Textile Science and Clothing Technology

Subramanian Senthilkannan Muthu
*Editor*

# Roadmap to Sustainable Textiles and Clothing

## Environmental and Social Aspects of Textiles and Clothing Supply Chain

Springer

# Textile Science and Clothing Technology

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## Environmental and Social Aspects of Textiles and Clothing Supply Chain

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# Preface

This is the second volume of a roadmap series on sustainable textiles and clothing. As discussed in Vol. 1, the textile and clothing supply chain represents a formidable threat to our living planet and the environmental footprint of this massive supply chain is of formidable size. Every life cycle of a piece of clothing, starting from the raw material stage, followed by the manufacturing process, transportation and retailing, consumer use, and the disposal phase is responsible for the creation of various potential environmental threats. This is the crux of the problem around which this second volume revolves and it will address this problem in detail. Following the first volume, which dealt with the eco-friendly raw materials, technologies, and processing methods employed to produce a sustainable textile product, this second volume is intended to deal with the environmental and social impacts of the textiles and clothing sector. This quite lengthy topic is discussed in this volume in ten very informative chapters.

"Environmental Impacts of the Textile Industry and Its Assessment Through Life Cycle Assessment"—presents an outline of environmental impacts pertaining to the textiles and clothing sector. Using the life cycle phases of textile products as a base, this chapter deals with the various potential environmental issues, such as the consumption of water, energy, chemicals, packaging materials, waste generation, and the corresponding environmental impact caused by the textile sector.

Clothing consumption is responsible for a major share of total life cycle impacts created by textile products. Though the percentage contribution of the consumption phase to the total environmental impacts is highly variable for various textile products and depends on many factors, from the outset this phase contributes significantly. This is evident from the many research studies on life cycle assessment of clothing products conducted so far. Hence this volume has a chapter to deal with this very important aspect: "Environmentally Sustainable Clothing Consumption: Knowledge, Attitudes, and Behavior". This chapter presents an overview of environmentally sustainable clothing consumption and disseminates information pertaining to the knowledge and attitudes of apparel consumers towards the various potential environmental issues related to the different life cycle phases of a textile product. It also presents the details of current consumer engagement levels in environmentally sustainable clothing consumption and an interesting analysis of the relationships between knowledge, attitudes, and clothing consumer behavior.

"Emerging Green Technologies and Environment Friendly Products for Sustainable Textiles"—deals with the details of various green technologies (such as supercritical carbon dioxide dyeing, plasma technology, and ultrasonic dyeing) to replace conventional textile wet processes, which are found to be environmentally detrimental. It also discusses the application of sustainable materials and utilization of by-products from other industries to achieve sustainable textile products.

Any product, including a textile product, is expected to be disposed of at the end of its life without environmental implications. This concept is addressed by biodegradation and the next chapter, "Biodegradation Studies of Textiles and Clothing Products"—revolves around this concept and discusses the biodegradation of textiles and clothing products. It addresses minute details pertaining to biodegradation, ranging from the mechanism behind it and the different factors influencing biodegradation, methods, techniques, and conditions of biodegradation assessment. It also presents an overview of biodegradation behavior and studies related to various textile and clothing products.

"Responsibility Without Means"—discusses the consumer phase of clothing products. It deals with consumer behaviour towards environmental impacts of clothing and investigates how consumers can help to reduce these environmental impacts together with the capability and willingness of customers to change their behaviour. Details are presented in the light of the results derived from the outcome of two research projects on environmental challenges connected to textiles and clothing in this chapter. Two research questions posed were elucidated with the aid of data from various desktop studies, in-depth interviews in combination with wardrobe studies, and consumer surveys.

"Environmental Analysis of Textile Value Chain: An Overview"—covers the environmental impacts of the textile value chain. Beginning by highlighting the environmental and social impacts of textiles and clothing sector, this chapter contains detailed discussions on various potential environmental impact areas of the clothing sector. It also deals with the environmental impacts of fibres and the various textile processes involved in the clothing and apparel production chain, along with a brief note on consumer responsibility.

"Who Influence the Environmental Adaptation Process of Small and Medium Sized Textile and Garment Companies in Vietnam?"—deals with the case study of Vietnam SMEs (Small and Medium sized Enterprises). This chapter begins with an overview of SMEs and the textile and garment sector in Vietnam. Discussing whether the stakeholders' involved in the environmental adaptation process is the first step to fill the related knowledge gap, this chapter briefs the stakeholders' theory. Stakeholders in this sector in Vietnam are dealt with in detail.

"The SURF Framework Applied to the Textile Industry"—deals with the details pertaining to the SURF (Supply chain, User, Relations, and Future) Framework, which addresses the quadruple bottom line of sustainability: social, environmental, economic, and intergenerational equity results and application to the textile industry. It includes discussions related to various textile-specific initiatives, standards, methods, and tools that relate to each component of SURF and presents interesting case studies on application of the SURF Framework to cotton textiles and to two different companies that sell cotton shoes and jeans, respectively.

"Sustainable Business Development Through Designing Approaches for Fashion Value Chains"—identifies and discusses the various challenges posed to the fashion value chain and the environmental, economic, and social impacts of the same. Having discussed the concept and model of sustainable business development, detailed discussions pertaining to a holistic designing approach on sustainable business development on fashion value chain are presented.

"Eco-friendly Coloration and Functionalization of Textile Using Plant Extracts"—includes discussion of the extraction and characterization of plant molecules suitable for textile coloration. Sustainable textile processing and finishing using plant molecules, textile coloration with the aid of natural dyes, and various natural dyes and their dyeing processes are also covered along with details pertaining to health and hygienic textiles and various other textile factors such as flame retardancy and producing well-being textiles using plant molecules.

I would like to take this opportunity to thank all the contributors of the different chapters included in this second volume of roadmap to sustainable textiles and clothing for their timely efforts in bringing out this book successfully with enriched technical content in their chapters. I have no doubt that the readers will benefit from this book which brings out the important details associated with the environmental and social impacts of the textiles and clothing sector. This second volume in the roadmap series of sustainable textiles and clothing will certainly become an important reference for the researchers and students, industrialists, and sustainability professionals working in this field.

# Contents

# Environmental Impacts of the Textile Industry and Its Assessment Through Life Cycle Assessment

**A. K. Roy Choudhury**

**Abstract** The textile industry is considered as ecologically one of the most polluting industries in the world. The issues which make the life cycles of textiles and clothing unsustainable are the use of harmful chemicals, high consumption of water and energy, generation of large quantities of solid and gaseous wastes, huge fuel consumption for transportation to remote places where textile units are located, and use of non-biodegradable packaging materials. The overall impact on the environment by a textile product or process may be best assessed by life cycle assessment (LCA) which is a systematic scientific approach to examine the environmental impacts of the entire life cycle of a product or service.

**Keywords** Water pollution · Harmful chemicals · Waste generation · Reuse and recycle · Restricted substances list

## 1 The Textile Industry

The global supply of manufactured fibers and the major natural fibers increased from 52.6 million tons in 2000 to 70.5 million tons in 2008, corresponding to an average annual growth rate of 3.3 % [67]. During that period, the share of the manufactured fibers increased from 59 to 63 %. Lenzing [57] reports that the global fiber usage in 2011 totaled more than 51 million metric tons of manufactured fibers and nearly 30 million metric tons of natural fibers, a record total representing a 1 % increase over 2010 fiber usage, and a per capita consumption of nearly 12 kg. Over the last 3–4 years, manufactured fiber usage has steadily

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increased, while natural fiber usage has either remained flat or has begun to decline.

Among the developing economies, China and India are expected to represent 45 and 20 % of global trade by 2014. Growth of new consumption markets, global expansion of modern retail business, booms in air and sea shipment, growth of textile and related production in Eastern Europe, the ex-Russian block, Turkey, the Middle East, Southeast Asia, India, China, and South America are all expected to drive growth in the global textile industry in the long term with Bangladesh, Vietnam, India, Cambodia, and Pakistan playing key roles [36].

Taking the textile and apparel sectors together, China has been the world's leading exporter of textiles and clothing since 1995. The EU, the United States, India, Turkey, Pakistan, Indonesia, Thailand, and Vietnam all rank among the top 15 exporters of textiles and clothing, according to the WTO trade statistics 2010 [6].

## 2 Structure of the Textile Industry

The majority of chemical use in textile production occurs during 'wet processing', i.e., in dyeing, washing, printing, and fabric finishing. Textile dyeing and finishing mills use considerably more water—as much as 200 tons of water for every metric ton of textiles produced.

Many of the chemicals used in textile production are non-hazardous, and only a relatively small proportion is potentially hazardous. However, in absolute terms, quite a large number of hazardous chemicals are used in textile production because of the very large number of chemicals deployed [46].

For example, the Swedish Chemical Agency has estimated that there are over 10,000 substances which can be used in dyeing and printing processes alone, about 3,000 of which are commonly used. The availability of such a large number of chemicals for use by industry poses obvious difficulties when it comes to sharing and maintaining information about them, as well as drawing up and enforcing regulations for their use [86].

The global textile supply chain is complex, involving many different stages and people. Multinational brand owners may contract suppliers directly or indirectly, through agents or importers. Normally it is the brand owner who triggers the product development process, including research and design. Brand owners are therefore best placed to bring about change in the production of textiles and clothing through their choices of suppliers, the design of their products, and the control they can exert over the use of chemicals in the production process and the final product [37].

A simplified textile product chain is shown in Fig. 1 [76]. For LCI analyses, environmental data and process inputs and outputs have to be collected. The major participants in the textile and clothing supply chain are multinational brand owners, raw material suppliers, textile and clothing producers, financiers, retailers, and customers.

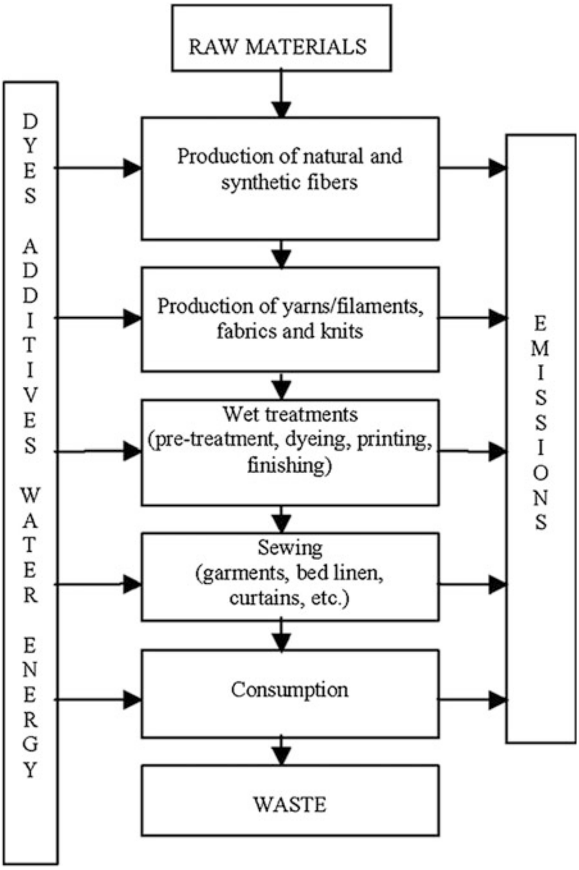


**Fig. 1** Simplified flow diagram of textile supply chain [76]

Figure 2 shows the main organizations involved in the textile and clothing supply chain, excluding the brand owners. Companies are sometimes responsible for more than one link in the supply chain; for example, the brand owner and retailer may be the same company, or the brand owner may have its own in-house production chain. The complexities of the supply chain inevitably lead to lack of transparency about the various steps involved in the manufacture of products and their potential environmental impacts [19].

## 3 Pollution and Textile Manufacture

A recent survey [37] of 15,000 people in 15 countries, across both the northern and southern hemispheres, found that the water scarcity and water pollution are two top environmental concerns of the world's population. China has some of the worst water pollution in the world, with as much as 70 % of its rivers, lakes, and

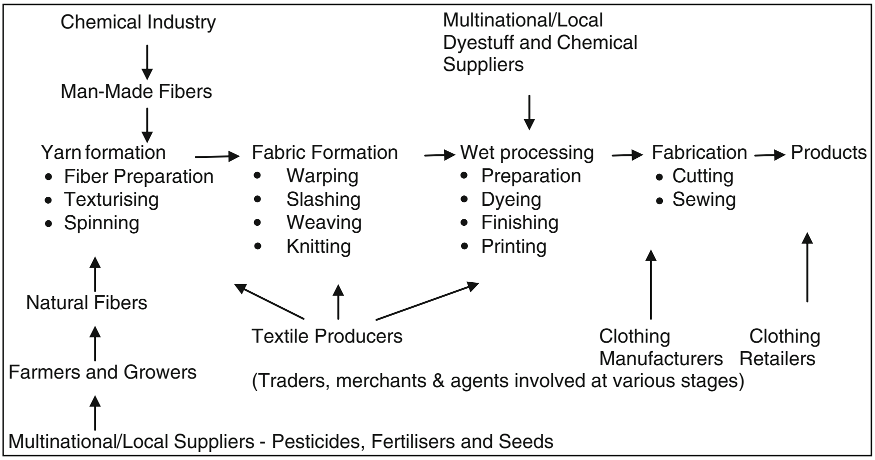


**Fig. 2** The businesses involved in the textile and clothing supply chain

reservoirs being affected, and the textile industry, an important sector of China's economy, with more than 50,000 textile mills in the country, contributes to this pollution. Building upon investigations by Greenpeace International, the report 'Dirty Laundry' profiles the problem of toxic-water pollution that results from the release of hazardous chemicals by the textile industry in China, water pollution which poses serious and immediate threats to both ecosystems and human health. The investigations forming the basis of this report focus on wastewater discharges from two facilities in China. Significantly, hazardous and persistent chemicals with hormone-disrupting properties were found in the samples.

Alkylphenols, including nonylphenol (NP), were found in wastewater samples from both facilities, and perfluorinated chemicals (PFCs), in particular perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate, were present in the wastewater from the Youngor Textile Complex, despite the presence of a modern wastewater treatment plant. The two facilities have commercial relationships (as suppliers) with a number of other Chinese and international brands [29].

New research commissioned by Greenpeace International [38] shows that residues of the hazardous chemicals NP ethoxylates (NPEs)—used in textile manufacturing—remain in many clothing items sold by major international clothing brands and, when washed, a significant percentage of the chemicals in these clothes is released and subsequently discharged into rivers, lakes, and seas, where they turn into the even more toxic and hormone-disrupting chemical NP.

The Institute of Public and Environmental Affairs, a leading environmental nongovernmental organization (NGO) in China, has released the second in a series of exposures about the severe water pollution problems caused by textile dyeing and finishing in China. The latest report criticizes brands such as Marks and Spencer, Disney, Polo Ralph Lauren, JC Penney, and Tommy Hilfiger, but also notes that H&M, Nike, Esquel, Levi's, Adidas, Walmart, Burberry, and Gap have proactively followed up on its first report earlier this year and established regular screening mechanisms on textile dye house suppliers [59].

The modern textile industry has migrated from one region or country to another. Most of this migration has been driven by one factor, the need to cut costs. Although large-scale pollution from the textile industry has been a problem throughout its history, the more recent use of persistent and hazardous chemicals poses a greater, and often invisible, threat to ecosystems and human health. Referring to all industries, the United Nations Environment Program stated: 'Worldwide, it is estimated that industry is responsible for dumping 300–500 million tons of heavy metals, solvents, toxic sludge and other waste into waters each year' [64]. When considering both the volume generated and the effluent composition, textile wastewater is considered to be the most polluted of all the industrial sectors [99]; with a complex global textile supply chain, involving many different stages and often several companies, brand owners may therefore be the best placed to bring about the required change.

Launched in July 2011, the Detox campaign [12], introduced by Greenpeace International, has exposed links between textile manufacturing facilities causing toxic water pollution in China and many of the world's top clothing brands. The Detox campaign is powered by more than half a million people, demanding toxic-free fashion and clean water. Fifteen global fashion leaders have committed to Detox in response to the growing international campaign (Nike, Adidas, Puma, H&M, M&S, C&A, Li-Ning, Zara, Mango, Esprit, Levi's, Uniqlo, Benetton, Victoria's Secret, G-Star Raw, and Valentino), but other clothing companies, such as Calvin Klein, GAP, and Abercrombie & Fitch still needed to respond.

## 4 Sustainability in Textile Manufacture

The textile industry has been cited as the most ecologically harmful industry in the world [66], whilst an argument said that water pollution is a major issue in China and that its textile industry, a large water user, has traditionally experienced wastewater problems [33]. In some cases, wastewaters are discharged (largely untreated) into groundwater with extreme pH values and temperatures as well as high chemical loading.

