treat the wastewater before disposal. The ultimate aim of wastewater disposal system is to treat the water up to a level that is safe for disposal into river streams. This chapter discusses various types of chemicals used in the fashion and textile industries that are responsible for polluting water. Various methods of waste water treatment including the recent trends and future directions are also discussed in this chapter.
14.2 Textile dyes used in the market

The textile industry accounts for two-thirds of the total dyestuff market and consumes large volumes of water and chemicals for wet processing of textiles. The chemical reagents used are very diverse in chemical composition, ranging from inorganic compounds to polymers and organic products (Banat et al., 1996). The textile industry is classified into three main categories: cellulose fibers (cotton, rayon, linen, ramie, hemp, and lyocell), protein fibers (wool, angora, mohair, cashmere, and silk), and synthetic fibers (polyester, nylon, spandex, acetate, acrylic, indigo, and polypropylene). More than 3600 individual textile dyes and 8000 different chemicals are being used by the industry in various processes of textile manufacturing (Kant, 2012).

The type of dyes and chemicals used in the textile industry are found to differ depending on the fabrics manufactured. More than 3600 individual textile dyes and 8000 different chemicals are being used by the industry in various processes of textile manufacturing (Kant, 2012). Reactive dyes (remazol, procion MX, and cibacron F), direct dyes (congo red, direct yellow 50, and direct brown 116), naphthol dyes (fast yellow GC, fast scarlet R, and fast blue B), and indigo dyes (indigo white, tyrian purple, and indigo carmine) are some of the dyes used to dye cellulose fibers (Ghaly et al., 2014). Protein fibers are dyed using acid dyes (azo dyes, triarylmethane dyes, and anthraquinone dyes) and lanaset dyes (Blue 5G and Bordeaux B). Other dyes, such as dispersed dyes (disperse yellow 218 and disperse navy 35), basic dyes (basic orange 37 and basic red 1), and direct dyes, are used to dye synthetic fibers (Ghaly et al., 2014). Various dye classes used for textile fabrics depending on the fiber types are shown in Fig. 14.1:

14.3 Textile wastewater treatment

For the synthesis of a garment, several processing stages are required, such as spinning, knitting, weaving, and garment production. All these processes are stimulated with wet treatments such as sizing, desizing, scouring, bleaching, mercerizing, dyeing, printing, and finishing. Thus, the textile effluent generated contains an ample amount of pollutants from each of these stages in the processing of fibers and fabrics.

![Fig. 14.1 Dye classes used for various textile fibers.](image)
The composition of textile effluent varies from industry to industry as different industries manufacture different types and quality of fabrics. But there are some common chemicals that are used by all the industries.

Various natural and synthetic dyes are being used in textile industry for dyeing of fabrics. Synthetic dyes, because of their ease of production in random colors and fastness, are used most commonly than natural dyes (Purwar, 2016). Various synthetic dyes are being used in market, e.g. azo, anthraquinone, sulfur, phthalocyanine, and triarylmethane (Popli and Patel, 2015). Textile industries utilize not only fabric dyes but also lots of other chemicals for dyeing of fabrics. The main chemicals utilized in industry are listed in Fig. 14.2.

Many other agents including the stabilizers, antifoaming agents, detergents, fabric softeners, fixing agents, whitening agents, sequestering agents, and bleaching agents are used in textile industry. Thus, the textile effluent is comprised not only of leftover dyes but also these chemical agents coming from various steps in fabric dyeing and processing, making the textile effluent a highly polluted effluent. The composition of textile water based on studies reported by Yassen and Scholz (2019) is given in Table 14.1.

The presence of even very small quantities of dyes in water (less than 1 ppm) is highly visible. The greatest environmental concern with dyes is their absorption and reflection of sunlight entering the water. Light absorption diminishes photosynthetic activity of algae and seriously influences the food chain (Verma et al., 2012).

**Fig. 14.2** Various chemicals used in textile industry.
Table 14.1 Composition of textile effluent.

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Parameters</th>
<th>Units</th>
<th>Values</th>
<th>Permissible limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>pH</td>
<td>-</td>
<td>6–11</td>
<td>5.5–9.0</td>
</tr>
<tr>
<td>2</td>
<td>Temperature</td>
<td>°C</td>
<td>30–60</td>
<td>Shall not exceed 5 °C above the receiving water temperature</td>
</tr>
<tr>
<td>3</td>
<td>Color</td>
<td>Pt–Co</td>
<td>50–2500</td>
<td>50</td>
</tr>
<tr>
<td>4</td>
<td>COD</td>
<td>mg/L</td>
<td>150–12000</td>
<td>250</td>
</tr>
<tr>
<td>5</td>
<td>BOD</td>
<td>mg/L</td>
<td>100–4000</td>
<td>30</td>
</tr>
<tr>
<td>6</td>
<td>TSS</td>
<td>mg/L</td>
<td>100–8000</td>
<td>100</td>
</tr>
<tr>
<td>7</td>
<td>TDS</td>
<td>mg/L</td>
<td>2,000–12,000</td>
<td>NA</td>
</tr>
<tr>
<td>8</td>
<td>Chlorine</td>
<td>mg/L</td>
<td>1000–6000</td>
<td>500</td>
</tr>
<tr>
<td>9</td>
<td>Free chlorine</td>
<td>mg/L</td>
<td>&lt;10</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>Dye</td>
<td>ppm</td>
<td>50 ppm</td>
<td>NA</td>
</tr>
<tr>
<td>11</td>
<td>Zinc (mg/L)</td>
<td>mg/L</td>
<td>&lt;10</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td>Nickel</td>
<td>mg/L</td>
<td>&lt;10</td>
<td>1</td>
</tr>
<tr>
<td>13</td>
<td>Manganese</td>
<td>mg/L</td>
<td>&lt;10</td>
<td>1</td>
</tr>
<tr>
<td>14</td>
<td>Iron</td>
<td>mg/L</td>
<td>&lt;10</td>
<td>1</td>
</tr>
<tr>
<td>15</td>
<td>Copper</td>
<td>mg/L</td>
<td>&lt;10</td>
<td>1</td>
</tr>
<tr>
<td>16</td>
<td>Boron</td>
<td>mg/L</td>
<td>&lt;10</td>
<td>1</td>
</tr>
<tr>
<td>17</td>
<td>Arsenic</td>
<td>mg/L</td>
<td>&lt;10</td>
<td>1</td>
</tr>
<tr>
<td>18</td>
<td>Silica</td>
<td>mg/L</td>
<td>&lt;10</td>
<td>1</td>
</tr>
<tr>
<td>19</td>
<td>Mercury</td>
<td>mg/L</td>
<td>&lt;10</td>
<td>1</td>
</tr>
<tr>
<td>20</td>
<td>Fluorine</td>
<td>mg/L</td>
<td>&lt;10</td>
<td>1</td>
</tr>
<tr>
<td>21</td>
<td>Sodium</td>
<td>mg/L</td>
<td>&lt;10</td>
<td>1</td>
</tr>
<tr>
<td>22</td>
<td>Potassium</td>
<td>mg/L</td>
<td>&lt;10</td>
<td>1</td>
</tr>
<tr>
<td>23</td>
<td>Chromium</td>
<td>mg/L</td>
<td>&lt;10</td>
<td>2</td>
</tr>
<tr>
<td>24</td>
<td>NaOH</td>
<td>mg/L</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>25</td>
<td>NaCl</td>
<td>mg/L</td>
<td>300</td>
<td>NA</td>
</tr>
<tr>
<td>26</td>
<td>Na₂CO₃</td>
<td>mg/L</td>
<td>20</td>
<td>NA</td>
</tr>
<tr>
<td>27</td>
<td>Sulfates</td>
<td>mg/L</td>
<td>600–1000</td>
<td>1.0</td>
</tr>
</tbody>
</table>