The following areas have the potential to make the life cycles of textiles and clothing unsustainable [81]:

1. Use of toxic chemicals
2. Consumption of water
3. Consumption of energy
4. Generation of waste
5. Air emissions
6. Transportation
7. Packing materials

## 4.1 Usage of Chemicals

About 25 % of the global production of chemicals is used in the textile industry globally [37]. As many as 2000 different chemicals are used in textile processing, especially in textile wet processing, and many of these are known to be harmful to human (and animal) health. Some of these chemicals evaporate, some are dissolved in treatment water which is discharged into the environment, and some are retained in the fabric. A list of the most commonly used chemicals, some of which are involved in fabric production, and linked to human health problems varying from annoying to profound, have been published by the National Institute for Environmental Health Sciences (part of the US Department of Health and Human Services) [63].

The chemicals causing particular concern when released into the environment display one or more of the following properties:

- Persistence (they do not readily break down in the environment)
- Bio-accumulation (they can accumulate in organisms, and even increase in concentration as they work their way up a food chain)
- Toxicity

Chemicals with these properties are described as PBTs (persistent, bio-accumulative, and toxic substances). Organic chemicals with these properties are sometimes referred to as persistent organic pollutants (POPs). Despite initial dilution in large volumes of water or air, such pollutants can persist long enough in the receiving environment to be transported over long distances, to concentrate in sediments and organisms, and some can cause significant harm even at what may appear to be very low concentrations.

The acceptability of all of the chemicals used in the textile industry, in terms of being eco-friendly, is difficult to determine. One difficulty, for example, is that a large number of dyes are used in the dyeing and printing of textiles; the Colour Index International (The Society of Dyers and Colourists, Bradford, UK. Http://www.colour-index.com) lists 27,000 individual products under 13,000 Color Index Generic Names. Volatile chemicals pose particular problems because they evaporate into the air or are absorbed into foods or through the skin. Some chemicals are carcinogenic or may cause harm to children, even before birth, while others may trigger allergic reactions in some people. Some reporters predict that the 5–10 % of the population allergic to chemicals will grow to 60 % by 2020 [80]. Various toxicity-reduction evaluations in North Carolina, conducted between 1985 and 1995, found recurrence of compounds identified as toxic agents [70], many of which were related to wet processing. A short, non-exhaustive list of such toxic compounds is given in Table 1.

Once identified, specific, identifiable compounds such as tributyltin oxide (TBTO), a biocidal preservative for cotton textiles, could be removed from the discharge waste stream or replaced with less toxic alternatives. Other, less specific compounds were more difficult to trace and eliminate.

**Table 1** List of a few popular but toxic textile chemicals and their fields of application

| Name of toxic chemical | Used as/in |
|---|---|
| Tri-butyl tin oxide (TBTO) | Biocide on hosiery and fabrics |
| Non-ionic surfactants | Detergents in textile preparation and dyeing |
| Cationic surfactants | Textile dyeing and finishing |
| Sodium chloride | Dyeing of cotton textiles |
| Sodium sulfate | Dyeing of cotton textiles |
| Copper | Dyeing of cotton and polyamide; in its elemental, non-complexed form, it is toxic |
| Cyanide | Anti-caking agent in salt |

Non-ionic surfactants pose a particular problem. Surfactants slow to degrade cause acute and chronic toxicity effects. Understanding their rate of biodegradability is a key factor in the treatment of effluents, as the only available options are either longer treatment times or substituting more rapidly degradable surfactants. It is estimated that there are over 500 unique non-ionic surfactants used in textile processing, and environmental data are scarce for these compounds. NPs and nonylphenol ethoxylates have been restricted in the EU as a hazard to human and environmental safety [30].

Sodium chloride and sodium sulfate, which are used as exhausting agents in the direct dyeing of cotton, also present a particular problem. These substances are particularly problematic in areas where the natural flows in the receiving streams were very small in relation to the discharge flows of the POTW. There still remains no practical treatment to remove these salts from textile wastewaters and, thus far, the only way to resolve the issue has been to dilute the effluent. The problem can, however, be minimized by using low-salt reactive dyes or adopting pad application methods. Copper was found to be present in many blue and black dyes with 'free,' noncomplexed copper acting as the immediate toxic agent; hence, their screening and the development of copper-free dyes was encouraged.

Even after eliminating several specific toxic compounds, there still remain a large group of textile chemicals called wet-processing auxiliaries. These 'name-brand' products are composed of complex mixtures of surfactants, softening agents, solvents, chelating agents, and water-based polymers. Most of these products are mixtures designed to perform a certain task in the preparation, dyeing, or finishing of textiles. Because of both the huge variety and different concentrations of chemicals which can be used in these products, there are significant difficulties in identifying the components of these mixtures, a problem exaggerated as producers keep the ingredients a trade secret. The lingering question is how to determine the relative environmental impacts of these products so that the end-user, the textile industry, can choose greener products and improve the environmental quality of the water being discharged from the textile facility.

## 4.2 Consumption of Water

Clean water is both essential to the planet's ecosystems and fundamental to people's well-being. It is a basic human right. Waterways such as rivers and lakes supply communities with vital resources, including drinking water, water for crop irrigation, and foods such as fish and shellfish. These waterways also serve as a support system for industrial activity, providing water for many manufacturing and cooling processes. However, such industrial activities can affect water quality and thereby jeopardise the other resources which rivers and lakes provide. Globally, water resources are being degraded by the increasing pressure of human activities. Economic and population growth places ever-greater demands on water supplies, reducing the quantity and quality of water available for wildlife, ecosystem function, and human consumption. Clean water is a finite resource which is becoming scarce, and it is used at every step of the wet-processing sequence both to convey the chemicals into the material and to wash them out before the beginning of the next step. Once charged with chemical additives, the water is expelled as wastewater, which, if untreated, may pollute the environment thermally by virtue of the high temperature of the effluent, extreme pH, and/or contamination with dyes, diluents of dyes, auxiliaries, bleaches, detergents, optical brighteners, and many other chemicals used during textile processing [66].

Problems become worse when there is inappropriate or incomplete effluent treatment or a discharge of polluted water directly without treatment, leading to polluted surface waters and polluted aquifers, i.e., layers of earth or rock containing water [53, 80]. As a result, any heavy metal constituents in effluents lead to pollution with both negative ecological impacts on the water-body environment and deterioration of human health.

The textile and related industries are considered by some to be the second highest consumer and polluter of clean water next to agriculture [66]. The textile services sector is an essential adjunct to the textile industry and is needed to manufacture, finish, market, and distribute the products [89]; the services related to the textile industry include computer-aided design, contract quilting, contract yarn spinning, custom printing, fabric welding, silk screen printing, textile designers services, contract knitting, contract sewing, custom embroidery, custom slitting, pleating, specialty weaving, contract napping, contract weaving, custom perforating, custom swatching, private labeling, testing of the end product, etc. [88]. Water is used in various steps during the textile dyeing process both to convey the chemicals used during the step and to wash them out before the beginning of the next step. In a traditional dyeing and finishing operation, for example, 1 ton of fabric could result in the pollution of up to 200 tons of water by a suite of harmful chemicals and, in the process, consumes large amounts of energy for steam and hot water [61]. With the industry now centered in countries with still-developing environmental regulatory systems, such as China, India, Bangladesh, and Vietnam, textile manufacturing continues to have a huge environmental footprint. Some commonly observed routes of wastage of water [66] are:

- Excessive use of water in washing
- Poor housekeeping measures such as broken or missing valves
- Unattended leaks through pipes and hoses
- Instances when cooling waters are left running even after shutdown of the machinery
- Use of inefficient washing equipment
- Excessively long washing cycles
- Use of fresh water at all points of water use

The reutilization of wastewater can present very important savings, namely in reduction of water, energy, and chemical consumption. The recycling of wastewater is effected in process baths and rinsing waters, before fresh water is taken for treatment for removal of remaining chemicals and other effluents generated. Steam condensate and cooling water are easily recoverable as they are clean and recovery of their thermal energy can very quickly pay back the investment.

Techniques and technologies of implementing energy management, including heat recovery, in the use of steam in the textile industry vary extensively in terms of the scope of their application, their costs, and their benefits. The case of the textile dyeing and finishing industry in Mauritius has been investigated thoroughly by Elahee [20]. energy management was applied to optimize the use of steam in dyeing and finishing plants. The state of energy management in the dyeing and finishing industry had similarities with that of its European or North American counterparts before the oil crisis of the 1970s. The dyeing and finishing industry in Mauritius consumed about 35,000 tons oil equivalent annually for steam generation, mostly in the form of fuel oil and coal. The potential reduction in fossil fuel consumption was about 35 % in small textile dyeing and finishing plants and 25 % in large ones. Out of the latter, 15 and 10 %, respectively, of the fossil fuel consumption can be saved with heat recovery, that is, essentially with low cost, short payback energy-saving measures.

The introduction of low cost techniques and technologies should yield significant reduction in steam consumption in plants, where energy management has not been applied before. This is the case for many African countries where the dyeing and finishing industry is new. Although new technology is relatively expensive, its benefits extend far beyond savings in energy. Quality, productivity, and response-time gains as well as environmental benefits are significant.

If properly applied, the overall payback for investment in such technology can be reduced to not more than 2 years. However, investing in such technology is not without risks, particularly in view of the fact that these are not easily set up in developing countries. In almost all cases know-how transfer and ancillary costs should be duly considered. The progress of such technology should also not be at the expense of indigenous techniques and technologies. Examples from the past show that there is significant scope to reduce production costs related to steam in textile dyeing and finishing plants in developing countries, including African countries. In most cases, no significant investment is needed and local indigenous technology and skills can be employed. The payback is normally less than 2 years.

Heat recovery, in particular, improves profitability and competitiveness on the international markets. Reduced reliance on imported fossil fuel is achievable, hence keeping the industry safe from rising oil or coal prices. The reduction in global and local pollution is also an important benefit. This will help to make the textile industry a pillar of sustainable development of these countries, many already producing high quality raw materials. Consequently, their chances of pursuing socioeconomic progress coupled with environmental protection will be much improved [21].

Pattanapunt et al. [71] studied how to recover heat waste from boiler exhaust gas by mean of a shell and tube heat exchanger. By processing the exhaust gas from the boiler dyeing process, which carries a large amount of heat, energy consumption can be decreased by using waste-heat recovery systems. The variations of parameters which affect system performance, such as exhaust gas and air temperature, velocity and mass flow rate, and moisture content are examined respectively. From this study it was found that heat exchangers could reduce the temperature of exhaust gases and emission to the atmosphere and payback time is very fast. The payback period was determined to be about 6 months for the investigated ANSYS.

### 4.2.1 Wastewater Pollutants

In the future, water is set to become an increasingly scarce and therefore extremely valuable resource. Demand for water is growing at more than twice the rate at which the world's population is growing. Over the past 100 years, the world's population has increased threefold, while water consumption has risen by a factor of seven. Since 1970, the available amount of water per capita has been reduced by 40 % as a result.

It takes approximately 2,500–3,000 L of water to manufacture a single cotton shirt. The bulk of this water is required to grow the cotton, followed in second place by the wet finishing process. The first consequences of water shortages and wastewater problems are already starting to be felt in the textile finishing industry. For example, new companies in China and India have not been granted approval to set up operations if they have not been able to present a convincing case to the authorities that their approach will help solve issues of water consumption and wastewater. In Europe, companies face closure for the same reason. Textile centers in Asia are reporting rapidly dwindling groundwater reserves and heavily salinated groundwater. As a result, many companies face challenges which threaten their very existence. A case study has been performed to understand how a traditional finishing plant performs, and what can be achieved through modernization [90].

Some wastewater is still being disposed of in an environmentally unfriendly way, into the sewage networks where available, or else into cesspools, without regard to the BOD, chemical oxygen demand (COD), and/or the heavy metal content of the wastewater. The untreated wastewater generated from textile production and processing can vary greatly depending on the chemicals and treatment processes involved and may include materials with a high BOD and COD, high total suspended solids (SS), oil and grease, sulfides, sulfates, phosphates, chromium, copper, and/or the salts of other heavy metals; of these, the most important are considered to be COD, biological oxygen demand (BOD), pH, fats, oil, nitrogen, phosphorus, sulfates, and SS [95, 96]. Total SS levels are low in raw textile dyeing wastewater compared to wastewater from many other industries. On the other hand, BOD and COD are relatively high in effluents from sizing operations and wet processing, and are therefore more important pollution-prevention targets [101]. Sulfates and phosphates are toxic at very high concentrations. Problems caused by sulfates are most frequently related to their ability to form strong acids which change the pH, whereas, in surface waters, phosphates cause eutrophication.

## *4.3 Consumption of Energy*

The textile industry is a major energy-consuming industry with low efficiency in energy utilization [62]. About 23 % of the total energy used is consumed in weaving, 34 % in spinning, 38 % in chemical processing, and another 5 % for miscellaneous purposes. Thermal energy dominates in chemical processing, being used mainly for heating water and drying textile materials, whilst electrical power dominates the energy consumption pattern in spinning and weaving [77].

The textile industry is one of the largest generators of GHGs (greenhouse gases), not least because of its enormous size. In 2008, the annual global production of textiles was estimated at 60 billion kg of fabric with the associated (estimated) energy and water needs of 1,074 billion kWh of electricity (or 132 million tons of coal) and 6–9 trillion L of water, respectively (Textile.2456.com [90]). A large quantity of non-renewable energy sources is eventually consumed in the form of electricity, not so much in the process of textile production (15–20 %) but mostly in subsequent laundering processes during consumer use (75–80 %) [81]. It is reported [74] that the total thermal energy required per meter of cloth (including both production and consumer use) is 18.8–23 MJ and the electrical energy required per meter of cloth is 0.45–0.55 kWh. Whilst data on energy usage for the textile industry are readily available, complications arise in estimating the associated $CO_2$ emissions arising from the sources (coal, electricity, natural gas, or other sources) from which the energy is produced because the textile industry is a fragmented and heterogeneous sector dominated by small- and medium-sized enterprises.

Energy is one of the main cost factors in the textile industry. Especially in times of high energy price volatility, improving energy efficiency should be a primary concern for textile plants, and various energy-efficiency opportunities exist in every textile plant, many of which are cost-effective but not implemented because of limited information or high initial cost. For example, the use of electricity for heating is associated with in-built inefficiencies as compared with the direct use of thermal energy, and the use of steam is less efficient than direct-fired gas heating in a mill. The share of the total manufacturing energy consumed by the textile industry in a particular country depends upon the structure of the manufacturing sector in that country. For instance, the textile industry accounts for about 4 % of the final energy use in manufacturing in China [55], while this share is less than 2 % in the United States [100].

Electricity is the main energy consumed in the textile industry, being used for driving machinery, cooling, temperature control, lighting, and office equipment, whereas fuel oil, liquefied petroleum gas, coal, and city gas are widely used to generate steam. Efficiencies have been achieved; between 1990 and 2005, the carbon emission intensity in the textile industry decreased for gray cloth, jute goods, and polyester chips by 1.90, 2.07, and 0.72 %, respectively. On the other hand, cotton yarn showed the highest increase in emission intensity of 7.37 %, meaning that cotton yarn continued to be produced inefficiently [18]. Emission intensity is the average emission rate of a given pollutant from a given source relative to the intensity of a specific activity, for example, grams of carbon dioxide released per megajoule of energy produced or the ratio of GHG emissions produced to GDP.

Emission intensities are used to derive estimates of air pollutants or GHG emissions based on the amount of fuel combusted, the number of animals in animal husbandry, industrial production levels, distances travelled, or similar activity data. Emission intensities may also be used to compare the environmental impact of different fuels or activities. The related terms, emission factor and carbon intensity, are often used interchangeably, but 'factors' exclude aggregate activities such as GDP, and 'carbon' excludes other pollutants [104].

Spinning consumes the greatest share of electricity (41 %) followed by weaving (including weaving preparation) (18 %), whereas wet-processing preparation (desizing, bleaching) and finishing together consume the greatest share of thermal energy (35 %). A significant amount of thermal energy is also lost during steam generation and distribution (35 %), but these percentages vary from plant to plant. Such analysis of energy efficiency improvement opportunities in the textile industry points to advantages to be gained from retrofit/process optimization, not just from complete replacement of current machinery with state-of-the-art new technology [44]. Table 2 shows the average values for thermal energy use in dyeing plants in Japan [44], indicating the proportion of thermal energy use for each step in a dyeing plant, and where the potential exists for the greatest energy-efficiency gains. The table also gives useful information about where losses are most significant, which losses should be addressed first, and the general means of reducing the losses.

There are various possibilities for using renewable energy in the textile industry examples are:

1. Installation of wind-powered turbo-ventilators on production plant roofs
2. Use of direct solar energy for fiber drying
3. Use of solar energy for water heating in the textile industry
4. Solar electricity generation

**Table 2** Average thermal energy use in dyeing plants of Japan

| Thermal energy consumed for | % Share | Required action to reduce heat loss |
|---|---|---|
| Heating of product | 16.6 | |
| Drying of product | 17.2 | Avoid over-drying |
| Heat loss of waste liquor | 24.9 | Recovery of waste heat |
| Heat loss from equipment | 12.3 | Improved insulation |
| Heat loss with exhaust | 9.3 | Reduction of exhaust gas |
| Heat loss from idle equipment | 3.7 | Stop energy supply during idle time |
| Heat loss from evaporation | 4.7 | Use covered equipment |
| Heat loss with unrecovered condensate | 4.1 | Optimize recovery of condensate |
| Heat loss during recovery of condensate | 0.6 | |
| Others | 6.6 | |
| Total | 100 | |

## *4.4 Generation of Waste*

As with any other industry, the textile industry generates all categories of industrial wastes, namely liquids, solids, and gases. For greener processes, non-renewable wastes need to be recycled and renewable wastes need to be composted if recycling is not an option. Various useful materials can be recovered from textile process wastes.

The recovery of chemicals such as sodium hydroxide from mercerization baths is achievable by heating to concentrate the solution; following such a step, 90 % of the sodium hydroxide can be recovered [48]. The EVAC vacuum suction system in the textile dyeing process recovers hot alkaline hydrogen peroxide, additives, and finishing chemicals [93]. Recently introduced to Thailand from the United States, the equipment has been installed by Chieng Sang Industry Co. in their plant at the finishing stage to suck the excess chemical solution from the fabric, and then transfer the solution to a storage tank for chemical recovery and recycling [97].

The polyvinyl alcohol (PVA) desize effluent is a major COD contributor to a textile plant's primary oxygenation treatment of water (POTW) operation, and, being biologically inert, it presents a threat to the environment. Unfortunately, no effective and efficient means to treat the PVA desize effluent has been implemented in the textile industry. Ultrafiltration (UF) reverse osmosis (RO) technology for the recovery and recycling of PVA size is more than 35 years old, but is not widely used because of its many disadvantages. The situation necessitates a new technology for the recovery and recycling of PVA size which can reduce energy and water consumption in an economical and environmentally-friendly manner. A new technology which would eliminate the disadvantages of the current UF process in the recovery of PVA from desize effluents is vacuum flash evaporation (VFE). The VFE process for recovery and concentration has been used in a variety of other industries, but has never been demonstrated for size recovery in the textile industry [42]. Industrial solid wastes from textile production include the following:

- Ashes and sludge
- Cardboard boxes, bale wrapping film, or non-recyclable soiled fabric
- Plastic bags containing chemical raw material
- Non-reusable paper cones and tubes
- Waste fabrics, yarns, and fibers from non-recyclable processing

Unmanaged solid waste is likely to be dumped as landfill.

## 4.5 Air Emissions

Burnt fossil fuels contribute to the emissions of carbon dioxide, a primary contributor to the greenhouse effect. Textile manufacture is also responsible for the following emissions:

- Nitrogen oxides and sulfur oxides (from fossil-fuel-heated boilers) which create acidity in the natural environment (freshwater lakes, rivers, forests and soils) and lead to the deterioration of metal and building structures. They also contribute to smog formation in urban areas.
- Solvent escaping into the air from drying ovens used in solvent coating operations.
- Solvents released from cleaning activities (general facility clean-up and maintenance, print screen cleaning).
- Emissions of volatile hydrocarbons which include non-methane hydrocarbons (NMHCs) and oxygenated NMHCs (e.g., alcohols, aldehydes, and organic acids).

## 4.6 Transportation

Long-distance transport is required to move the finished products from the factories located in low-labor-cost countries to the consumer in a developed country, thus adding to the overall quantity of non-renewable fuel consumed.

## 4.7 Packaging Materials

Packaging is the science, art, and technology of enclosing or protecting products for distribution, storage, sale, and use. Packaging also refers to the *process* of design, evaluation, and production of packages. Packaging can be described as a coordinated system of preparing goods for transport, warehousing, logistics, sale, and end use. Packaging contains, protects, preserves, transports, informs, and sells [83].

For consumer packaging, the packaging used to present products in stores, materials often used are plastic, paper, metal, aluminum, cotton, hemp, and biodegradable materials. Companies implementing eco-friendly actions are reducing their carbon footprint by using more recycled materials, increasingly reusing packaging components for other purposes or products, and employing recycled materials (e.g., paper, cotton, jute, hemp, wood), biodegradable materials, natural products grown without the use of pesticides or artificial fertilizers, and reusable materials (e.g., cotton bags or hemp). Reducing packaging waste is one of the best ways to minimize environmental impact. EU Directive 94/62/EC specifies a number of requirements relevant to packaging and packaging waste. It also sets specific recycling targets and maximum levels for heavy metals. Sustainable packaging is the development and use of packaging which results in improved sustainability. At the end stage of design, it involves increased use of LCI and life cycle assessment (LCA) which considers the material and energy inputs and outputs to the package, the packaged product (contents), the packaging process, and the logistics system [106].

## 5 Non-Eco-Friendly Substances

The terms ‘environmentally friendly,’ ‘eco-friendly,’ ‘nature friendly,’ and ‘green’ are used to refer to goods and services, laws, guidelines, and policies claimed to inflict minimal or no harm on the environment [103]. ‘Green’ is a very subjective term which could be interpreted in different ways, but whatever the definition, becoming green is important in that it means having made a commitment to protecting people and the planet; green or eco-friendly goods, services, and practices assure the use of environmentally-friendly materials, free from harmful chemicals, compounds, or energy waste, which do not deplete the environment during production and transportation [8], whereas non-eco-friendly substances, such as non-biodegradable organic materials and hazardous substances, may do harm to the environment.

### *5.1 Non-Biodegradable Organic Materials*

A non-biodegradable material is a substance which is not broken down by microorganisms, has an oxygen demand only if it is a chemical reducing agent, but has no biochemical oxygen demand (BOD) [82]. BOD is the amount of dissolved oxygen needed by aerobic biological organisms in a body of water to break down organic materials present in a given water sample at a specified temperature over a specific time period. The BOD value is most commonly expressed in milligrams of oxygen consumed per liter of sample during 5 days of incubation at 20 °C and is often used as an indicator of the degree of organic pollution of water.

## 5.2 Hazardous Chemicals

As defined by the Occupational Safety and Health Administration under the US Department of Labor Standard 1910.1200 [68], a hazardous chemical is one which is a health hazard or a physical hazard. Being designated as a health hazard means that there is statistically significant evidence that acute (short-term) or chronic (long-term) health effects may occur in humans exposed to that particular substance. The term ‘health hazard’ includes chemicals which are carcinogens or otherwise toxic or highly toxic agents, which damage the lungs, skin, eyes, or mucous membranes. A chemical is designated as a physical hazard when there is scientifically valid evidence that it is a combustible liquid, a compressed gas, explosive, flammable, organic peroxide, oxidizer, pyrophoric, unstable (reactive), or water reactive.

On the basis of chemical behavior, therefore, hazardous substances may be categorized as combustible and flammable substances, oxidizers, reactive substances, or corrosive substances, but perhaps the greatest concern is with toxicity. Toxic heavy metals and volatile organic compounds (VOCs) are two important sub-groups of hazardous substances.

## 5.3 Toxic Metals/Heavy Metals

Bjerrum [72] defined ‘heavy metals’ as those metals with elemental densities above 7 g/cm$^3$; over the years, this definition has been modified by various authors. However, there is no consistency; the term ‘heavy metal’ has never been defined by any authoritative body such as the International Union of Pure and Applied Chemistry (IUPAC) and, in any case, density is not of great significance in relation to the reactivity of a metal. A more useful definition is that heavy metals are the group of metals with atomic numbers between 22 and 34 and 40 and 52, and members of the lanthanide and actinide series which have a specific gravity four to five times greater than that of water [35]. With regard to toxicity, differentiation between metals depends upon the chemical properties of the metals and their compounds and upon the biological properties of the organisms at risk [15], and heavy metals are some of the most harmful ecologically. In the case of humans, they may enter the body through food, water, or air, or by absorption through the skin, and exhibit a tendency to bio-accumulate, with many forming lipid-soluble organo-metallic compounds which accumulate within cells and organs, thereby impairing their functions. The health hazards associated with some heavy metals and metalloids (e.g., arsenic) are listed in Table 3 [46].

Heavy metals are inherently persistent and some of them (for example cadmium, lead, and mercury) are also able to bio-accumulate and/or are toxic. Although they occur naturally in rocks, their use by industry can release them into the environment in quantities that can damage ecosystems. Heavy metal

**Table 3** Health hazards associated with heavy metals and metalloids used in the textile industry

| Metal/metalloid | Associated health hazard |
|---|---|
| Lead (Pb) | Damage to the brain, nervous system, and kidneys (causes in mild cases insomnia, restlessness, loss of appetite, and gastrointestinal problems) |
| Mercury (Hg) | Damage to the brain |
| Cadmium (Cd) | Disorders of the respiratory system, kidneys, and lungs |
| Chromium (Cr) | Skin and respiratory disorders, ulceration of skin and cancer of the respiratory tract on inhalation |
| Arsenic (As) | Skin cancer, hyper-pigmentation, kurtosis, and black foot disease |

compounds do not break down into harmless constituents but can react to form new compounds.

Some types of toxicity make it difficult to define ‘safe’ levels for substances, even at low doses, for example, substances may be:

- Carcinogenic (causing cancer), mutagenic (able to alter genes), and/or repro-toxic (harmful to reproduction)
- Endocrine disruptors (interfering with hormone systems)

Some possible sources of heavy metals in textile operations are incoming fiber, water, dyestuffs (heavy metals are constituents of some classes of dyes and pigments), auxiliaries, finishing chemical impurities, and the plumbing fittings used in dyeing and finishing plants [73]. Heavy metals may also be found in plant fibers because of absorption from the soil in which they are grown. Once absorbed by humans, heavy metals tend to accumulate in internal organs such as the liver or the kidneys with serious effects on health, particularly when high levels of accumulation are reached. For example, high levels of lead can seriously affect the nervous system. The heavy metals typically concerned are antimony (Sb), arsenic (As), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), lead (Pb), mercury (Hg), nickel (Ni), silver (Ag), tin (Sn), titanium (Ti), and zinc (Zn), many of which can be found in effluents from textile operations [73, 105]. Both cadmium and lead are classified as carcinogens. Cadmium has been restricted in Europe for a long time. Cadmium and cadmium oxide were classified as carcinogens and aquatic acute and chronic toxic. Since 31 December 1992, cadmium has been prohibited under the Council Directive 76/769/EEC of the European Union (Regulation Concerning the Registration, Evaluation, Authorization and Restriction of Chemicals, henceforth REACH) [75]. Lead is restricted in the United States under the Consumer Product Safety Improvement Act [10] and children’s products which contain more lead than 600 ppm have been banned in the United States since 10 February 2009, whilst the permissible lead content in paint and similar surface-coating materials for consumer use has been reduced from 600 to 90 ppm; there are similar European regulations controlling the content [16]. Chromium (VI) is an undesirable by-product generated during the leather-tanning process, whenever chrome tanning is employed. Chromium (VI) is a strong oxidant and skin irritant and is classified as a carcinogen which needs to be controlled [3]. Nickel is found in alloys used for metal accessories on garments such as buttons, zippers, and rivets. Some people are allergic to nickel and may experience serious skin irritation on coming into contact with nickel-containing accessories for an extended period. The release of nickel is restricted under the EU REACH Regulation (EC) No 1907/2006, Annex XVII [31]. Heavy metals which have been transferred to the environment are highly toxic and can bio-accumulate in the human body, aquatic life, natural water-bodies, and also possibly become trapped in the soil [69].

Heavy metals enter the environment through wastewaters from different branches of the textile industry, in particular from discharged spinning baths, from man-made fiber manufacturing plants, and from effluents discharged from dyeing machines. However, although it contributes, the textile industry is not the only source of this type of pollution [24]; significant amounts of heavy metals enter the environment in many cities from vehicle emissions, and solid industrial wastes also contribute to contamination. Several other sources contribute to trace metal impurities, such as:

- Natural levels in our environment
- Impurities in reactants or raw materials
- Use of metal catalysts or reactants
- Corrosion of manufacturing plant equipment

Limits on heavy metal content do not apply to products containing a listed metal as an inherent part of the molecular structure or formula such as metal-complex dyes [91].

## *5.4 Toxic Volatile Organic Compounds*

VOCs are organic chemicals with a high vapor pressure under normal atmospheric conditions. Their high vapor pressure results from their low boiling points causing large numbers of molecules to evaporate and enter the surrounding air. An example is formaldehyde, with a boiling point of –19 °C, which will steadily evaporate unless kept in a closed container.

VOCs include both man-made and naturally occurring chemical compounds and many are dangerous to human health or cause harm to the environment. VOCs may cause several health disorders, namely eye, nose, and throat irritation, headache, loss of coordination, nausea, and damage to the liver, kidneys, and central nervous system (CNS). Some VOCs can cause cancer in animals; some are suspected or known to cause cancer in humans. Key signs or symptoms associated with exposure to VOCs include conjunctival irritation, nose and throat discomfort, headache, allergic skin reaction, dyspnoea (difficulty in breathing), decline in serum cholinesterase levels, nausea, emesis, epistaxis (bleeding from nose), fatigue, and dizziness. The ability of organic chemicals to cause adverse health effects varies greatly from those chemicals which are highly toxic to those with no known health effect. The extent and nature of the health effect depends on many factors, including the level of exposure, the length of time exposed, and an individual's body mass [25].

Anthropogenic VOCs are regulated by law, especially in indoor applications, where the concentrations can potentially become the highest, whereas unregulated VOCs from substances such as citrus oils and terpenes may still have the ability to develop an unpleasant reaction in chemically-sensitive people. VOCs are typically not acutely toxic, but instead often display compounding long-term health effects. Because concentrations resulting from slow release from products are usually low, and the symptoms are slow to develop, research on VOCs and their long-term effects is difficult to conduct, but respiratory, allergic, or immune effects in infants or children have been associated with man-made VOCs and other indoor or outdoor air pollutants [60].

Some VOCs, such as styrene and limonene, can react with nitrogen oxides or with ozone in the atmosphere to produce new oxidation products and secondary aerosols, which can cause sensory irritation symptoms [5]. Unspecified VOCs are said to be important in the creation of smog [8].

### *5.5 Conventional Solvents*

Most organic solvents are volatile and, unless controlled, will escape into the workplace and the atmosphere, where they can be instrumental in causing photochemical smog. Many hydrocarbon and oxygenated solvents readily evaporate and are highly flammable. Hence, their use needs to be managed carefully to minimize the risks of fire or explosion, particularly during loading and unloading for storage or transport, during storage itself, and when being used in bulk. Safe-handling information provided by the supplier should be carefully followed [2].

The US Federal EPA classifies benzene as a known human carcinogen. Hydrocarbons and hydrocarbon derivatives (e.g., chlorinated solvents), in addition to serving as reaction media, are also used as cleaners, degreasers, and agents for the extraction of organic substances from solids. Tetrachloroethylene (also known as perchloroethylene) is widely used for dry-cleaning of fabrics and for metal-degreasing operations, but the effects of exposure to tetrachloroethylene in humans can be neurological, liver and kidney damage following acute (short-term) and chronic (long-term) inhalation. Adverse reproductive effects, such as spontaneous abortions, have also been reported from occupational exposure to tetrachloroethylene; however, no definite conclusions can be reached because of the limitations of the studies. Results from epidemiological studies of dry cleaners occupationally exposed to tetrachloroethylene suggest increased risks for several types of cancer. Animal studies have reported an increased incidence of liver cancer in mice, via inhalation and gavage (experimentally placing the chemical in the stomach), and kidney and mononuclear cell leukaemia in rats.

### 5.5.1 Chlorinated Solvents

Dry cleaning is any cleaning process for clothing and textiles using a chemical solvent other than water and is often used for delicate fabrics or those in which the dye shows low wet-fastness. The most widely used solvent is tetrachloroethylene, also known as perchloroethylene or PERC. PERC is classified as carcinogenic to humans by the EPA [26] and effluents must be handled as a hazardous waste, so, to prevent contamination of drinking water, dry cleaners must take special precautions.

When released into the air, PERC can contribute to smog on reaction with other volatile organic carbon substances [23]. A recent study conducted at Georgetown University [34] shows that PERC is retained in dry-cleaned clothes and that its levels increase with repeated cleanings.

Some alternatives, such as liquid $CO_2$, offer a possible solution to the PERC problem; however, liquid $CO_2$ may be inferior in removing some forms of grime. Consumer reports rated this method superior to conventional methods, but the Drycleaning and Laundry Institute commented on its ‘fairly low cleaning ability’ in a 2007 report [13].

Glycol ethers (dipropylene glycol *tert*-butyl ether) (Rynex, Solvair, Lyondell Impress) are in many cases more effective than PERC and in all cases more environmentally friendly. Dipropylene glycol *tert*-butyl ether (DPTB) has a flashpoint far above current industry standards, yet at the same time possesses a degree of solvency for water-soluble stains at least equivalent to, and in most cases better than, PERC and the other glycol ether dry-cleaning solvents presently in commercial use. A particular advantage of the DPTB—water solutions in dry cleaning is that they do not behave as a typical mixture but, rather, the behavior is that of a single substance. This permits a better defined separation than azeotropic distillation at a lower boiling point, facilitating reclamation more effectively (at a level of 99 % or greater), and also enhancing purification using conventional distillation techniques.