*BOD*, biological oxygen demand; *COD*, chemical oxygen demand; *TSS*, total suspended solids; *TDS*, total dissolved solids.
Dyes can remain in the environment for an extended period of time because of high thermal and photo stability (Gao et al., 2018). Thus, textile industry is also identified as heavily polluting Red category industry by Ministry of Environment and Forests, Government of India, and covered under Central Action Plan. Increasing environmental legislation is being imposed to control the release of dyes.

Moreover, the chemicals used in textile industries cause serious health problems. About 40% of the chemicals used in textile industries contain chlorine, a carcinogenic chemical. These harmful chemicals evaporate into the air and internalized with breathing or absorbed by the skin. These when comes in contact with a pregnant lady can harm her child even before birth. The development and spread of cancer in developing countries so vastly is the result of increased industrialization. The normal functioning of cell is disturbed resulting in change in physiological and biochemical alternations in pathways causing diseases such as cancer.

In addition, the basic mechanisms of life respiration, osmoregulation, reproduction, and even mortality are disturbed. Heavy metals in textile effluent accumulate in primary organs of the body leading to serious diseases. Thus, untreated or incompletely treated textile effluent can be harmful to both aquatic and terrestrial life by adversely affecting the natural ecosystem and causing long-term health effects (Khan and Malik, 2014).

At present, the effluent water discharged from the textile industries is treated by various physicochemical processes followed by biological treatments (Verma et al., 2012). Several primary, secondary, and tertiary treatment processes have been used to treat these effluents (Fig. 14.3). These included flocculation, chemical coagulation, simple sedimentation, aerated lagoons, aerobic activated sludge, trickling filters, reverse osmosis (RO), and electrodialysis (Eswaramoorthi et al., 2008). However, many of these conventional and even advanced treatment technologies suffer the limitation of not being able to treat highly colored wastewater from textile manufacturing (Wang et al., 2009). Another drawback of these treatments is their high energy costs and low efficiency in degrading the dye stuffs (Nawaz and Ahsan, 2014). Therefore, degradation of textile dyes is becoming an important aspect to control the pollution caused by the dyes.

Fig. 14.3 The treatment processes used in textile industry.
14.4 Physical methods

Physical methods including coagulation/flocculation are used before sedimentation and filtration to remove particles. Coagulation resulted in neutralization of charges causing formation of gelatinous mass that can be filtered out easily. Flocculation is the agitation process that agglomerates particle masses to be filtered from solution. The process removes small amount of color of reactive and vats dye as well. The major disadvantage of the process is the transfer of toxic compounds into solid phase and formation of sludge that has to be treated subsequently (Mehta, 2012). The coagulation/flocculation of wastewater treatment has been shown in Fig. 14.4.

Another physical method is adsorption of dyes by the adsorbent that reduces the color of the effluent. Activated carbon, peat, bentonite clay, fly ash, and polymeric resins are some of the absorbent used for the treatment of effluent water (Rao and Rao, 2006; Igwegbe et al., 2016). High affinity of adsorbents and their capability of regeneration are the major advantages of adsorbents to be used in textile wastewater treatment (Jadhav and Srivastava, 2013). Rao and Rao (2006) used fly ash for the treatment of methylene blue and congo red. Igwegbe et al. (2016) used activated carbon produced from *Mucuna pruriens* seed shells for the treatment of congo red and malachite green. Mehta (2012) utilized 10% lime, 5% ferrous sulfate, and 0.1% polyelectrolyte and observed that maximum flocks were formed between pH 10—11. Chemical oxygen demand (COD), total suspended solids (TSS), and hardness of water were found to be reduced by 60%, 50%, and 77%, respectively. The configuration of the sand filtration and activated carbon adsorption columns has been shown in Fig. 14.5.

Couto-Junior et al. (2013) treated the wastewater using natural coagulant, tannin, and chemical coagulant, aluminum sulfate. The results showed that tannin reduced the COD to 94.81% and color by 99.17% compared with 91.71% reduction in COD and 99.06% color removal by aluminum sulfate. Parihar and Malvia (2013) used saw dust for the treatment of textile effluent and observed a reduction of 37% in TSS. Nevertheless, their high cost and generation of sludge restricted the use of absorbent in effluent treatment. Other physical methods such as ultrafiltration (UF),

![Fig. 14.4 Coagulation/flocculation methods of wastewater treatment.](https://example.com/fig14.4)
nanofiltration (NF), and RO have also been used to treat effluent water. But the cost incurred reduces their use at industrial scale. UF and NF setup used for water filtration are shown in Figs. 14.6 and 14.7, respectively.