The silicone fluid, decamethylcyclopentasiloxane or D5, is gentler on garments than PERC and does not cause color loss. Although considerably more environmentally friendly, its price is more than double that of PERC as it is licensed by GreenEarth Cleaning which charges an annual affiliation fee [47].

Chlorinated solvents such as trichloroethane (TCE) are sometimes used by textile manufacturers to dissolve other substances during manufacturing and to clean fabrics. TCE is an ozone depleting substance which can persist in the environment. It is also known to affect the CNS, liver, and kidneys. Since 2008 the EU has severely restricted the use of TCE in both products and fabric cleaning [37].

Chlorobenzenes are persistent and bio-accumulative chemicals. They have been used as solvents, biocides, in the manufacture of dyes, and as chemical

**Table 4** A few safe and green solvents [4]

| Sr. no. | Name | Sr. no. | Name | Sr. no. | Name |
|---|---|---|---|---|---|
| 1 | Acetic acid | 7 | Tetrahydrofuran | 13 | Dimethyl ether |
| 2 | Acetophenone | 8 | Diethylene glycol | 14 | Glycerol |
| 3 | Benzyl benzoate | 9 | Dimethyl sulfoxide (DMSO) | 15 | Hexane |
| 4 | *tert*-Butanol | 10 | Dimethyl ether | 16 | Methanol |
| 5 | Diethylene glycol | 11 | Ethyl acetate | 17 | Polyglycol E 200 |
| 6 | Dibutyl ether | 12 | Ethylene glycol | 18 | Propylene glycol |

intermediates. They commonly affect the liver, thyroid, and CNS. Hexachlorobenzene (HCB), the most toxic and persistent chemical of this group, is also a hormone disruptor. Within the EU, pentachlorobenzene and HCB are classified as 'priority hazardous substances' under regulations requiring measures to be taken to eliminate their pollution of surface waters in Europe. They are also listed as 'persistent organic pollutants' for global restriction under the Stockholm Convention and, in line with this, they are prohibited or scheduled for reduction and eventual elimination in Europe [37].

The safe or green solvents recommended by Ash and Ash [4] are listed in Table 4.

Solvents produced from renewable resources such as ethanol produced by fermentation of sugar-containing feedstock, starchy materials, or lignocellulosic materials may be selected [78]. This substitution for petrochemical solvents leads to an avoidance of the use of fossil resources (petrochemicals) and fossil-fuel-related emissions of $CO_2$ into the environment.

## *5.6 Perfluorinated Chemicals (PFCs)*

PFCs are man-made chemicals which are not produced by natural processes and hence never occur in nature other than as a result of human activity. They are highly resistant to chemical, biological, and thermal degradation, and many are also relatively insoluble in both water and oils. Their unique properties have led to their widespread use as water, grease, and stain-repellent finishes for textiles and papers, specialized industrial solvents and surfactants, ingredients in cosmetics, plastics, and fire-fighting foams, and ingredients in lubricants for high-temperature applications [65].

The PFCs manufactured over the past 60 years fall into four broad categories:

1. Perfluoroalkyl sulfonates (PFASs) (the best-known is PFOS)
2. Perfluorinated carboxylic acids (PFCAs) (the best-known is PFOA)
3. Fluoropolymers (the best known is polytetrafluoroethylene (PTFE), marketed as Teflon and widely used in clothing, being the basis of waterproof fabric and for non-stick cookware)
4. Fluorotelomer alcohols (FTOHs)

PFOS and other PFCs have been found in blood and breast milk from people living in many countries around the world, even in remote areas such as the Canadian Arctic. In the US, average concentrations of PFOS, PFOA and perfluorohexansulfonate ($PFH_xS$) in blood samples have fallen in recent years, perhaps because of the discontinuation of industrial production of PFOS and related chemicals in the US in 2002. Conversely, in Shenyang, China, levels of PFOS and PFOA in human blood increased between 1987 and 2002. It has been suggested that sea fish and other seafood may account for the majority of human exposure in China. Studies of laboratory animals indicate that PFCs can cause adverse impacts during both development and adulthood. PFOS and PFOA have both been reported to have adverse effects on the liver in rodents and monkeys [54]. PFCs have also been shown to act as hormone disruptors in humans as well as other animals [49]. High combined levels of PFOA and PFOS in the blood of men in Denmark were found to be associated with a reduced count of normal sperm [50].

However, the durability of this group of chemicals also leads to potentially devastating consequences for the environment, as it means that they persist for long periods in nature once they are released, whether as a result of manufacturing or disposal operations or during the lifetime of a product. PFOS, for example, is a compound so resistant to degradation that it is expected to persist for very long periods in the environment [51].

PFASs (especially PFOS) and PFCAs (especially PFOA) have been reported as contaminants in almost all environmental media, including freshwater, groundwater and seawater sediments, and soils [37].

There have been indications that PFOA has caused developmental toxicity and other unwelcome effects in laboratory animals. The EPA has issued a preliminary risk assessment of PFOA and requested scientific data and assessment concerning the risks for this chemical. On 30 December 2009, the EPA posted four action plans, including an action plan on long-chain PFCs (LPFCs). Further, the EPA has taken action to understand better the sources and exposures which have led to the presence of PFOA in humans and has established its 2110/15 PFOA Stewardship Program under which eight large companies are committed to reduce emissions and product content by 95 % before 2010 and eliminate PFOA emission by 2015 [27].

## *5.7 Short-Chain Chlorinated Paraffins*

Chlorinated paraffins (CPs) are a complex mixture of polychlorinated *n*-alkanes and were introduced in the 1930s. The chlorination degree of CPs can vary between 30 and 70 %. CPs are subdivided according to their carbon chain length into short-chain CPs (SCCPs, C10–C13), medium-chain CPs (MCCPs, C14–C17), and long-chain CPs (LCCPs, $C > 17$). Currently, more than 200 CP formulations are in use for a wide range of industrial applications, such as FRs and plasticizers, as additives in metal working fluids, in sealants, paints, and coatings, and as solvents. SCCPs are classified as persistent and their physical properties imply a high potential for bio-accumulation; furthermore, CPs are classified as toxic to aquatic organisms, and carcinogenic to rats and mice. SCCPs were categorized as possibly carcinogenic to humans by the International Agency for Research on Cancer (IARC); their use has been restricted in the EU since 2004 [37]. A global ban on SCCPs is being considered under the Stockholm Convention POPs convention [85].

### *5.8 Phenol Derivatives*

NPs and octylphenols (OPs) and their ethoxylates, particularly nonylphenol ethoxylates (NPEOs), have been widely used in the textile industry in cleaning and dyeing processes. Alkylphenol ethoxylates (APEOs) and especially NPEOs are, however, considered to be very toxic to aquatic life. APEOs are themselves believed to be endocrine disruptors and to cause feminization of male fish. More importantly, however, they produce metabolites which are believed to be many times more potent endocrine disruptors than the parent compounds. The most potent of these are octylphenol and nonylphenol. Nonylphenol is listed as a priority hazardous substance under the OSPAR convention. The sale of products containing more than 0.1 % of nonylphenols or NPEOs has been severely restricted in the EU since 2005 [39].

Chlorophenols are used as biocides in the textile industry. Pentachlorophenol (PCP) in particular is highly toxic to aquatic organisms and can damage human organs and the CNS. The production and use of PCP has been banned in the EU since 1991 [37].

### *5.9 Phthalates*

Phthalates are a group of chemicals (plasticizers) used in textile coating and printing processes, in the manufacture of artificial leather and rubber, and in some dyes, but most commonly they are used to soften PVC. There are substantial concerns about the toxicity of phthalates such as bis(2-ethylhexyl) phthalate (DEHP), which is reprotoxic (i.e., it has a negative influence on contact on the viability and function of human gametes and embryos by reducing the fertilization rate and impairing embryo development in mammals). The phthalates DEHP and dibutyl phthalate (DBP) are classed as 'toxic to reproduction' in Europe and their use is restricted. Under REACH legislation all applications of benzyl butyl phthalate (BBP) and DEHP are banned from 1 August 2014 and those of DBP from 1 February 2015. The list of banned and restricted substances, substances with reporting requirements, and those under observation has been produced by Ericsson [28].

### 5.10 Organotin Compounds

One of the best-known organotin compounds is tributyltin (TBT). TBT compounds are a group of compounds containing the $(C_4H_9)_3Sn$ moiety, such as tributyltin hydride or TBTO; they are considered toxic chemicals which have negative effects on humans and the environment. One of the main uses of organotin compounds was in antifouling paints for ships, until evidence emerged that they leach into the aquatic environment, causing irreversible damage to aquatic life, they persist in the environment, build up in the body, can affect the immune and reproductive systems, and trigger genes which cause the growth of fat cells [79]. Use of organotin compounds in antifouling marine paints is now largely banned. TBT has also been applied to textiles. Organotin compounds are used in biocides and as antifungal agents in a range of consumer products such as socks, shoes, and sport clothes to prevent odor caused by the breakdown of sweat. TBT is listed as a 'priority hazardous substance' under EU regulations requiring measures to be taken to eliminate its pollution of surface waters in Europe; products (including consumer products) containing more than 0.1 % of certain types of organotin compounds are banned across the EU [32].

### 5.11 List of Restricted Substances

Sustainable textiles should be environmentally friendly and should satisfy the rational conditions to respect social and environmental quality by pollution prevention or through installing pollution-control technologies. Certification, however, is a voluntary process. Any entity conducting a business for which a standard exists may be asked to have its output or services certified. Certification is a procedure through which a third party, the certification body, gives a written assurance that an organizational system, process, person, product, or service complies with requirements specified in a standard or benchmark. Certification is awarded for a limited period, during which the certification body carries out monitoring. Third-party certification bodies and governments have issued the Restricted Substances List (RSL) linking production ecology to human ecology [9, 19, 63].

Lists of restricted substances (RSL) are constantly changing as more information from scientists and health professionals becomes available, leading to an enhanced understanding of chemicals and their effect on human health and the environment. The inclusion of substances listed in the RSL is based in large part on global legislation regulating chemical usage in the manufacturing of apparel products. The EU has developed REACH, which is aimed at ensuring a high level of protection of human health and the environment from the risks which can be posed by chemicals [75]. Other countries that have developed or are developing similar lists of restricted substances are China, Canada, and South Korea. In the United States, several states, including California, Washington, and Maine, have adopted laws regulating chemicals in consumer products. These regulatory requirements are incorporated into the RSL.

The RSL released by the American Apparel and Footwear Association includes only those materials, chemicals, and substances restricted or banned in finished home textile, apparel, and footwear products because of a regulation or law. The list includes the names of selected arylamines, certain disperse dyes, solvents, pesticides, asbestos, certain fluorinated compounds, GHGs, dioxins and furans, FRs, metals, organotin compounds, phthalates, and miscellaneous other chemicals [1].

The various approaches being undertaken by the industry include avoiding the use of hazardous chemicals, reducing the extent of use of such chemicals, or totally substituting the process by using safe chemicals [87]. Because of driving factors such as the increased demand for eco-friendly processing and intensified control on polluting technologies, the use of biotechnology is increasing day by day. Various enzymes are being used to substitute a number of hazardous chemicals in the textile industry [92], giving a global enzyme market for textiles of approximately $US178 million.

## 6 Eco-Friendly Substitutes

The characteristics of green chemicals are as follows [58]:

- Prepared from renewable or readily-available resources by environmentally-friendly processes
- Low tendency to undergo sudden, violent, unpredictable reactions such as explosions
- Non-flammable or poorly flammable
- Low toxicity and absence of toxic constituents, particularly heavy metals
- Biodegradable
- Low tendency to undergo bio-accumulation in food chains in the environment.

Some of the harmful textile chemicals and their eco-friendly substitutes are given in Table 5 [76].

## 7 Cleaner Production

As part of the cleaner production approach, a textile processor has to be lean, efficient, and innovative [56], which can be achieved by the following ways:

- Lean: good housekeeping, conservation and control
- Efficient: ‘right-first-time’ (RFT) approach, chemical/water/energy/machine audits, optimization/rationalization
- Innovative: reuse, recovery and recycle initiatives for process change

**Table 5** Some harmful textile chemicals and their eco-friendly substitutes

| Existing chemicals | Uses | Proposed substitutes |
|---|---|---|
| Polyvinyl alcohol (PVA) | Yarn size | Potato starch or carboxymethylcellulose (CMC) |
| Pentachlorophenol, formaldehyde | Size preservative | Sodium silicofluoride |
| Carbon tetrachloride (CTC) | Stain removers | Detergent stain removers |
| | | Detergent (non-ionic, ethoxylates) and water-miscible solvent (glycol ethers) mixtures |
| | | Enzymatic stain-removers |
| Calcium and sodium hypochlorite | Bleaching | Hydrogen peroxide, Ozone dissolved in cold water |
| Sodium silicate, phosphorus-based compounds | Peroxide stabilizer | Nitrogenous stabilizers |
| Nonylphenyl ethylene oxide adducts (APEO) | Detergent, emulsifier | Fatty alcohol ethylene oxide adducts, alkylpolyglycosides |
| Synthetic non-biodegradable surfactants | Various purposes | Sustainable and highly biodegradable surfactants from dextrins |
| Synthetic non-biodegradable surfactants + solvent | Coatings and degreasing | 'Solvosurfactants' acting as both solvent and surfactant, derived from glycerol (bio-diesel) |
| Dichlorobenzene and trichlorobenzene | Carriers in dyeing | Butyl benzoate, benzoic acid |
| Kerosene | Pigment printing | Water-based thickeners |
| Formaldehyde | Finishing, dye fixing | Polycarboxylic acid, non-formaldehyde products |
| Sodium dichromate | Oxidation in dyeing | Hydrogen peroxide |
| Silicones and amino-silicones + APEO emulsifier | Softener | Eco-friendly softeners, wax emulsions |
| Functional synthetic finish | Finishing | Beeswax, aloe vera, and vitamin A |

Some important areas where chemical recovery and reuse has proved most effective are:

- Reuse of dye solutions from the dye-bath.
- Recovery of sodium hydroxide in mercerizing (by effective evaporation or using membrane technology).
- Recovery of size in cotton processing (using technologies such as UF).
- Recovery of grease in raw-wool fiber scouring (by acid cracking, centrifuging, or by solvent extraction).
- Recovery and recycling of PVA size from desize effluent streams.

Recovery of PVA size by UF is more than 35 years old, but is still not widely used in the global textile industry because of certain disadvantages, including high energy costs for pumping and high membrane cleaning/replacement costs. Environmentally-friendly and economical technology for PVA size recovery and recycling is still needed to reduce energy and water consumption. One example which may prove useful is VFE, which overcomes most of the disadvantages of the current UF process. In this system water is evaporated under vacuum at low temperature, leaving extracted cotton impurities from the previous desizing process, non-evaporated water and PVA in the concentrate [43].

Many textile companies invest in—or plan to invest heavily in—effluent treatment, in many cases not knowing that the pollution load may be reduced by 30–50 % by applying the techniques of pollution prevention given in Table 6.

The general approaches to textile waste reduction in textile wet processing are as follows.

**Preparation Stage**

- Recovery systems
- Waste steam reuse
- Chemical substitutions
- Alternative processing

**Dyeing**

- Reconstitution/reuse of dye-bath
- Chemical substitution
- Alternative processes

**Finishing**

- Reuse
- Substitution
- Alternative processes

**General**

- Waste characterization
- Raw materials
- The fate of processing chemicals
- Equalization

**Table 6** Techniques of pollution prevention in textile processing

| Object | Implementation techniques |
|---|---|
| Reduction of wastewater volume | Good housekeeping |
| | Counter-flow processing |
| | Reuse of process water |
| | Automation of the machinery |
| Reduction of the amount of dyes and chemicals consumption | Good housekeeping |
| | Process optimization by careful selection of dyestuffs, auxiliaries and process conditions |
| | Recovery and reuse of process chemicals |
| | Automation of the machinery |
| | Computerized recipe optimization |

**Table 7** Ten best practices suggested by US Natural Resources Defense Council (NRDC)

| Sr. no. | Best available techniques |
|---|---|
| 1 | Carry out leak detection, preventive maintenance, improved regular cleaning |
| 2 | Reuse cooling water from (1) singeing, (2) air compressor system, and (3) preshrinking |
| 3 | Reuse condensate |
| 4 | Reuse process water from (1) bleaching, and (2) mercerizing |
| 5 | Recover heat from hot rinse water |
| 6 | Use pre-screened coal |
| 7 | Maintain steam traps |
| 8 | Insulate pipes, valves, and flanges |
| 9 | Recover heat from smokestacks |
| 10 | Optimize compressed air system |

The Natural Resources Defense Council (NRDC) summarizes the ten best practices that save water, energy, fuel, and electricity with little upfront investment and no risk to product delivery times, price or quality, as given in Table 7 [40].

## 8 LCA of Textile Products

The overall impact on the environment by a product, process, or service may be best assessed by LCA, eco-balance, or cradle-to-grave analysis. LCA involves a systematic scientific approach to examine the environmental impacts of the entire life cycle of a product or service. It is not simply the quality of the product, nor the amount of waste ending up in a landfill or an incinerator, but the life cycle of the product determines its environmental impact.

LCA is a technique to assess environmental impacts associated with all the stages in the life cycle of a product, from raw material extraction, through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling [22]. LCA is also a way of measuring whether green improvements have been made or not. LCA is used for much more than just waste minimization; it is also used for estimating $CO_2$ and GHG emissions and, perhaps most commonly, as a way to investigate the flow of energy and water in a process [52]. The immediate precursors of LCAs were the global modelling studies and energy audits of the late 1960s and early 1970s. These measures attempted to assess the resource cost and environmental implications of different patterns of human behavior. As an environmental assessment tool which accounts for the use and emission of various raw materials at all stages in the product chain, from raw material extraction, through production, use, and final disposal, LCA is used to give a better assessment of environmental impact by identifying total energy use, material inputs, and waste generated from the point that the raw materials are obtained to final disposal of the product [102]. LCA is a method in which the energy and raw material consumption, different types of emissions, and other important factors related to a specific product's environmental impact are measured, analyzed, and aggregated for the entire life cycle of the product, attempting to include all impacts from raw material to disposal ('cradle-to-grave') or at least from raw material to the point of sale ('cradle-to-gate'), since, in many cases, the individual consumers are either not known or not traceable. Cradle-to-gate is an assessment of a partial product life cycle from resource extraction (cradle) to the factory gate (i.e., before it is transferred to the consumer). The use phase and disposal phase of the product are omitted in this case. Cradle-to-gate assessments sometimes form the basis for the environmental product declarations (EPDs) termed business-to-business EDPs. LCAs are considered to be the most comprehensive approach to assessing environmental impact.

On behalf of the Dutch Ministries of the Environment and Economic Affairs, the Leiden Centre for Environmental Sciences has drafted a manual for the execution of an environment-oriented LCA [41]. This manual contains guidelines regarding the contents of an LCA and presents arithmetic methods for the quantification of environmental impact categories, and has, in the main, been used in the formulation of international guidelines regarding LCA (ISO 14040–14043, Environmental Management—LCA) as drafted by the International Organization for Standardization. Subsequently, an LCA study was conducted for four representative mattresses, namely polyether foam, latex foam, spring interior, and a 'Scandinavian mattress', the aim being to give an overview of all environmental aspects related to the life cycle of mattresses and to identify the most important processes and emissions from an environmental point of view (the key issues) [17].

A retailer in The Netherlands, interested in developing an environmentally-friendly range of shirts, undertook an LCA project for a man's shirt [98], focusing on which phase in a shirt's life cycle produced the most pollution and whether natural or synthetic fibers were environmentally preferable.

The environmental impacts of the shirts were assessed over four phases in the life cycle:

1. Production (cotton growing, spinning and weaving, dyeing and finishing)
2. Transportation
3. Use (washing, drying, and ironing)
4. Disposal (reuse, recycling, composting, and incinerating)

The results showed that most of the environmental impact occurs during transportation to the retail outlet and during the use phase. In the use phase, for example, washing the shirts at 60 °C used twice the amount of energy over the life cycle as did washing at 40 °C. Synthetic or mixed textile fibers are environmentally preferable because they retain less moisture and are therefore easier to dry and require little, if any, pressing, which further reduces energy consumption. The economic benefits from following the preferred composition and care regime environmentally were a 10 % reduction in energy use for washing, drying and pressing in total and over 20 % reduction in detergent use.

A simplified LCA model for textile companies may be designed based on the energy and chemicals used, excluding transport [11]. At first the fiber type is selected. If more than one fiber is used in a product, the model has to be run separately for each fiber and a final calculation made, considering their relative amounts. Various unit operations such as spinning, texturing, weaving/knitting, chemical processing processes (preparation, dyeing, printing, finishing), item-making (furnishing garment), separate cleaning step (if any), and waste management for the particular product are identified. The practitioners choose a fiber type, and for each unit operation insert their own or default values for type and amount of energy, chemical or detergent and incineration use, data for the yield of the fiber/fabric, and costs.

Default values and a description of from where the data were obtained and for what conditions they are valid are found in the database; for the different unit operations the following elementary and money flow data are available:

1. Resource use of crude oil, coal, natural gas, water, fossil fuel, water, arable land, forest land, and other land
2. Air emissions of $CO_2$, $CH_4$, $SO_x$, $NO_x$, $NH_3$, VOC, and particulate matter with aerodynamic diameters less than 10 μm
3. Water discharges with BOD, COD, total phosphorus, and total nitrogen (sulfates are not mentioned in the model)
4. Cost

The model may include aggregation of inventory data, characterization of global warming, acidification, eutrophication and photo-oxidant creation potential, and interpretation of the eco-efficiency (the relation between environmental impact and the benefit). It may be important to include transport in the model if, for instance, garments transported in a non-efficient way are being assessed. Packaging material may be of importance for products where significant amounts of packaging are used. When more is known about how to assess chemical discharges

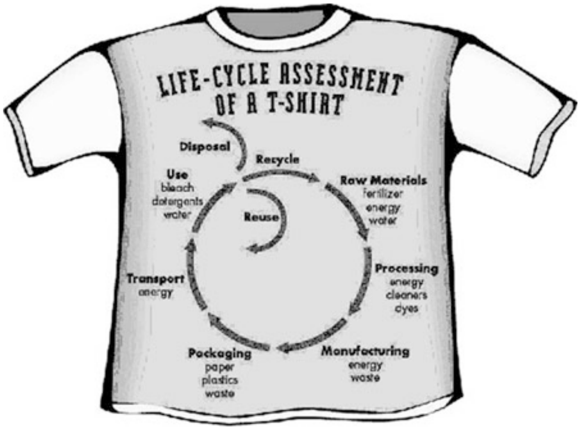


**Fig. 3** LCA of cotton T-shirt [14, 76]

to bodies of water, it may be important to include wastewater treatment plants in the model. The model could also be supplemented with data for chemicals which affect the environment negatively [11].

Figure 3 shows the life cycle of a cotton T-shirt. Products can be evaluated through each stage of their life cycles [14, 76], namely:

- Extraction or acquisition of raw materials (mainly cotton fibers)
- Manufacturing and processing (making of yarn, fabric, preparation, and dyeing)
- Packaging (paper, plastic, etc.)
- Transportation and distribution of products
- Use and reuse
- Recycling
- Disposal

For each stage, inputs of materials are identified and energy required is assessed; outputs of useful products and waste emissions are measured. Optimal points for improvement are identified and eco-efficiency is estimated.

## 9 Location-Specific LCA

Julia Steinberger and others [84] describe the challenges of applying LCA to a global production–consumption chain for textiles, accounting for specificities of the production of cotton in India and polyester in China, with consumption in Germany. Such location-specific LCA is promising for understanding the environmental costs and benefits of globalized production–consumption chains. The functional unit was considered to be 100 days of a single garment being worn. This corresponds to wearing a single garment 2 days a week for 6 months in each of 2 years, and is understood to be a reasonable lifetime for a garment. The use phase of a cotton T-shirt and polyester jacket differs considerably—the cotton T-shirt was washed much more often (after every 2 weeks or 50 times, in this study), whereas the polyester jacket was only washed 2 or 3 times a season (6 times in total in this study). Dryers were used at roughly 75 % of the frequency of the washing machines.

Because Germany, India, and China all have predominantly coal-fired power stations, the $CO_2$ emissions track the electricity consumption along the textile chains. Despite the fact that the functional units of a cotton T-shirt and a polyester jacket are different, the contrast between the emission fractions in the producing and the consuming countries is noteworthy and striking. The $CO_2$ emissions for a cotton T-shirt and polyester jacket washed and dried with C-rated (i.e., inefficient) appliances show the opposite behavior in the geographic distribution of emissions: the frequent washing and drying in the consuming country of a cotton T-shirt is responsible for over 60 % of the total lifetime emissions, whereas, because the polyester jacket is washed less often, the consuming country emissions account for less than 20 % of the total. By examining various practical scenarios, it was concluded that the most important factors in reducing use phase emissions are:

1. Substituting air drying for machine drying
2. Decreasing the temperature of washing
3. The appliance efficiency rating

By switching to air drying and reducing the washing temperature from 60 to 40 °C, the total $CO_2$ emissions are almost halved. This highlights the importance of developing laundry detergents which are effective at lower temperatures. Another consideration is the necessity of frequent washings. If a garment requires less washing (e.g., through resistance to stains or sweat), the impact on the environment during use will be correspondingly low. Emissions of $SO_2$ exhibit very different behavior, reflecting not only the coal-based source of the country's power sector, but also the existence (or not) of emissions-control technology. The lack of effective emissions abatement in China and India causes the production phase to be responsible for over 70 % of the sulfur dioxide emissions for both cotton and polyester garments.

Tobler-Rohr [94] described eight cases of LCA, namely cotton growing, spinning and weaving of cotton fabrics, mixed fabrics, finishing in two companies, finishing of two fabrics in the same company, laundry industry, production and recycling of a polyester product, and Nylon 6.

Some of the observations are discussed below.

## *9.1 Cotton Growing*

In cotton growing, the lower the yield, the higher the environmental impacts. The impacts are focused on ecotoxicity, because no other impact category indicates a significant impact. In the case of cultivation of organic cotton, the impact categories of ecotoxicity and summer smog are mainly affected, followed by the GHG effects mainly caused by the manure applied and the gas used as the energy source [94].

### 9.2 Spinning and Weaving

Before spinning and weaving can be carried out, cotton fibers are often transported over long distances to the mill because of the geographically limited growing area. The highest impacts are therefore caused by overseas transportation and spinning and weaving processes (wherein impact caused by air conditioning is considerable). The fiber production process (cotton, polyester, or both) influences the environment more strongly than the fabric production method; the main impact categories in the production of open-end-spun (OE-spun) cotton yarns for denim fabrics are acidification and heavy metal contamination followed by winter smog (probably because of the chemicals used in fiber production/cultivation). A comparison of jeans fabrics produced with different spinning and knitting technologies shows that the highest impact on environment was with ring-spun jeans followed by OE-spun jeans; the lowest impact was with knitted shirts, even with equal weight as jeans. In fact, knitting technology has less impact on the environment than modern air jet weaving technology [94]. However, advanced four-phase weaving was even more eco-friendly than conventional knitting because of its higher productivity. Fiber production influences the environment more strongly than the production processes. The environmental impact is greater in cotton growing than in polyester production. Hence, when fiber production is integrated with spinning and weaving, the impact is more with cotton than with polyester [94].

### 9.3 Chemical Processing

Bleaching, mercerizing, dyeing, and printing of knitted cotton fabric were carried out on a cold pad–batch system with cold dye fixation, an energy-saving technology which requires careful process control to avoid dimensional changes. The rotary-screen printing process caused by far the largest impact, where eutrophication, acidification, human toxicity, energy, and greenhouse effect were mainly affected. Mercerization had a much lower impact than rotary screen printing, followed by the dyeing process. The dyeing process included a variety of chemical recipes and minor differences in eutrophication occurred between different classes of dyestuffs. Additional rinsing and drying processes required more energy. The spinning and knitting process of polyester causes lower impacts than with cotton and other cellulosic fibers. There is little pre-treatment and finishing applied, but energy consumption is higher in wet processing because of the high-temperature dyeing of polyester.

### 9.4 Laundry Processes

Professional drying processes are carried out with tumble-drying, mangling, and tunnel finishing, whereas in private homes, drying processes rely on tumble-drying and ironing. Professional laundries gained a better ranking for the same unit weight of laundered goods. It was observed that the washing machinery for a professional laundry operation is optimized only in terms of water consumption, but not in terms of energy consumption, a trend which must have changed since the time of study (i.e., since the end of the 1990s) [94].

### 9.5 Polyester Recycling

A comparison of the product life cycle from raw material to the point of sale was made with four different options:

- Recycling (by melt spinning)
- Reuse (by injection molding)
- Household waste treatment (with heat recovery)
- Incineration with landfill

Recycling, reuse, and incineration all gave a 30 % better ranking.

The results from the individual process LCA have only limited importance for the whole life cycle of textiles in general, because there are many diverging parameters, particularly with respect to quality aspects; moreover, the same fabric quality produced via different processes on different equipment or with different recipes will result in different impacts.

## 10 Conclusions

Industrial pollution can have devastating impacts on river systems and lakes which are vital to wildlife and to the lives of billions of people. Toxic substances dumped by industry have a wide range of harmful properties—such as causing cancer, affecting the hormone system, and interfering with reproductive systems. These effects can apply not just to humans but to all living creatures. There is evidence that the textile industry is responsible for a large proportion of the water pollution problem, with its use and discharge of hazardous chemicals contributing to the chemical load in the river systems.

The presence of hazardous substances in the environment shows that the traditional approach to industrial discharges is not working—wastewater treatment plants are unable to cope with many hazardous substances. The consequences for ecosystems and human health are severe, and the clean-up of hazardous substances is a difficult and costly process. What is needed is a new approach to hazardous chemicals—one addressing the problem at source rather than retrospectively. The idea of eliminating all discharges of hazardous chemicals into the aquatic environment—'zero discharge'—is based on the understanding that it is impossible to define safe levels for many hazardous pollutants. Redesign of products and processes to phase out the use and discharge of hazardous chemicals has proven to be the best approach [37]. LCA should be done on a regular basis, especially for new products and processes, to keep track of their impact on the environment. Accordingly, steps need to be taken to reduce pollution load and make textile products and processes greener.

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# Environmentally Sustainable Clothing Consumption: Knowledge, Attitudes, and Behavior

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**Abstract** The purpose of this chapter is to overview the current body of knowledge related to environmentally sustainable clothing consumption. The chapter discusses consumers' knowledge of and attitudes towards environmental issues related to the production, consumption, and distribution of clothing. Additionally, the chapter examines current consumer engagement levels in environmentally sustainable clothing consumption and analyzes the relationships between knowledge, attitudes, and clothing consumer behavior. Finally, the chapter concludes with a consideration of consumers' perceived barriers to environmentally sustainable clothing consumption.

**Keywords** Environmentally sustainable clothing · Consumption · Attitudes · Knowledge

## 1 Introduction

As humans consume goods and services, we also contribute towards environmental change and degradation. Consumption not only depletes the Earth of both renewable and nonrenewable resources, but also creates unmanageable quantities of solid waste and emits dangerous substances into the air, water, and land. As stated by Winter [62], "Unsustainable human behaviors destroy water, land, forests and energy reserves throughout the world. Similar pictures of ecological decline could be drawn for air pollution, mineral depletion, and loss of biodiversity."

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Our current patterns of consumption are unsustainable. The *Living Planet Report* [63] is a biannual ecological footprint assessment report of the area of biologically productive land required to meet human consumption demands. The 2012 report assessed humans to be overshooting Earth's biocapacity by approximately 50 %, providing evidence that humans are consuming beyond Earth's carrying capacity and are contributing towards environmental vulnerability. Therefore, consumption of both goods and services, including textiles and clothing, is an environmentally significant human behavior which needs to be addressed as an immediate environmental research priority.

The purpose of this chapter is to overview the current body of knowledge relating to environmentally sustainable clothing consumption. The chapter discusses consumers' knowledge of and attitudes towards environmental issues related to the production, consumption, and distribution of clothing products. Additionally, the chapter examines current consumer engagement levels in environmentally sustainable clothing consumption and analyzes the relationships between consumer knowledge, attitudes, and clothing consumption behavior. Finally, the chapter concludes by considering consumers' perceived barriers to environmentally sustainable clothing consumption.

## 2 Clothing Consumption and Environmental Change

Because consumption transforms both matter and energy, it is environmentally important. Environmental change associated with consumption of goods and services, including clothing and textiles, is the result of two primary factors. The first is the pollution and waste generated through consumption and the second the amount of natural resources expended through consumption.

Both the manufacturing processes involved in the production of goods and the actual consumption of goods generate pollutants. For example, the manufacturing requirements for a typical cotton T-shirt results in the production and release of harmful pollutants such as pesticides, heavy metals, and other harmful chemicals to air, water, and soil. While humans have devised numerous methods for capturing some of these pollutants, there is still a significant portion released into the natural environment. The discharge of harmful chemicals and other pollutants into the atmosphere, water systems, and soil subsequently alters biological, chemical, and physical processes. While Earth's natural systems are able to absorb pollutants and maintain equilibrium to a certain degree, human behavior releases pollutants into the natural environment at a rate and degree to which natural systems cannot always self-regulate effectively. Therefore, in many instances, the net result of the release of environmental pollutants and alterations to these systems is increased vulnerability of Earth's natural ecosystems [10].