14.5 Chemical methods

Chemical oxidation methods are other class of method used for the treatment of effluent water. In this method, electron moves from oxidant to the pollutant and resulted in structural modification to safer compounds. Oxidizing agents such as O₃ and H₂O₂ forms strong nonselective hydroxyl radicals at high pH values.

\[
H_2O_2 \rightarrow OH^* + OH
\] (14.1)

These radicals due to this high oxidation potential can effectively break down the conjugated double bonds of dye chromophores as well as other functional groups such as the complex aromatic rings of dyes. Subsequent formation of smaller nonchromophoric molecules decreases the color of the effluents. The disadvantage of ozonation is the cost, as constant ozonation is essential due to its short half-life of 10 min in water at pH 7. Zhang et al. (2017) reported that use of hydrogen peroxide can reduce the color of methylene blue dye by 86%. Thao and Nguyen (2017) also reported a reduction of 99% rhodamine B dye with the use of H₂O₂.
Fenton’s reagent, a mixture of H$_2$O$_2$ and ferrous ion, has also been used for the removal of dyes. The reaction carried out is given in Eq. (14.2):

\[
Fe^{2+} + H_2O_2 \rightarrow OH^{*} + OH
\]  

(14.2)

The free radical generated from the oxidative degradation of hydrogen peroxide leads to degradation of organic dyes. It has been reported in literature that the process becomes efficient only when the pH is kept in between 3 and 5 (Ma et al., 2005).
The oxidation process involving Fenton’s reagent resulted in complete degradation of organic compounds into CO$_2$, water, and inorganic compounds. Rahman et al. (2009) reported 99.5% removal of malachite green with the use of Fenton reagent under xenon beam irradiation. However, the generation of ferrous hydroxide in the disposal stream limits the use of this method.

### 14.6 Biological methods

Biological processes involve the removal of dissolved matter in textile effluent. It comprises of aerobic and anaerobic processes that use microorganisms for the treatment of wastewater. The combination of anaerobic and aerobic method is typically implemented in real practice that uses an anaerobic process to treat textile wastewater to reduce COD, followed by the use of aerobic polishing treatment to treat the resulting textile wastewater of low COD. In these biological methods, microorganisms adapt themselves to textile dyes, and new resilient strains grow naturally out of survival requirement, which then convert several dyes into less hazardous forms.

In biological system, the biodegradation mechanism for recalcitrant dyes is based on the enzymes such as laccase (Lac), lignin peroxidase (LiP), NADH-DCIP reductase, tyrosinase, hexane oxidase, and aminopyrine N-demethylase produced by microorganisms. The biological methods for the complete degradation of textile wastewater have benefits of being eco-friendly, cost competitive, less sludge production, giving nonhazardous metabolites or full mineralization, and less consumption of water compared with physical/oxidation methods.

The efficiency of biological methods for degradation depends on the adaptability of the selected microbes and the activity of enzymes. Therefore, a large number of microorganisms and enzymes have been isolated and tried for the degradation of several dyes. The isolation of potent microbes and its use for degradation is an interesting biological aspect of textile wastewater treatment. A wide range of microorganisms such as bacteria, fungi, and algae are able to degrade a wide variety of dyes present in the textile wastewater. However, the harsh nature of textile wastewater and the ineffectiveness of microbial system result in improper removal of color from textile effluent.

#### 14.6.1 Fungi reported for textile effluent degradation

Different fungal species have been reported to treat textile effluent water. White-rot fungi are mostly reported for effluent degradation. Miranda et al. (2013) utilized the potential of two fungal strains *Curvularia lunata* URM6179 and *Phanerochaete chrysosporium* URM 6181 by the formation of static bioreactor under aerated and nonaerated conditions. Enzymatic assays revealed higher production of enzymes Lac, LiP, and manganese-dependent peroxidase by *P. chrysosporium* URM 6181. Decolorization of effluent water was achieved in 10 days.

Hossain et al. (2016) formed a bench-scale submerged microfiltration membrane bioreactor (MBR). The fungus used was white-rot fungus *Coriolus versicolor.*
98% decoloration, 40%—50% reduction in BOD, 50—67% reduction in COD, and 95% reduction in total organic carbon was achieved. However, intensive growth of fungi and their attachment to the membrane leads to its fouling, requiring a periodic change of sludge and membrane cleaning. Molla and Khan (2018) have reported that two fungal strains viz. *Trichoderma harzianum* and *Mucor hiemalis* significantly detoxified textile effluent by removal of 76% total solids, 91.35% COD, 77.34% absorbance against optical density, and increased 87.31% DO. The process for MBR wastewater treatment is shown in Fig. 14.8.

### 14.6.2 Bacteria reported for textile effluent degradation

Different bacteria involved in lignin degradation are reported in literature for their dye degradation ability. Degradation of azo dyes by wide range of bacteria has been of significant importance as high degree of decolorization and degradation of textile wastewater can be achieved by using bacterial enzymes. Azo reactive dyes decompose under anaerobic conditions to yield reductive products that can further be degraded by aerobic processes (Parmar and Shukla, 2018). Novotny et al. (2011) utilized both bacterial and fungal culture for the effective treatment of textile wastewater. Bacteria generally have low efficiency for dye removal, while white-rot fungi have high efficiency of dye removal. They combined the efficacy of both the families and designed a trickling filter. The combined treatment resulted in 91% removal of color from effluent water depicting the large potential of combined treatment.