Consumption also creates solid waste through waste raw materials, disposable packaging, and the actual discarded products. While approximately 35 % of all municipal solid waste is recycled or composted [23], the majority is either incinerated or sent to landfills. On a yearly basis the United States creates approximately 7.6 billion tons of industrial waste and 250 million tons of municipal waste—which, after recycling approximately 1.53 pounds of waste per person, equals close to 4.4 pounds of waste per person per day [23]. The environmental concerns related to solid waste are multifaceted and include issues such as degradation of land, leaching of toxins into water systems, and release of methane gases and other emissions into soil and the atmosphere [10].

The second major way the consumption of goods contributes towards global environmental change is through the depletion of finite natural resources. Within mainstream modes of production and consumption it is difficult to produce and consume products without expending both renewable and nonrenewable resources. Production requires natural resources such as fossil fuels (coal, oil, and natural gas) as energy inputs for operating manufacturing processes and as raw materials for manufacturing the actual products (for example, a vast majority of plastic is synthetically derived from petrochemicals). Additionally, in most instances, the consumption of the products requires further inputs of natural resources. For example, washing and drying clothing requires inputs such as water, fuel, and chemical detergents. Unfortunately, the consumption of both nonrenewable and renewable resources significantly contributes to both localized and global environmental change [10].

It is evident that, because of the waste and pollution generated and the natural resources depleted, production and consumption of goods is a significant anthropogenic cause of environmental change. As stated in Stern et al. [57]:

> Consumption consists of human and human induced transformations of materials and energy. Consumption is environmentally important to the extent that it makes materials or energy less available for future use, moves a biological system toward a different state, or through its effects of those systems, threatens human health, welfare, or other things people value.

Clothing consumption refers to an individual's clothing acquisition decisions and the use of clothing by the individual. It encompasses acquisition, storing, using, maintaining, and discarding of clothing products [61]. When considering consumer behavior that degrades the natural environment, it is common to focus on obvious culprits such as the dependence on products which consume petroleum or the high reliance on disposable, single use products. However, most individuals do not consider the associated environmental impacts of their clothing purchases and other consumption behavior. Throughout the product life cycle of clothing, practically everything from the manufacturing of fibers to the disposal of garments contributes towards the degradation of ecosystem health. Consequently, clothing consumption, in the aggregate, is a contributory cause of environmental change and the environmentally unsustainable consumption of textile and clothing products is an increasingly important phenomenon.

As long as the unsustainable consumption of clothing products persists, environmental degradation will continue as well. Environmental integrity and overall sustainability not only require efforts by textile and clothing firms to produce more sustainable products, but also necessitate the modification of clothing consumption behavior of individuals so that they become more environmentally responsible and benign.

In a National Academies report, Brewer and Stern [7] identified attaining an improved and more thorough understanding of environmentally significant individual behavior to be one of the most important current research priorities:

> Because the activities of individuals and households have major environmental consequences in the aggregate, considerable environment improvement can in principle result from change in their behavior. However, fundamental understanding is only beginning to develop regarding how various influences interact to shape and alter that behavior.

In order to expand the understanding of environmentally significant individual behavior, Brewer and Stern [7] encourage a focus on increasing fundamental knowledge of consumer choice and how factors such as information, incentives, and constraints combine and interact with personal values, attitudes, and beliefs to inform and shape the consumer decision-making process. This type of knowledge and understanding is essential for policy and other decision makers who are working to modify environmentally significant consumer behavior.

## 3 Variables Influencing Sustainable Clothing Consumption

Clothing consumer behavior is complicated; many different factors, both internal and external with respect to the consumer, influence this behavior. Key to understanding clothing consumer behavior and thus being capable of promoting behavioral modifications is a better understanding of how and why consumers engage in particular behavior. A variety of variables influence sustainable consumer behavior. Stern [56] categorizes these relevant variables into four major types: personal capabilities, attitudinal factors, contextual forces, and habit or routine. For example, because all individuals have different skill sets, knowledge, and capacities, personal capabilities are a major variable influencing consumer decisions and behavior. Another variable, attitudinal factors include an individual's values, beliefs, and attitudes. In the most recent research on consumers' environmentally sustainable clothing behavior, the emphasis has been on the knowledge and attitudinal variables in encouraging the consumption of environmentally sustainable clothing. Therefore, because of the scholarly emphasis on these variables, this chapter also focuses on the variables of knowledge and attitudes.

## 4 Knowledge and Environmentally Sustainable Consumer Behavior

Research investigating environmentally significant human behavior commonly considers the role played by personal capability variables, including knowledge of general and behavior-specific environmental issues [56]. Knowledge is a variable which can strongly influence many aspects of consumer behavior [51]. Environmental knowledge defined by Arcury and Johnson [2] is the “factual information that individuals have about the environment, the ecology of the planet, and the influence of human actions on the environment.” As evidenced in previous research, environmental knowledge is an important predictor of environmentally sustainable behavior [1, 30, 49, 50, 58].

A prevailing perception is that a lack of sufficient knowledge about environmental issues is one of the reasons why consumers make decisions leading to behavior which is not ecologically conscious. According to Thøgersen [59] there are a number of reasons why limited knowledge may act as a constraint. First, consumers may be unaware that particular behavior is even associated with negative environmental impacts. Second, while consumers might be aware of the environmental impact associated with different behavior, they may be uncertain of the exact nature of the impact and thereby not understand the nature of the necessary behavior change. Further, while some consumers may be aware that a particular behavior is negative for the environment, they may not know how to change their behavior in order to be more environmentally sustainable.

There is considerable evidence that ecologically conscious consumers have more knowledge about environmental issues when compared to other consumers. For example, Thøgersen [59] examined how a lack of environmental knowledge may prevent formation of environmental attitudes and engagement in environmentally preferable behavior. Thøgersen concluded that knowledge is one important reason why consumers make unsustainable choices and that the more knowledge a consumer has about an environmental issue, the more likely the individual is to engage in environmentally preferable behavior. A study by Antil [1] presented similar relationships, as did Henion [30], who concluded that, when consumers are informed about the environmental consequences of high phosphate content detergents, they are more likely to purchase environmentally safe detergents than consumers who are not provided with the information. In their study, Granzin and Olsen [28] found that knowledge about environmental protection was a significant predictor of environmental behavior such as walking for conservation purposes or recycling household waste.

Borden and Schettino [5] tested the relationships between environmental concern, environmental knowledge, and environmentally consequential behavior. According to the authors, a high level of concern about the environment does not consistently translate into a person actively seeking out information related to the environment. The study also indicated that the reverse is true; as individuals increase their knowledge about environmental issues, they do not necessarily show increased concern for the environment. Additionally, in contrast to previously reviewed literature, the study found that increased knowledge about environmental conditions does not necessarily result in increased participation in proenvironmental behavior.

Stern [55] considered possible explanations as to why knowledge may not translate into behavior. He stated that providing consumers with information and increasing their understanding of the impact of environmentally significant behavior may sometimes encourage consumers to engage in behavior which is positive for the environment. However, the commitment to environmentally preferable behavior depends on the effectiveness of both the design and the delivery of relevant information to the consumer. Stern established that, when there are considerable external constraints on particular behavior, the relationship between knowledge and behavior is much less certain. For example, a consumer may know that buying organically-grown food is environmentally beneficial, and the individual may even know where to buy organic products, but the higher cost of the food acts as a constraint on behavior and, as a result, behavior modification does not occur.

## *4.1 Consumers' Knowledge of Environmental Issues Related to Clothing Consumption*

In recent years, the extent of consumers' knowledge of environmental issues involved in the production, distribution, and consumption of clothing has been a focus of research. What the predominance of this research has demonstrated is that consumer knowledge about environmental issues resulting from the production, distribution, and consumption of clothing and textiles is low. For example, one of the first known studies to investigate environmentally sustainable clothing consumption found that awareness of the environmental consequences associated with clothing and textile products is less than with other products such as gasoline and soft drink bottles [54].

In more recent years, studies assessing consumers' knowledge of environmental issues associated with clothing and textiles have primarily utilized the Environmental Apparel Knowledge Scale [38]. The scale includes statements regarding chemical pollutants produced in the manufacture and processing of fibers, the recyclability and biodegradability of goods, and federally mandated standards for clean air and water imposed on manufacturing firms. Studies employing the Environmental Apparel Knowledge Scale consistently report low levels of knowledge among consumers [38, 41, 43].

Additional studies validate the notion that consumers are generally uninformed about the environmental consequences of the clothing industry. A qualitative research study with self-identified environmentally conscious consumers also supports indications that knowledge about environmental issues in the clothing and textiles industry is low, even among individuals well informed about other environmental issues [11]. Finally, Hill and Lee [31] and Goworek et al. [27] also reported limited consumer understanding regarding how clothing production and consumption affect the environment.

As noted previously, the personal capability of knowledge of environmental issues in the clothing and textiles industry is theorized to be an important driver of consumer engagement in environmentally sustainable clothing consumption. Unfortunately, empirical research has also demonstrated that this knowledge is minimal among most consumers. As a result, it is plausible that knowledge is constraining environmentally sustainable behavior. For example, when consumers are unaware of the environmental effects associated with different fibers and are misinformed about fibers which are "good" or "bad" for the environment, they lack the information they need to compare the environmental footprints between different garments which impacts on their abilities to select those which are more environmentally preferable [11]. Therefore, initiatives to increase participation in environmentally sustainable clothing consumption may, at least in part, need to focus on consumer education.

## 5 Attitudes and Environmentally Sustainable Consumer Behavior

Attitudes, the positive or negative evaluations of the quality(ies) of a specific object or behavior [18, 45], are also significant drivers of human behavior. Two of the attitudes commonly included in studies on sustainable consumer behavior include perceived consumer effectiveness (PCE) and degree of environmental concern.

The degree to which consumers believe their behavior is effective at mitigating environmental impact and at affecting environmental problems, or their PCE, is one of the attitudinal factors differentiating between consumers' commitment to proenvironmental behavior [1, 39, 48, 60]. In a national survey of American adults, Roberts [48] found that PCE accounted for 33 % of the variation in sustainable consumer behavior. Earlier studies by Antil [1], Kinnear et al. [39], and Webster [60] produced similar results. Similarly, Balderjahn's [3] study determined that the more a consumer believes in the power of individual consumers to affect environmental issues, the more the consumer will engage in nonpolluting consumer behavior such as energy conservation and environmentally responsible purchasing and use of products. These research findings suggest that, when consumers are aware of environmental issues and believe that they, through their personal behavior, have the ability to contribute towards solving an environmental problem, they are much more likely to engage in environmentally positive behavior.

A consumer's level of environmental concern is also an important attitudinal variable which differentiates the extent of ecologically conscious behavior among consumers. The general conceptualization of environmental concern is the degree to which an individual is troubled about environmental vulnerability, the ecological repercussions of this vulnerability, and the inadequate nature of actions taken to ensure environmental protection [21]. Predictably, most studies find that consumers who are more likely to be concerned about environmental issues display higher levels of ecological consciousness within their consumer behavior [1, 4, 6, 25, 29, 46, 48, 52]. For example, in their study, Fraj and Martinez [25] found that consumers who are concerned about environmental issues such as pollution are "predisposed to act in an environmentally friendly manner." However, Schlegelmilch et al. [52] cautioned that the strength of the relationship between environmental concern and behavior depends on the actual behavior.

### *5.1 Consumer Attitudes and Sustainable Clothing Consumption*

One of the first studies to examine environmental issues in relation to clothing consumption was Stephens [54]. By focusing on clothing acquisition and discard behavior, Stephens sought to understand the attitudes related to environmentally sustainable clothing consumption. The major finding of the study was that consumers with an attitude of concern about the natural environment associated clothing consumption with increased environmental vulnerability.

Generally speaking, people are concerned about the state of the natural environment and believe it should be protected. National surveys in the United States support this notion, with 69 % of individuals having either a great deal or a fair amount of concern about the quality of the environment and 49 % of the population believing that the quality of the environment is getting worse [26]. Research examining various aspects of sustainable clothing consumption also supports the notion that a majority of consumers are concerned about the state of the natural environment [9, 35, 38, 41, 43]. For example, participants in a study by Butler and Francis [9] not only indicated a general concern about the environment but also believed it is the responsibility of governments, industries, and individuals to engage in behavior which protects and improves the natural environment. Hustvedt and Dickson [36] found a majority of respondents perceived organic agriculture as positive for the environment, and 80 % of participants in a study by Kozar and Connell [41] asserted that humans are severely abusing the natural environment.

In terms of consumer attitudes towards environmentally sustainable clothing consumption, through a nationally administered survey of American adult female consumers, Butler and Francis [9] examined factors influencing the purchasing of clothing and the relationships between general environmental attitudes, clothing related environmental attitudes, and environmentally sustainable clothing purchase behavior. Although consumers in the study held environmental attitudes which were at least somewhat proenvironment, they were more neutral in their attitudes about clothing and the environment. In another study, Hustvedt and Dickson [36] concluded that respondents seldom agreed they would buy organic clothing even if it was a burden—suggesting consumers are rather neutral in their attitudes towards sustainable clothing.

There is also evidence to suggest that consumers do not always hold very positive attitudes towards attributes and characteristics of environmentally sustainable clothing. For instance, as discussed in Connell [12], there is a perception among some consumers that environmentally sustainable clothing is less stylish compared to mainstream apparel. Further, many consumers perceive environmentally sustainable clothing as being very counter-culture in style, not well-fitting, and generally uncomfortable.

## 6 Consumers' Environmentally Sustainable Clothing-Consumption Behavior

Broadly speaking, behavior is concrete, intentional actions taken by individuals and groups often rooted in values and attitudes [45]. More specifically, consumer behavior is "the behavior that consumers display in searching for, purchasing, using, evaluating, and disposing of products and services which they expect to meet their needs" [51]. Environmentally sustainable clothing consumption includes clothing consumption behavior (acquisition, storing, using, maintaining, and discarding) which is environmentally preferable to mainstream clothing consumption behavior because the intent of engaging in the behavior is: (1) to create less pollution and waste and/or (2) to consume fewer natural resources [12].

The next section of the chapter discusses the current state of knowledge regarding consumer engagement in environmentally sustainable clothing consumption. Scholarship examining environmentally sustainable clothing consumption tends to focus on two aspects—acquisition and discarding behavior. Minimal research has investigated the other aspects of storing, use, and maintenance from a sustainability perspective.

### *6.1 Consumer Engagement in Environmentally Sustainable Clothing Acquisition Behavior*

Environmentally sustainable clothing acquisition behavior includes acquiring clothing designed with environmentally preferable attributes, including garments made from environmentally preferable fibers (such as organically-grown cotton, hemp, or recycled fibers) or clothing manufactured using environmentally preferable processes (such as closed loop manufacturing cycles or reduced utilization of toxic dyes and other harmful chemicals). Environmentally preferable clothing attributes may also relate to the design and construction of a garment. For example, clothing designed to be multifunctional, durable, and or classic in styling are all examples of environmentally preferable clothing attributes as they permit a consumer to reduce personal consumption and acquire fewer garments [12, 24].

Additionally, acquiring clothing through environmentally preferable sources such as second-hand sources, is another form of environmentally sustainable clothing acquisition. Second-hand sources include (but are not limited to) consignment or thrift stores, garage sales, family, or friends. Other environmentally sustainable sources for clothing acquisition include environmentally conscious companies and, in some instances, producers of homemade clothing [12].

Finally, limiting the quantity of clothing acquired is also a form of environmentally sustainable clothing acquisition. This might occur by purchasing clothing to meet needs and not wants, taking care of clothes so that they last longer, repairing or altering clothing, or reconstructing clothing to update the style of garments [12].

Some research indicates consumers are willing to pay more for environmentally sustainable clothing. For example, Ellis et al. [22] found consumers were willing to pay up to 25 % more for an organic cotton shirt compared to a shirt made from conventional cotton. Hustvedt and Bernard [34] also demonstrated consumers' willingness to pay premium prices for organic socks.

Yet, despite some participation in environmentally sustainable clothing consumption, overall consumer engagement in environmentally sustainable clothing acquisition behavior is low [9, 13, 14, 15, 27, 38, 43]. In one study, Butler and Francis [9] reported that 90 % of respondents never or only sometimes considered the environment when purchasing clothing. Among the participants in the Kozar and Connell [41] study, only 41 % of participants were willing to pay premium prices for eco-conscious garments and only one-third of the sample reported that a firm's environmental record influenced clothing-purchase decisions. Additionally, merely 12 % of participants in the Kozar and Connell study indicated that they had actively sought out or inquired about a firm's environmental policies or practices prior to making purchasing decisions. In another study, Connell and Kozar [14] reported approximately 70 % of participants had never considered the environmental impacts of garments when making clothing purchases and 50 % had never purchased clothing made from environmentally preferable fibers.

Despite the limited engagement among consumers in environmentally sustainable clothing consumption, there are select consumer segments engaged in sustainable clothing acquisition behavior. Hustvedt [33] examined environmental attitudes and clothing consumption behavior within the context of consumer preferences for cotton clothing in which a portion of organically-grown cotton fiber is blended with mainstream cotton fiber. Among her findings, Hustvedt determined that market segments using the attribute of organic content in their clothing acquisition decisions do exist. The author concluded that, while some consumers desire and are willing to pay price premiums for 100 % organically-grown cotton clothing, another segment of consumers acquire clothing where the organically-grown cotton is blended with mainstream cotton—resulting in lower prices compared to 100 % organically-grown cotton clothing.

In a qualitative study utilizing eco-conscious research participants, Connell [12] determined a variety of environmentally sustainable clothing acquisition behavior, including establishing acquisitions limits, acquiring clothing with environmentally preferable attributes, and acquiring clothing through environmentally preferable sources. In setting limits for their clothing purchases, the participants in Connell's study consistently questioned personal needs and focused on purchasing clothing only when there was a genuine need and extending the technical and aesthetic lifetimes of garments already owned. The participants also focused on purchasing clothing made from environmentally preferable fibers, clothing classic in styling, and clothing produced in an environmentally preferable manner. Finally, the participants reported that, for environmental reasons, they purchased clothing from second-hand sources and companies with reputations of being environmentally responsible.

## *6.2 Consumer Engagement in Environmentally Sustainable Clothing Discard Behavior*

In a 2014 report, the Council for Textile Recycling [16] indicated that approximately 15 % of post-consumer textile waste entering municipal solid waste streams is recovered by the textile recycling industry and reused or recycled. Within that 15 % of recycled post-consumer textile product waste, 35 % is resold as used clothing, 33 % is reprocessed into fibers, 25 % is used as rags or wipers, and 7 % is unusable and sent to landfill. Because of the low rate of post-consumer textile product recycling, the end-of-life fate for 85 % of clothing and textile products is a landfill. Annually, US consumers throw away 70 pounds of clothing and textile products [16]. Yet, through second-hand clothing stores and other avenues, it is possible to recycle clothing and keep it out of landfills. Consequently, the question remains as to why consumers are not engaging more consistently in sustainable behavior regarding the disposal of their garments.

Numerous studies have examined clothing discard behavior and consumers' levels of engagement in environmentally sustainable discard behavior. When consumers are done with a garment, Goworek et al. [27] and Daneshvary et al. [17] both found donating to charity shops, friends, and family a common practice for disposing of clothing. Koch and Domina [40] indicated, among their sample, passing clothing along to family and friends and utilizing the clothing for rags as the most common methods for clothing disposal. Donations to charitable organizations were another frequent action among the respondents.

However, despite some engagement in environmentally sustainable clothing disposition behavior, Goworek et al. [27] also found that, instead of donating or reusing items, consumers commonly threw away garments perceived to be inexpensive and poorly constructed. The authors determined that consumers commonly perceived low-priced garments as "throwaway clothes" and only occasionally repaired clothing for continued use. Furthermore, a study by Domina and Koch [19] indicated that, compared to younger adults, older adults were less likely to donate items to charities and were more likely to see clothing recycling as being time-consuming and, therefore, threw their used clothes away.

## 7 Relationships Between Consumers' Knowledge, Attitudes, and Behavior

Findings on the relationships between knowledge of clothing-related environmental issues, attitudes, and behavior are inconclusive. Some researchers have suggested a positive relationship between these variables [32, 36, 43, 44, 53, 54], while other studies report that, despite maintaining attitudes of environmental concern or being knowledgeable about environmental issues related to clothing, consumers are limited in their engagement of environmentally sustainable clothing consumption [8, 9, 15, 38, 41]. In other words, even when consumers are knowledgeable about and concerned with environmental issues associated with clothing production, distribution, and consumption, a significant positive relationship between knowledge, attitudes, and environmentally sustainable clothing consumption does not always exist.

Some research asserts that those who understand how clothing consumption affects the environment try to decrease clothing waste through behavior such as purchasing second-hand clothing, recycling clothing, and purchasing classically styled garments [43, 54]. Additionally, there is evidence to support positive relationships between attitudes and behavior. For example, Hustvedt and Dickson [36] examined environmental attitudes and clothing consumption behavior within the context of consumer preferences for cotton clothing in which a portion of organically-grown cotton fiber is blended with mainstream cotton fiber. The authors concluded that, compared to consumers indifferent to organic cotton, market segments which use the organic content of clothing to inform their acquisition decisions are more aware of the environmental impacts of clothing products, are more supportive of organic agriculture, and have more positive attitudes towards purchasing organic cotton garments. Further, Lee [44] demonstrated that, when consumers are concerned about the state of the natural environment, they are more willing to pay for higher priced sustainable clothing.

Shim [53] and Koch and Domina [40] explored the relationship between attitudes and behavior within the context of clothing disposal. Shim examined the influence that consumers' environmental attitudes and recycling behaviors have on their patterns of clothing disposal. The clothing disposal patterns examined in the study were resale to a second-hand store, donation to a clothing charity, reuse, and discarding. Understanding the motivations underlying a consumer's disposal patterns was of particular interest in the study. A second objective was to determine how variables related to economics, the environment, convenience, or lack of awareness influenced disposal patterns. The study established that a consumer's environmental attitude had a positive impact on charity motivated donation, environmentally motivated donation, and environmentally motivated reuse. Additionally, environmental attitudes had a negative impact on convenience discarding and unawareness discarding. Shim's conclusion was that environmental attitudes are influential in clothing disposal patterns. Consumers with proenvironmental attitudes are likely to consider the environmental impacts when disposing of their garments and find ways to dispose of their clothing in such a way as to minimize environmental impact. A very similar finding by Koch and Domina lends support to this relationship.

However, there is also evidence to support the existence of a gap between consumer knowledge, attitudes, and behavior regarding sustainable clothing consumption. For instance, Butler and Francis [9] reported that, although consumers may hold environmentally conscious attitudes, most consumers never, or only sometimes, consider the environmental impacts of their clothing purchasing behaviors. Butler and Francis concluded that the existing discrepancy between consumers' attitudes and purchasing behavior may be because consumers make clothing-related purchasing decisions based on a variety of different factors (such as price, style, fit, and fashion) which outweigh any environmental considerations by the consumer.

Similar to Butler and Francis [9], Kim and Damhorst [38] focused on the relationships between environmental attitudes and clothing consumption behavior. However, this study also assessed the influence of environmental awareness and knowledge, a variable not factored into the Butler and Francis study. The authors accomplished this by investigating the level of knowledge consumers have about environmental issues related to textile and clothing production and the relationship between general environmental concern, knowledge of environmental issues related to clothing, general environmentally sustainable behavior, and environmentally sustainable clothing consumption. The environmentally sustainable clothing consumption behavior considered in the study included the acquisition of second-hand clothing, clothing which was environmentally preferable, and avoidance of certain garments for environmental reasons.

According to the conclusions of Kim and Damhorst [38], there was only a limited degree of environmentally sustainable clothing consumption among respondents. The study also found that the research participants were not highly involved in sustainable behavior in other areas of their lives and there were only low levels of knowledge about environmental issues in the textile and clothing industry. The only strong relationship between variables proved to between the variables of general sustainability behavior and environmentally sustainable clothing consumption behavior. Therefore, the authors concluded that "many intervening factors disrupt a clear and direct predispositional path between attitude and consumer behavior," and "environmental concern and environmental knowledge are not strongly related to specific environmental behaviors for apparel consumption" [38].

Several studies have also demonstrated that, even when consumers are knowledgeable about how clothing production, distribution, and consumption impact the natural environment, engagement in environmentally sustainable clothing consumption habits is minimal [8, 15, 41, 44]. A study by Goworek et al. [27] demonstrated that even environmentally-knowledgeable consumers "bought low-priced clothing from 'value retailers,' despite being aware of the potential environmental impact of their actions and the fact that this clothing was unlikely to be durable." In another study, changes in consumers' knowledge of sustainability issues related to the clothing and textiles industry were assessed on two occasions—prior to and upon completion of a course that addressed topics specific to the global production and distribution of clothing and textiles. As part of their study, the authors also examined modifications in clothing purchasing behavior. The outcome of the study produced interesting results. Although consumers' knowledge of clothing production environmental issues significantly increased after completing the course that addressed these topics, there was no significant change in clothing purchasing behavior. In fact, even those consumers displaying a higher knowledge of these issues did not report more engagement in sustainable clothing purchasing [15].

## 8 Consumers Perceived Barriers to Environmentally Sustainable Clothing Consumption

Given the inconsistency in findings regarding the relationships between the variables of knowledge, attitudes, and behavior, and the apparent overall gap between consumers' knowledge of and concern with issues in the textiles and clothing industry and their actual purchasing decisions, scholars have sought to identify the personal and contextual barriers perceived by consumers in engaging in sustainable clothing purchasing [11, 32, 37].

### *8.1 Personal Barriers to Environmentally Sustainable Clothing Consumption*

On a personal level, barriers to consumers' environmentally sustainable clothing consumption behavior include a lack of knowledge about environmentally sustainable clothing, attitudes and beliefs about environmentally preferable clothing, clothing acquisition patterns and preferences, and personal resources and priorities [11].

A lack of knowledge about environmentally sustainable clothing consumption may act as a personal barrier in several ways. First, consumers have very limited awareness as to how clothing production affects the natural environment. This is a barrier because it limits understanding of how clothing consumption behavior affects the environment. Connell [11] explained how limited knowledge acts as a barrier to environmentally sustainable clothing consumption in terms of consumers' lack of knowledge about options for environmentally preferable clothing and sources for its acquisition. According to Connell, this limited knowledge means that consumers are unaware of the full range of environmentally preferable clothing and sources available to them, and therefore do not always consider the full range of available alternatives during consumption decisions.

Attitudes of consumers to attributes and relational characteristics of environmentally preferable clothing also act as personal barriers to ecological decision making. As discussed by Connell [11], consumers may not want to purchase environmentally preferable clothing because they do not like the style, fit, and/or tactile qualities. More specifically, consumers sometimes feel that environmentally preferable clothing is not stylish enough and often too counter-cultural. They also do not like the tendency of environmentally preferable clothing to be untailored and believe that some environmentally preferable fibers, such as hemp, are uncomfortable. Kang and Kim [37] also attributed consumers' hesitancy to purchase environmentally sustainable clothing to perceptions of the clothing not being fashionable enough to enhance personal image.

A final personal barrier to environmentally sustainable clothing consumption is a lack of economic resources [11, 13, 32, 37]. In their research, Hines and Swinker [32] investigated factors that influence consumers' willingness to purchase clothing containing recycled polyester fibers. The study used six identical sweatshirts with manipulated information on the garment tags. The researchers labeled three of the sweatshirts as containing 100 % polyester and the other three as containing 100 % recycled polyester. After pairing the sweatshirts into three sets, the researchers manipulated the price of the sweatshirts. The first set priced the recycled garment higher, the second set had the non-recycled garment priced higher, and in the third set both garments were the same price. So that the subjects would not determine the purpose of the study, the authors also included three additional product sets with different factors manipulated on the labels. The authors reported that 53 % of the subjects always selected the lower priced garment and only 27 % always picked the recycled fiber garment. However, when the price was constant between the two sweatshirts, 66 % of participants selected the recycled polyester sweatshirt. The results of this study suggest that consumers are willing to purchase clothing made from recycled fibers, but the higher prices of the products act as an external constraint on their behavior.

Kozar and Connell [42] explored the validity of perceived barriers among consumers in engaging in sustainable clothing purchasing behavior. This study discovered that consumers might be correct in their perceptions that clothing sold by sustainable retailers is more expensive than that sold by mainstream brands. However, findings indicated that a smaller discrepancy in the average price points between better and sustainable retailers as compared to moderate and sustainable retailers existed. Price points also varied in product categories; smaller overall price differences for women's V-neck T-shirts existed as compared to women's boot-cut jeans.

## *8.2 Contextual Barriers to Environmentally Sustainable Clothing Consumption*

The contextual barriers confronting consumers in their environmentally sustainable clothing consumption include limited availability of environmentally preferable clothing, inadequate information about environmentally sustainable clothing consumption, qualities of retail environments, the structure of the global clothing and textile complex, and societal norms [11].

In terms of contextual barriers, according to Connell [11], the limited availability of environmentally preferable clothing significantly constrains the environmentally sustainable consumption habits of consumers. More specifically, Connell highlighted how consumers find it difficult to locate sources for acquiring environmentally preferable clothing because only a minority of mainstream clothing retailers include sustainable goods in their merchandise assortment. Connell attributed the barrier of limited availability to the fact that it is difficult for consumers to locate environmentally preferable clothing which also has other desirable attributes and characteristics—such as being stylish, work-appropriate, and well-fitting. Consumers also perceive it difficult to acquire specific articles of clothing which are environmentally preferable, including footwear, formal wear, and men's pants [11, 13]. However, Kozar and Connell [42] asserted that consumers may be somewhat misguided in their perceptions that sustainable clothing retailers offer fewer product choices as compared to mainstream brands. As shown in their study, the product offerings for women's denim jeans and V-neck T-shirts were comparable among moderate, better, and sustainable retailers in terms of style, silhouette, and fabrication.

In addition to the limited availability of environmentally preferable clothing, the lack of information related to environmentally sustainable clothing acquisition is another contextual barrier to consumers' ecological decision making [11, 13]. Participants in the Connell [11] study lamented the insufficient and unreliable information about the environmental impacts of clothing production and environmentally preferable alternatives. Therefore, as consumers aim to make environmentally sustainable decisions related to their clothing consumption, they have inadequate information to guide that decision making.

For some consumers, a third contextual barrier to the consumption of environmentally sustainable clothing relates to the nature of clothing retail environments [12]. First, as highlighted in Connell [11], some consumers avoid purchasing second-hand clothing because of a perception that the merchandise in second-hand clothing stores is poorly organized. For these consumers, this poor organization results in frustrating shopping experiences and, sometimes, avoidance of second-hand sources altogether. Second, Connell stated that the lack of knowledge of salespeople also occasionally acts as a contextual barrier to consumers' environmentally sustainable consumption, especially when the salespeople are unable to provide consumers with environment-related product information.

Another contextual barrier affecting consumers' environmentally sustainable clothing consumption behavior relates to societal norms [11]. Evidence suggests that consumers see societal norms surrounding appearance and dress expectations in their personal and professional lives as constraining their environmentally sustainable clothing consumption behavior—particularly because of the generally casual style of environmentally preferable clothing and the limited availability of business wear which is environmentally preferable [11].

In terms of contextual barriers to engaging in sustainable clothing disposal behavior, as suggested by Nordlund and Garvill [47], participation in sustainable consumer behavior is partially influenced by the convenience of the action. In other words, an important reason why consumers do not recycle household waste, including clothing, is because they consider the process inconvenient and time-consuming. In fact, research by Daneshvary et al. [17] and Domina and Koch [20] suggested that one of the most important contributors towards the low rate of post-consumer textile recycling is that clothing and textile recycling is not available as part of most kerbside recycling programs. These studies also conclude that the willingness to recycle more materials depends on the expansion of kerbside recycling programs to include items such as clothing.

## 9 Conclusions

Research has shown that a key factor in enhancing consumers' engagement in environmentally sustainable clothing consumption is the availability of education and knowledge development. In their work with students, educators can advocate and encourage students' knowledge about environmental issues in clothing and textile production, distribution, and consumption, and can help students overcome personal barriers to sustainable clothing consumption. Trade associations and industry firms can also foster sustainability education and enhance consumers' knowledge and abilities to identify, evaluate, and analyze the impact of their purchasing decisions, clothing consumption, and disposal practices.

Through various initiatives, consumers also need more information on the range of affordable possibilities for engaging in more environmentally preferable clothing practices, including limiting total consumption and purchasing better quality, classically-inspired apparel. Moreover, encouraging the purchase of second-hand goods can be worthwhile in advancing environmentally sustainable consumption. However, as noted previously, researchers have identified possible barriers which limit consumers in purchasing second-hand goods. Additional effort should be made to overcome these barriers and identify methods of "best-practices" for second-hand retailers, including merchandising and personnel training.

Many researchers have noted that consumers may be limited in their environmentally responsible consumption behavior because of a lack of knowledge and information. Future research should explore the best marketing strategies and media outlets for informing consumers about environmental issues in association with the clothing and textiles supply chain and the differences in the operations and practices of sustainable vs mainstream firms. An important implication for clothing and textile companies operating with a greater commitment to environmental sustainability is the need to inform consumers more effectively about their brands and create additional visibility through targeted media campaigns. Continued research is also needed to explore reasons for the attitude–behavior gap existing among consumers, determining the most effective means for empowering consumers to practice more environmentally sustainable consumption habits. The power of social norms in modifying the behavior of certain market segments should also be a focus of additional research.

Future research should also explore further the extent to which consumers are knowledgeable about the use of organic materials in environmentally preferable clothing. Additional research should focus on identifying those market segments most likely to consider the organic content of their clothing when making clothing purchasing decisions. Previous researchers have determined that some consumers are motivated to purchase more environmentally preferable goods made of organic materials. However, limited information exists about the specific characteristics of these market segments. Further research in this area would not only assist in expanding the consumer groups motivated to buy more environmentally preferable goods, but also enables researchers and textile and clothing firms to understand better whether consumers might perceive price differences as less of a barrier if firms more effectively promoted the use of organic raw materials in environmentally preferable goods.