Fross et al. (2017) developed biofilters containing rice husks in which the indigenous consortium of bacteria *Dysgonomonas* and *Pseudomonas* and the fungal strains of *Gibberella* and *Fusarium* resulted in >90% decolorization at a hydraulic retention time of 67 h. Ito et al. (2018) isolated dye degrading bacteria from the hands of ordinary people. There were two groups of bacteria, azo dye decolorizing and anthraquinone dye decolorizing. The former were capable of decolorizing real textile wastewater, whereas the latter could achieve only partial decolorization.
14.7 Hybrid methods

Recently, a hybrid technology based on a combination of all these methods is suggested for the efficient removal of color from the effluent. These combined treatments not only treat the water efficiently but also lowers the cost of individual treatment processes. The application of physical/chemical processes with biological methods has the potency to treat the effluent water significantly. The biological treatment is applied either first or at last of physiochemical processes. However, because of the presence of harsh chemicals in the effluent, it is preferred that biological treatment is carried out at the end of the process. Generally high concentrations of suspended solids are present in effluent stream. Therefore, it is advised that before advanced oxidation processes, physiochemical treatment of the wastewater is carried out to reduce TSS.

Aouni et al. (2009) coupled electrocoagulation process with nano-UF process. Electrocoagulation resulted in the removal of color and reduction in COD, while nano-UF was utilized for further reducing the color, TDS, COD, conductivity, and alkalinity.

Lafi et al. (2018) used the integrated UF-electrodialysis process for the treatment of textile wastewater. UF led to the reduction in COD and also prevented the clogging of membrane during electrodialysis. The results showed significant reductions in all parameters tested.

Photocatalytic process is also a method of significant use for the treatment of effluents derived from the textile industry. Photocatalysis method utilized the photo-chemical activation of catalyst such as titanium dioxide (TiO$_2$), zinc oxide (ZnO), etc. UV radiation resulted in the release of pair of electrons (e$^-$) and holes (h$^+$) from the catalyst resulting in photoexcitation of electrons. The bandgap between the valence state and the excited state releases energy that degrades complex organic molecules (Fig. 14.9).

de Brito-Pelegrini et al. (2007) carried out treatment of textile effluent through after biological treatment with activated sludge through photocatalysis using TiO$_2$ as semiconductor. Optimization of the process was carried out in terms of the mass of the semiconductor (1.4 g l$^{-1}$), flow of air (150 mL s$^{-1}$), temperature (55 °C), and time of treatment (240 min). The treated effluent showed reduction in color by 92%, COD (65%), BOD (40%), and TOC (29.3%).

Abraham ponsingh et al. (2018) treated textile effluent with advanced oxidation process and found reduction of pH (7.2), COD (1200 mg/L), 91% reduction in 10g of TiO$_2$, calcium hardness (290 mg/L), 79.26% reduction in 10g of TiO$_2$, alkalinity (450 mg/L), 66% reduction in 10g of TiO$_2$, TSS(1.3 g), TDS (22.3 g), TS (21g), 69% reduction in 10g of TiO$_2$, turbidity (44NTU), 79% reduction in 10g of TiO$_2$, BOD (121.82 mg/L), 53% reduction in 2g of TiO$_2$, and color intensity.

RO has also been applied on a large-scale throughout the world for the treatment of effluent water from textile industry. RO membranes resulted in retention of 90% of ionic compounds and produce a clear permeate of high quality (Fig. 14.10). RO technology in a single step can lead to decolorization and elimination of chemicals in
textile wastewater. Many researchers have used RO method in combination or alone and found that RO is the best method of textile effluent treatment (Wang et al., 2010; Yin et al., 2019).

RO is a good treatment method, but membrane fouling is a major problem associated with RO system that causes a rapid flux decline. Blocking of membrane pores and cake formation reduces the efficiency of membrane. Therefore, to reduce the membrane blocking by particles in effluent water, a combination between two membrane processes is also used. UF can be used as pretreatment for NF process.

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**Fig. 14.9** Mechanism of photocatalysis.

**Fig. 14.10** Reverse osmosis.
This result in improving the quality of textile permeates by increasing the retention values of the majority of analyzed parameters.

Fersi and Dhabhi (2008) showed that the color retention was increased to about 95%, total dissolved salt retentions were about 80%, and the bivalent ions retention values exceeded 95%. In the case of direct NF, permeate flux remained constant until a volume reduction factor (VRF) reaching 1.35. After coupling UF with NF process, a stable permeate flux was observed until a VRF equal to 2.77. This result showed that using UF process as pretreatment for NF process improved the efficiency of textile effluent treatment by increasing the membrane run time.

14.8 Conclusions and future prospective

A vast literature is available showing the use of physical, chemical, biological, and hybrid methodology for the treatment of textile effluent. Most of the studies focus on the treatment of one or two dyes. Nevertheless, there is still complete dearth of literature, where actual textile effluent is used. Moreover, use of bacteria and fungi cannot meet the requirement of treatment processes due to their short life and unstable nature in the presence of toxic textile effluent. Use of enzymes are effective in textile effluent treatment, but the cost of enzyme production and its stability are always a matter of concern. The harsh nature of effluent results in improper removal of colors from textile effluent with some enzymes, which is a drawback of enzymatic processes. The application of enzymes immobilized in various supports with the physical and chemical processes can be more effective, which can be realised in future.

References


15.1 Introduction

This chapter will discuss the sustainability credentials of different fibers and fibrous materials that are common in the business of fashion and apparel and will delve deeper into what might be the future materials that could satisfy the needs of the industry in the coming decades. The textiles and fashion industry have long been criticized for its unethical activities across developing countries reflected in poor working conditions, low wages, limited rights to union membership, child labor, unreliable building structures, and inadequate occupational health and safety.

The industry is also responsible for the use of large volumes of water and energy and polluting the environment by emitting carbon and dumping industrial wastes (Deng et al., 2018; Deraniyagala, 2017). The vertically integrated textiles value chain, starting from the sourcing of raw materials to the manufacturing and final retailing of apparels, is blemished with shadowy activities as well. From the supply point of view, the textiles industry is criticized for producing fabric using unethically processed natural fibers or synthetic fibers. They are also condemned for maintaining a working environment similar to other manufacturing facilities, which are not safe.

The fashion and textiles retailers including reputable fashion brands, on the other hand, are regularly blamed for their exploitative behavior. They are reluctant to pay a fair price for the finished products they buy from the manufacturers, while selling the same with a high margin to the market. Most of these retailers do not take the ethical sourcing issue seriously and are reluctant to put any pressure on their suppliers as it could affect the ex-factory pricing of the fashion and textiles products. It often becomes difficult as well to know the actual trajectory of these products. Despite the unethical nature of the value chain, most of these activities are considered legitimate depending on country-specific laws or regulations and international business practices (As-Saber et al., 2015).

“Sustainable” raw material to many is a lucrative term coined for business of fashion and textiles. To the mass consumers, it gives them the guilt-free purchasing option, and for the fashion business perspective, it is the marketing hook attached to the garments. From both parties, the term is undervalued and to some extent exploited to become a label-only ritual. In this day and age, the term “sustainability” needs to be defined in the context of current economy, environment, and cross-cultural borders.
that are losing its definition and moving into a global paradigm shift. Things can always be termed to suit the business marketing hooks, and the question would still remain: is there really something called the elusive “sustainable raw material”? The United Nations (UN) Sustainable Developmental Goals (SDGs) are a case in point (Fig. 15.1).

It is a constant search for the materials and innovations that will tick all the boxes of the 17 goals put forward by the United Nations. SDGs are a set of goals defined by the United Nations, which the organization claims as the leading driver of building a better world for the people and the planet itself, by the year 2030. SDGs are a call for action to for all member countries of United Nations to promote prosperity while protecting the environment. The 17 SDGs developed work as drivers to improve on world issues under the themes of water, energy, climate, oceans, urbanization, transport, science, and technology (United Nations, 2019).

This chapter will search for a suitable material of the future that could be sustainable for the growth of population reaching 12 billion beyond 2050 (Slaper and Hall, 2011).

### 15.2 Definition of fashion

According to Macchion et al. (2015), fashion can be defined as a “cross-sector concept” that encompasses several industries such as apparel, footwear, leather, jewelry, perfumes, and cosmetics (Brun et al., 2008). Currently, most apparel companies also retail shoes, bags, and even perfumes and cosmetics, whereas shoes and bag manufacturers are diversifying into apparel and even jewelry, searching for new and attractive ways to expand their brands and build sustainable businesses for the future (Cappellari, 2010). Fashion is, therefore, a broad term that typically

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**Fig. 15.1** Sustainable development goals declared by United Nations (2019).
encompasses any product or market in which style, as an ephemeral key element, is present and relevant (Christopher et al., 2006).

As these industries in the fashion and textiles value chain combine to provide for the 8 billion and rising population today. The basic need of clothing and apparel for the fortunate portion of people who can afford fashion and its offspring industries will always be the drivers of the business. The fashion industry is often regarded as coinciding with the apparel sector, which indeed is its main component (Brun and Castelli, 2008). Since the origin of the fashion theory (Blumer, 1969), it was observed that “fashion” is the word used to describe trends that affirm themselves in a spontaneous way in accordance to the zeitgeist, i.e., the spirit of the age prevailing at a given moment.

The textile manufacturing sector often lives in the greenroom when the fashion is running its broadways appearances, and everyone is at awe on the aspect of design, embellishments, and the sparkly nature of the show. However, the story of the materials cannot live in that greenroom if we are going to consider sustainability and the practices associated in fashion and/or the apparel industry.

The textile industry and the supply chain should be discussed in detail to the miniscule price points and cost associated with individual operations involved to radically trace back sustainable and ethical production practices and traceability. In this context, sustainability can be defined in Fig. 15.2 with the “triple P (people, planet and profit)” bottom line approach (Slaper and Hall, 2011).

Since the Industrial Revolution, the textile industry has always played a significant role in the economy and has continuously moved to lower cost manufacturing countries. Starting with Britain in the late 18th century after the invention of the spinning jenny, the yarn and fabric manufacturing industry moved to Japan in the 1950s and 1960s. The mass production of ready-to-wear garment was introduced in the 1950s, and the production then followed along to Hong Kong, Taiwan, and Korea in the 1970s and the 1980s. The next geographical shift was to China, India, Pakistan, Sri Lanka, Bangladesh, Indonesia, Malaysia, the Philippines, and Thailand in the 1980s and the 1990s.

![Fig. 15.2 The triple P approach to sustainability.](image-url)
Today, we are seeing the fourth shift to countries such as Myanmar, Nicaragua, Kenya, Madagascar, and Ethiopia (Nimkar, 2018). These shifts have posed a lot of issues in terms of geopolitical influences, trade barriers, ethical employment conditions and litigations, and the overall transparency or the traceability of the fashion and textiles value chain (Blackburn, 2009; Brosdahl and Carpenter, 2010). Recent studies (As-Saber et al., 2015; As-Saber, 2018) have termed this as the “black business value chain” as it fails to address the ethics and moral standards of modern society.

The global population is rising exponentially, from a mere 1 billion in 1800 to 8 times today and counting toward a predicted 11 billion by the time we reach the turn of the century. Per capita consumption of apparel is about 7 kg annually, which results in a consumption of over 49 billion kg of textile products per year. This growth can be directly linked with the exorbitant growth in chemical production as well: from a mere 1 million tonnes produced in 1930 to 400 million tons in the year 2000 (Nimkar, 2018). The arguments arising from the value chain are quite daunting and more complex than understood.

The apparel markets and their buyers (brands) will always search for the low-cost manufacturing options where they can maximize their profit margin, and the traceability of the value chain will remain questionable in many years to come. Based on available evidence, both historical and current, it could be argued that a significant proportion of farms worldwide involved in the fashion, and textile value chains are engaged in shadowy activities that could be considered unethical or illegal or both. Using a critical thinking approach, the fashion and textiles value chain may be considered as a nontransparent chain of activities shrouded with darkness and doubts.

15.3 Defining sustainability in the context of fashion

The word “sustainability” is very subjective and depends on a lot of variables from all works of life. If we say some material is sustainable that essentially means that the substrate could be sustainable for a very context-specific time and place. Once we have manufactured something, for example, raw cotton to a T-shirt which could be claimed as sustainable would mean that the T-shirt manufacturing processes and till it goes to the customer could be sustainable. However, what the customer is doing with the material and what happens to the end of life of that T-shirt might not be following sustainable practices at all.

We, in the current social context, seem to neglect the perennial question about the durability, serviceability, or responsibility of the end of life of that T-shirt. Whose responsibilities are these? As fashion is an ephemeral phenomenon, that T-shirt could have lost its serviceability and can be thrown out, although it could be worn for longer. Therefore, the term “sustainability” needs to be used and defined within the context of the claim or the claimant. In the global climate change, issues are becoming more prevalent, and sustainability in the fashion and textiles industry is not a trend anymore and should be addressed with utmost priority. The choice of raw materials is the first step toward the sustainable approach.
15.4 Raw materials

Raw material refers to the commodity that is used to produce goods or materials. For example, a cotton T-shirt will be made out using raw cotton that is then converted to yarn to make knitted structures and finally a patterned cut and then trimmed and sewn to be sold as a T-shirt for retail. If we generally look at the current scenario of textile fibers, they exist in great variety and are used for a broad spectrum of applications in a diversity of structures. Much more could be written on their place in materials science and technology than can be included in this chapter. However, in another sense, the materials are limited. About 80% of the world’s textile fibers are now based on either cellulose (Rana et al., 2014a) or polyester; 18% are nylon, polyacrylonitrile, and polypropylene; and 2% are proteins (Hearle, 2001; Houck and Siegel, 2015). A small number of vinyl polymers and the newer high-performance and the specialty fibers account for about only 0.5%. The diversity of application of each of these types of fibers are primarily achieved by forms, shapes, staple lengths or cut sizes, processing parameters, copolymerization, additives, and finishes used within the processes.

In textiles, there are three major fiber types as shown in Table 15.1, and origins of the fibers have been summarized in Fig. 15.3.

15.5 Natural fibers

15.5.1 Cotton

Cotton is one of the most grown and utilized plant-based fibers in the planet. Cotton fabric is common in our lives, occurring in everything from domestic consumables to commercial and industrial applications. Till the synthetic fibers were introduced, cotton had the demand in applications such as the denim industry that still relies on cotton. Although unparallel in comfort and versatility, unfortunately, conventional cotton fails short in its long processing steps before it reaches the retail floor.

Table 15.1 General classification of the textile fibers.

<table>
<thead>
<tr>
<th>Type</th>
<th>Origin</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural</td>
<td>Natural resources, both cellulosic and protein bases</td>
<td>Cellulosic: cotton, hemp, jute, flax Protein: wool, silk</td>
</tr>
<tr>
<td>Regenerated</td>
<td>Principally from natural resources, however, requires further chemical and mechanical processing</td>
<td>Viscose, bamboo, chitosan, alginate</td>
</tr>
<tr>
<td>Synthetic</td>
<td>Nonrenewable resources such as by-product of the refinery industry</td>
<td>Polyester, nylon, acrylic, polypropylene</td>
</tr>
</tbody>
</table>
Furthermore, a mere 2.5% of the world’s cultivated land is cotton, which is not sufficient for growing needs of a drastically increasing world population (Sadashivappa, 2009).

The growth of organic cotton has been encouraged in recent years, which does not require any treatment of pesticides or herbicides and uses natural fertilizers, such as compost and animal manure. With the priority of food cultivation, synthetic fibers such as polyester, have taken the application share of cotton. However, energy consumption wise, cotton performs better than polyester (Van Winkle et al., 1978). In future the fashion trend will be the use of organic cotton or other cotton such as BCI (better cotton initiative) certified cotton, which will help in achieving sustainability.

15.5.2 Hemp

Hemp is a taproot herbaceous plant with an erect stem reaching up to 4 m in height (Amaducci and Gusovius, 2010). Its benefits (suppressing weeds, free from diseases, improving soil structure, zero consumption of pesticides, and more than one harvest) make hemp an attractive crop for a sustainable fiber production in comparison to cotton. Hemp is a crop that has great adaptability to a variety of climatic conditions, and it does not require chemical pesticides or water for irrigation. The consumption of fertilizers is modest, and hemp as plant suppresses weed growth and some soil-borne diseases, which means that at the end of its cultivation, soil condition is improved and healthier (González-García et al., 2007).

15.6 Protein fibers

15.6.1 Wool

Sheep wool has superior heat insulation and heat retention properties alongside other properties such as resiliency, moisture absorption, acoustics (Rottenbury et al., 1983),
and medical applications (Islam, 2012). The fiber is in today’s context a luxury fiber and one of the most used natural protein fibers (Johnson and Russell, 2008). Its unique thermoregulation property has enabled it to survive through the test of time; however, with the growth in population and the environmental impact of sheep farming, the production will slowly decline in the coming years.

### 15.6.2 Silk

Silk fiber is made from silkworm cocoons. The fiber has superior moisture absorption and desorption property, heat retention property, and staining property. This fiber is the only one formed naturally in filament from spider silk.

### 15.7 Man-made fibers

#### 15.7.1 Polyester

Polyester fiber is an example of synthesized polymers that do not exist in nature, and raw material is found as a by-product of the refinery industry. Many types of polyester can be synthesized; however, all of them are produced by a condensation reaction, and they all contain ester functional group (COO—). The most common and important type of polyester is polyethylene terephthalate (PET), simply termed as polyester. This is the product of condensation reaction between ethylene diglycol and terephthalic acid. Polyester is a thermoplastic polymer that can be remelted and remoulded. This property is used in the production and recycling of polyester fibers and potential to be used many a times. Typically, polyester fibers are produced as continuous filaments either from a granulated polymer (batch process) or by a continuous polymerization (Grishanov, 2011). It is cheap to produce and has good utility as a textile fiber in many applications.

#### 15.7.2 Nylon

Polyamide (PA) is a polymer that contains recurring amide groups (R−CO−NH−R’ ) as integral parts of the main polymer chain. Nylons are members of the family of PAs, which are polymers whose structural units are interlinked by the amide linkage NHCO. Generically, the term nylon refers to synthetic PAs derived predominantly from aliphatic monomers (Reimschuessel, 2001). Nylons also have good credential to be recycled and reused several times.

### 15.8 Regenerated fibers

One of the key innovations in fiber science is the regenerated fibers (Rana et al., 2014b). In the current context, this avenue shows more promise in terms of ecological
impact and sustainable practices such as recyclability and reusability. Processing cellu-
losic materials through viscose production route has opened processing to be synchro-
nous, and fibers such as viscose, bamboo, tencel, and lyocell have provided new 
avenues for cellulosic fibers to be utilized in the textile manufacturing and apparel 
production.

15.9 Ecological footprint of the fibers

There has been lot of attention on underpinning the sustainability credentials of 
different fibers (Blackburn, 2009; Allwood et al., 2008; Roos et al., 2016). According 
to a comprehensive study (Muthu et al., 2012), there are life-cycle assessments, and 
quantifications of environmental impact and ecological substantiality of a few fibers. 
The model developed in this study results in Environmental Impact Index (EI) and 
Ecological Sustainability Index (ESI) of ten chosen fibers as seen in Table 15.2.

These two indices were derivatives from a scoring system considering factors, 
namely quantity of oxygen produced and carbon dioxide captivated, and therefore 
contributing to offset global warming during the manufacturing/processing phase of 
a fiber, utilization of renewable resources, landmass use, usage of fertilizers and 
pesticides/herbicides, fiber recyclability, and biodegradability of chosen fibers. In 
addition, this “scoring system” also considered specific life-cycle impact categories 
resulting from energy and water consumption and greenhouse gas emission. Of the 
chosen fibers, acrylic is the least preferred fiber in terms of environmental impact 
and ecological sustainability. Fibers from nature were better performers in this system.

However, this system did not consider continuous increase in demand for more 
materials with the population growth. The cultivable land will be given preference 
to grow food for the increased population and will be scarce for plant production.

<table>
<thead>
<tr>
<th>Fiber</th>
<th>EI</th>
<th>ESI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic cotton</td>
<td>11</td>
<td>71</td>
</tr>
<tr>
<td>Flax</td>
<td>12</td>
<td>68</td>
</tr>
<tr>
<td>Commercial cotton</td>
<td>16</td>
<td>57</td>
</tr>
<tr>
<td>Viscose</td>
<td>19</td>
<td>49</td>
</tr>
<tr>
<td>Polyester</td>
<td>29.5</td>
<td>21</td>
</tr>
<tr>
<td>Nylon 6</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>Nylon 6,6</td>
<td>31</td>
<td>19</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>34</td>
<td>10</td>
</tr>
<tr>
<td>Acrylic</td>
<td>38</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 15.2 EI and ESI of some natural and synthetic fibers (Muthu et al., 2012).
In addition, the depreciation of natural fibers when used and limited shelf-life compared with synthetic fibers are also not calculated.

### 15.10 Garment lifecycle

The value chain begins with raw materials, followed by fiber, fabric, fashion and textiles production, output, retail, and consumer disposal in order. Fig. 15.4 captures the firms involved in the value chain and each subsection of the value chain.

Within each of the stages, there are many micro- and macrolevel transactions, development, and value addition activities that are associated and make this value chain tedious to trace back. Building on concepts of the “black economy,” “black market,” and “black international business” As-Saber (2018) developed to describe illegal, unethical, and shadowy activities across all these sections and subsection activities shown in Fig. 15.4, it is important for the supply chain to open up information for the consumer as well as the downstream processes to follow. Recent controversy of Better Cotton Initiative and Uyghur concentration camp incident is a case in point. The retailers sourcing from China, part of the initiative, however, the yarn, and fabric production were questionable to many.

### 15.11 Problems associated in textile recycling

Apart from these direct problems from textiles manufacturing, another problem the world will face is safe disposal of used clothes (Hvass, 2014), where 90% of the dyes and chemicals that are on the fabrics will end up in landfills and will degrade over time and leach out to the same waterbodies we are trying to preserve. There is a major concern in textile recycling as there is no control over any material in terms of application areas. This lack of control has led to a very complicated task (Fig. 15.5) for recycling bodies who are struggling to find a way to solve this issue other than waste, landfill, or incineration.

Once a product is sold and the consumer takes it away, brand manufacturers, marketers, and retailers transfer the ownership of the product completely to the consumer. This means that unless a product is returned before usage begins, a warranty or a refund is claimed or exchanged, the product becomes the sole responsibility of the consumer. This includes the disposal of the product as well.

The root of this problem lies within the different stakeholders working in silos as well as “innovation for convenience.” Recycling and reusing of textiles and apparels are not considered anywhere in the design process, raw material sourcing, and utilization.

One of the key problems is the variety of material choices that are available to make products. However, this choice has backfired on the industry that is struggling to address the disposal or postconsumer waste. In this context, if the brands are encouraged or even forced to take back the garments they manufacture, automatically,
Fig. 15.4 Subsections of a textile value chain (As-Saber, 2018) (RMG-ready made garment).
it would push the brands to design and manufacture products that can be recycled and upcycled.

The coloration and finishing industries are one of the key polluters in the manufacturing stakeholders. The chemicals used are a threat to the soil quality and fresh waterways on a long term and need to be addressed immediately.

15.12 Fashion and textiles—a chemical heavy industry

More than 8000 different chemicals are used in textiles (Nimkar, 2018). Assessing the impact of these chemicals on human health and environment is a huge task and is not really appreciated by consumers, who are not always willing to pay adequate prices for product safety, except in the case of branded products that may also need to go through review processes as we keep discovering the impact of these chemicals.

A myriad of colors and pigments are used for textile coloration. Along with technological advancements in coloration, specialty chemicals were also developed, to impart functional properties such as softening, wrinkle-free effect, oil and water repellence, flame retardancy, antibacterial property, and many more. Approximately 90% of these finishing chemicals remain on the substrate, and the balance is washed off during processing and subsequent consumer use (Correia et al., 1994).
Many of the chemicals used to impart these beneficial properties are found to be harmful today, and a constant and rigorous search is on to tackle these chemicals when applied in textiles. Use of antibacterial chemicals/agents in softeners and in oil-repellent finish, formaldehyde in wrinkle-free finishing resins, and chlorinated and brominated chemicals in flame-retardant formulations are few cases in point. Although the harmful effects of several chemicals used in textile and apparel manufacturing were known for some time, they were formally addressed only in the 1990s.

Cases in point are, an embargo on the use of azo dyes liberating carcinogenic amines, to residues of pentachlorophenol, the usage of allergenic disperse dyes, organotin compounds, formaldehydes, nonyl phenol ethoxylates, phthalates and heavy metals components such as lead, iron, and cadmium used as mordants and the list has continued to grow over the decades (Nimkar, 2018). Government agencies, brands (Strand and Mulvihill, 2016), and several private organizations took some remedial measures toward cleaner production of textiles; however, lot of research and development needs to be done (Deng et al., 2018) toward sustainability goals (Varadarajan and Venkatachalam, 2016; Schenten et al., 2019).

The textile industry has various initiative to control the use and discharge of hazardous chemicals in their supply chain, such as Restricted Substances List and the recent ZDHC (Zero Discharge of Hazardous Chemicals) Program, which was a response to the Greenpeace “Detox” campaign (Amutha, 2017). The ZDHC MRSL (Manufacturing Restricted Substances List) endeavors to establish limit values for hazardous substances in commercial chemical formulations (Cattermole, 2016).

Besides these initiatives, long-term sustainable chemistry solutions will be the way forward for the textile industry to address the problem. These could be in terms of use of biowaste sources (such as EarthColors from Archroma), biodegradable chemicals/additives (such as clay), or techniques such as digital coloration, where there is no water usage or waste discharge (Nimkar, 2018). The target should be zero remnants from the chemical finishes to damage soil quality or contaminate waterways. The long-term effect of newly developed chemicals is unknown and needs attention.

15.13 The opaque, transparent, and translucent scale

Most of the textiles and fashion materials that can be bought from retail encompass a lot of manufacturing stages to reach there. Textile and fashion supply chain or the value chain is global and can be produced and sourced from many countries. This feature has posed a lot of challenges for the consumers and retailers to trace back all the components and countries and whether the material was sourced ethically, free from child labor and dangerous substances.

There is a growing awareness in the consumer market when the Rana Plaza incident happened in Bangladesh on March 24, 2013, where many big brands were involved sourcing from that factory causing fatality over 1100 workers. There was an overnight shock within the fashion and apparel supply chain to reconcile this huge loss.
Consumers are lot more inquisitive about the brands they buy their clothes from to be conforming to the standards of sustainable and ethical practices, sourcing of raw materials as well as the transparency throughout the value chain. This chapter proposes a scale (Fig. 15.6) to measure the traceability using textile terminologies such as opaque, translucent, and transparent (OTT) (details of this scale is a scope of another study).

All the value chain activities would be listed as an activity for compliance and would be traced by block chain with an Ethereum layer of finance, RFID (Radio Frequency IDentification), and QR (Quick Response) to ensure traceability. A percentage rating of 0–100 points is possible, ranging from black to white referring to the accountability of the enterprise. This will ensure the black value chain to improve its practices for the coming years. This approach needs to be centralized to conform cross-border data acquisition and communication from financial and manufacturing stakeholders in the business of fashion and textiles.

### 15.14 Conclusions and future trends

Climate change is a dynamic process that is affecting global temperatures and carbon dioxide levels in the atmosphere. The solar radiations quality and heat stress have become a main concern for researchers, and the climate change should be acknowledged as a global priority. Within the fashion and textile industry, a step back to reconcile the concept of fast and luxury fashion driven by capitalism and the asynchronous use of material together with failing to introduce design choices for consumers accommodating recycling or reuse options has created enormous problems of ethics, morality, environmental responsibility, and responsible consumption of the mass population.

![Fig. 15.6 The proposed OTT framework.](image)
To date, sustainability is seen as a trend and used merely to greenwash and label-only marketing hook for the fashion enterprises to profit more. It is evident from the state of global fashion and textile waste issues mentioned in the discussion in this chapter that “triple P” approach of sustainability aims only at “profit” sacrificing the need of people and the planet. There is a consensus in the developed economies on slow and responsible fashion, and this needs to be treated as a mainstream approach from all walks of life and socioeconomical backgrounds. The global textiles and fashion enterprises need to address their share of climate change caused by human consumption practices from this point forward and take the responsibility to mitigate the threat of extinction of human race from the face of our beloved planet.

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Sustainable Technologies for Fashion and Textiles

Edited by Rajkishore Nayak

Sustainable Technologies for Textiles combines the latest academic research and industrial practice to shed light on a wide range of activities that influence how the textiles industry affects the natural environment.

Pressure from regulators, customers, and other stakeholders has pressed companies to translate general sustainability concepts and ideas into business practices. This is leading to improvements in how the industry consumes water, electricity, and chemicals and a reduction in the amount of waste generated by textile processes.

The different approaches to this topic are grouped into four themes in this book: fiber, yarn, and fabric production; chemical processing; garment manufacturing; and recycling. This holistic approach is essential in treating an issue which needs to be addressed across the supply chain.

End User Key Features:

- Addresses sustainability challenges that occur throughout the supply chain, from the sourcing of raw materials to recycling finished products.
- Provides introductions to sustainability both in general and within the textiles industry, making this topic accessible for readers of all backgrounds
- Compares the advantages and disadvantages of different approaches to sustainability, helping readers to avoid pitfalls when devising their own strategies.

About the Editor

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