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# Emerging Green Technologies and Environment Friendly Products for Sustainable Textiles

**Shahid-ul-Islam and Faqeer Mohammad**

**Abstract** Textiles production processes such as sizing, scouring, bleaching, mercerizing, dyeing, printing, and finishing are characterized by a huge consumption of water, energy, and chemicals. The toxic effluent discharge generated in these processes mainly contains by-products, residual dyes, salts, acids and alkalis, auxiliary chemicals, and other solvents. Their discharge into neighboring water bodies is posing a serious threat to the flora and fauna. At present, however, development in the textile and clothing industry has focused on the use of some green technologies as alternatives to conventional wet processes to promote sustainable production and consumption of textiles and clothing. In recent years, emphasis has been put on developing cleaner, cost-effective, and value-added textile products for a variety of applications without compromising the issues related to health and the environment. This chapter is intended to provide a summary of recent developments in the coloration and finishing of textile fibers and to provide details of the ecofriendly strategies developed to reduce the waste generation in the textiles and clothing sector. Finally, their implications in the sustainability of clothing products are also outlined.

**Keywords** Bleaching · Dyes · Effluents · Printing · Sizing

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# 1 Introduction

The textile and clothing industry is a diverse and the world's largest growing sector which involves the use of many types of chemical entities and physicochemical processes in the production of a wide variety of products [1]. Different processing stages in textile manufacturing include sizing, bleaching [2], mercerizing [3], dyeing [4], printing and finishing [5-8], etc. The textile effluents produced in these processes is highly-colored, contains substantial concentrations of organic and inorganic chemicals such as finishing agents, surfactants, inhibitor compounds, active substances, chlorine compounds, salts, dyeing substances, total phosphate, dissolved solids, suspended solids, and total solids [9, 10]. The characteristics of wastewater from textile chemical processing are illustrated in Table 1 [11]. Owing to the generation of these effluents, the textile industry has come under severe criticism for its role in polluting the environment. Environmental concerns arising because of accelerated development in the textile wet processing industry paved the way for ongoing interest in the development of cleaner production strategies for making cost-effective value added textile products. Therefore, a great deal of research is being under taken all over the world on the application and substitution of chemicals having lower hazard potential for chemicals having higher hazard potential.

This chapter is intended to provide a summary of recent developments in the coloration of textile fibers and presents detailed information about the waste minimization approaches initiated by the textile industry by introducing new technologies and more biodegradable chemicals in production pipelines. Finally their implications in sustainability of clothing products are also outlined.

# 2 Waste Minimization Approaches

Wet processing is the segment of textile production involving the use of many types of chemical entities and physicochemical processes [12]. Wet processing involves cleaning, bleaching, dyeing, and finishing of textile fibers and yarns in aqueous solutions, therefore producing large volumes of wastewater as by-products [1]. Because of the complexity and broad classes of wet processing wastes, the textile industry has been faced with some serious challenges. This has led to tremendous current excitement in the search for environmental friendly technologies which can offer suitable alternatives to wet processing. Material scientists and textile researchers on the other hand are also working to find alternative environmentally friendly agents for textile and clothing industry which have the ability to reduce costs and develop clean, nontoxic, environmentally benign textiles with improved quality and functionality. Up to now, several novel green technologies for textile processes and many natural substitutes for synthetic and toxic counterparts have been reported. Recently, Ahmed and El-Shishtawy [13]

**Table 1** Characteristics of wastewater from textile chemical processes [11]

| Characteristics | Scouring | Bleaching | Mercerizing | Dyeing | Composite | Discharge limit into inland water (Bureau of Indian Standards) |
|---|---|---|---|---|---|---|
| pH | 10–12 | 8.5–11 | 8–10 | 9–11 | 8–10 | 5.6–9.0 |
| TDS (mg/L) | 12,000–30,000 | 2,500–11,000 | 2,000–2,600 | 1,500–4,000 | 5,000–10,000 | 2,100 |
| TSS (mg/L) | 1,000–2,000 | 200–400 | 100–400 | 50–350 | 100–700 | 100 |
| BOD (mg/L) | 2,500–3,500 | 100–500 | 50–120 | 100–400 | 50–550 | 30 |
| COD (mg/L) | 10,000–20,000 | 1,200–1,600 | 250–400 | 400–1,400 | 250–8,000 | 250 |
| Chlorides (mg/L) | – | – | 350–700 | – | 100–500 | 1,000 |
| Sulphates (mg/L) | – | – | 100–350 | – | 50–300 | 1,000 |
| Color | – | – | Highly colored | Strongly colored | Strongly colored | Colorless |

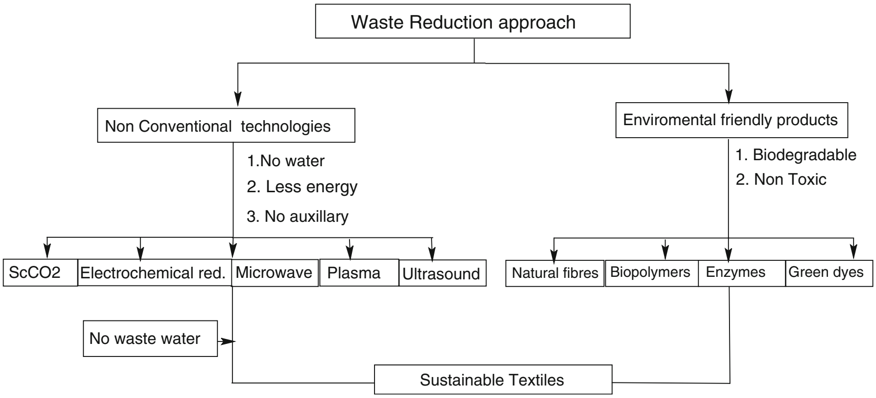



**Fig. 1** Sustainable textile production using green technologies and products

reviewed the developments in coloration of textiles using new technologies, particularly those based on physicochemical means. Use of low-environmental impact technologies based on sustainable biopolymers such as chitosan, cyclodextrin, sericin protein, and alginate as suitable alternative agents for the functional finishing of textile materials was more recently reported by Islam et al. [14]. This chapter looks at some recent studies which are oriented towards greening of the textile industry by introducing ecofriendly processes such as supercritical carbon dioxide ($scCO_2$) dyeing, electrochemical reduction of vat dyes, microwaves, plasma, ultrasound, and materials in the production pipeline (Fig. 1).

Some of the important green technologies and renewable natural materials such as natural fibers, biopolymers, enzymes, and natural dyes adopted recently for sustainable textile production are discussed below.

# 3 Use of Green Technologies in the Textile and Clothing Sector

## *3.1 Supercritical Carbon Dioxide Dyeing*

Supercritical carbon dioxide dyeing is a water free process and therefore is a revolutionary and green attractive alternative to conventional wet methods in the textile industry [15, 16]. $scCO_2$ can be used as a medium in yarn preparation, coloration, and finishing of polyester, nylon, cotton, wool, silk, and other fabrics without generating aqueous effluents; this new method has many advantages, such as no wastewater, no auxiliaries, high dyeing rate, and good leveling results [17, 18]. Recent literature shows that textile dyeing is extensively being carried out using $scCO_2$ as a medium. Guzel and Akgerman [19] studied mordant dyeing

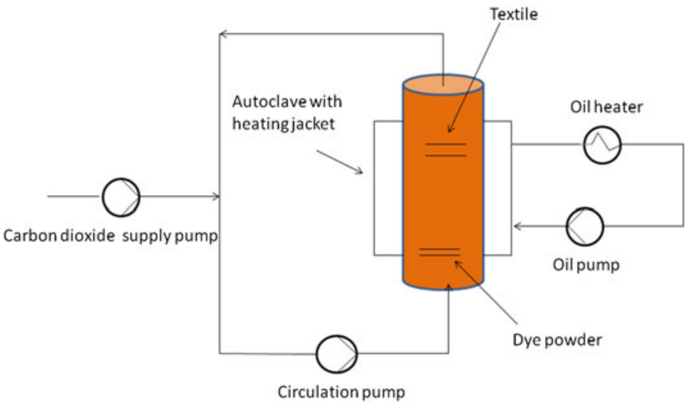



**Fig. 2** Experimental set-up for textile dyeing in $scCO_2$ [20]

of wool using three mordant dyes which have chelating ligand properties, 2-nitroso-1-naphthol (C.I. Mordant Brown), 5-(4-aminophenylazo) salicylic acid (C.I. Mordant Yellow 12), and 1,2-dihydroxyanthraquinone (C.I. Mordant Red 11, also called Alizarin). These chelating synthetic dyes were dissolved in $scCO_2$ and subsequently examined for dyeing properties on wool in the presence of five different mordanting metal ions, such as Cr(III), Al(III), Fe(II), Cu(II), and Sn(II). The wool fabric dyed with these dyes showed excellent wash fastness properties. Various synthetic and natural fiber-based textile substrates such as polyester, nylon, silk, and wool were dyed with disperse reactive dyes in $scCO_2$ by Kraan et al. [20] (Fig. 2). A series of reactive disperse dyes incorporating the halogenated acetamide group were recently synthesized by Gao et al. [21] for dyeing cotton fabric in $scCO_2$. The results showed that the color strength of dyed cotton fabric increased favorably with increasing temperature and time, and found that color fastness to washing and rubbing were also reasonably good. Likewise Cid et al. [22] synthesised a series of fluorotriazine reactive dyes and applied these dyes to cotton fabrics using $scCO_2$ for better results. The fluorotriazines are very reactive and therefore the application of fluorotriazines cotton dyeing in water has limited use. Use of water in textile dyeing process hydrolyses the fluoride atom of the triazinyl reactive group, making it inactive for reaction with cotton; for this reason, disperse dyes with fluorotriazines dyes as reactive group shows excellent dyeing properties in supercritical $scCO_2$ [23]. Özcan et al. [24] reported on $scCO_2$ as dyeing media for cotton fabrics previously modified by treatment with benzoyl chloride. Their results suggest that $scCO_2$ dyeing can produce good color intensity and wash fastness.

To illustrate the dyeing mechanism of an acid dye on natural protein fibers in supercritical $CO_2$, Sawada and Ueda [25] used a reverse micellar system comprising pentaethylene glycol *n*-octyl ether (C8E5)/1-pentanol for the solubilization of an acid dye and studied the subsequent dyeing of protein fibers in supercritical $CO_2$. Likewise, Long et al. [26] investigated level dyeing of fabrics in $scCO_2$ by employing an improved beam (a perforated pipe on which the knitted or woven fabric/warp is wound around). They examined leveling properties under various conditions such as system temperature, pressure, dyeing time, time ratio of fluid circulation to static dyeing, different fabric layers on the beam, and the species of dyestuffs. Their results showed that the leveling properties of polyester fabric samples were improved on the new beam compared with the traditional one. More recently, Hori and Kongdee [27] have improved the dyeability of polypropylene by forming its composite with polyester (PET) followed by dyeing with three disperse dyes in the presence of $scCO_2$.

## *3.2 Electrochemical Reduction of Dyes*

At present, a number of reducing agents such as sodium sulfide, sodium hydrosulfite (sodium dithionite), hydroxyacetone, or glucose are required in the dyeing process for vat and sulfur dyes to ensure that these dyes stay in soluble leuco-form for adsorption and diffusion into the textile surface [28-30]. The reduction mechanism of vat/indigo and sulfur dyes is shown in Fig. 3 [13]. However, because of the non-regenerable nature and formation of sulfite, sulfate, thiosulfate, and toxic sulfur, their use causes adverse health and environmental problems [31]. Therefore, the demand for alternative reduction methods for vat dyes has increased markedly in recent years [32]. The direct and indirect electrochemical reduction of vat, indigo, and sulfur dyes has been studied as novel environmental friendly technology in which non-regenerable reducing agents are being replaced by a dissolved redox couple which is reactivated by cathodic electron transfer [28, 33-38]. The schematic view for the reduction of indigo using direct electrochemical reduction, electro-catalytic hydrogenation, indirect electrochemical reduction (anthraquinonoid mediator), and indirect electrochemical reduction (iron-complex mediator, TEA, triethanolamine) is shown in Fig. 4 [39]. The use of electrochemical reduction for vat and sulfur dyes reveals similar results to those obtained in chemical reducing agents and is a very promising concept which should be popularized as an alternative method that may help to reduce environmental pollution in the textile industry.

## *3.3 Microwave-Assisted Textile Processing*

Microwave technology involves electromagnetic radiation associated with electric and magnetic fields, which are oscillating at perpendicular directions with respect to each other. The use of microwaves as a heating source for de-sizing, scouring, and bleaching processes, dyeing, and drying processes has been well documented in the literature. The application of microwave technology for curing cotton fabrics treated with nonformaldehyde finishing agents such as glyoxal, glutaraldehyde and

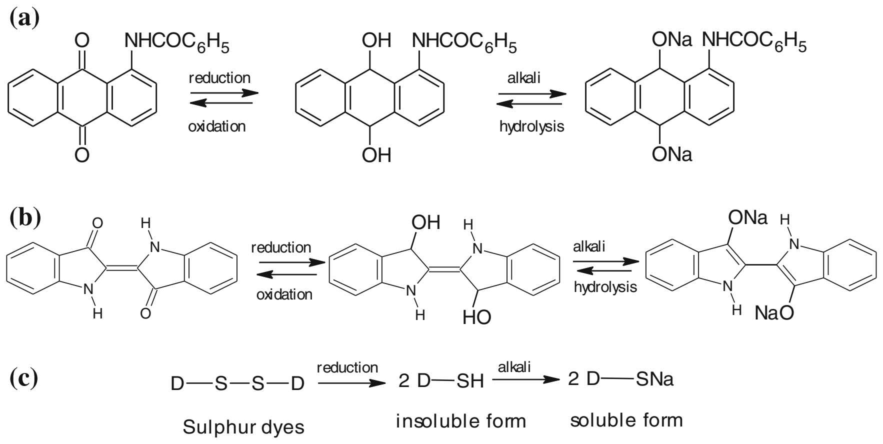



**Fig. 3** **a** Mechanism of reduction/oxidation of vat dyes. **b** Mechanism of reduction/oxidation of indigo dyes. **c** Mechanism of reduction/oxidation of sulfur dyes [13]

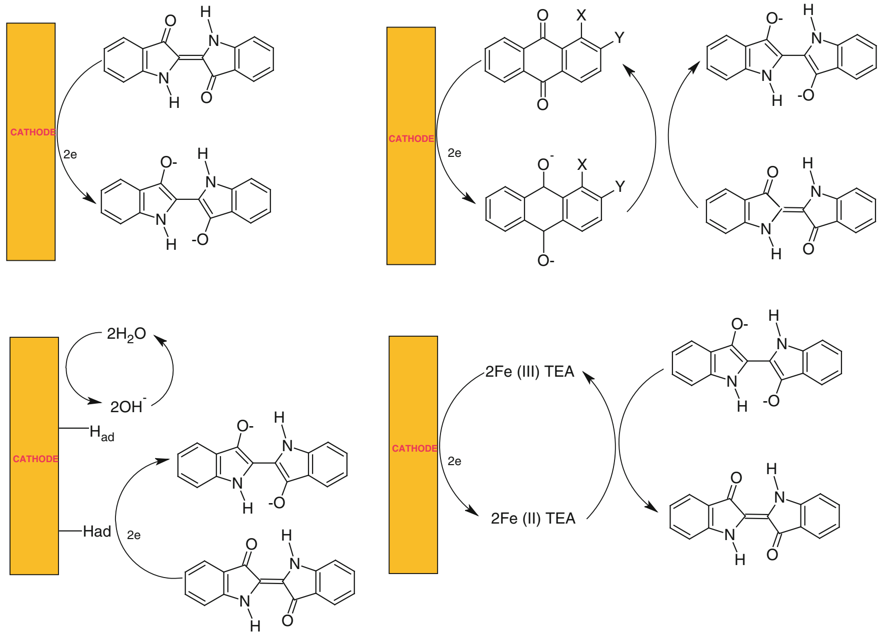



**Fig. 4** Electrochemical indigo reduction schemes [39]

1,2,3,4-butanetetracarboxylic acid (BTCA) along with water-soluble chitosan has resulted in production of cotton fabrics with easy care antibacterial properties without high losses in strength properties [40]. Recently Hashem et al. [41] studied the effect of microwaves on the physicochemical and performance properties of desized, scoured, and bleached cotton fabric and compared their results with those obtained on using conventional thermal heating. They found that cotton fabric preparation requires only 5 min longer than conventional, which takes 2.5–3 h. Bhat and Kale [42] studied the interaction of microwave radiation with partially oriented polyester yarns and concluded that microwaves have a significant effect on tensile strength, shrinkage, and dye uptake of polyester filaments. Hakeim et al. [43] carried out the printing of wool fabrics with henna dye using different modes of fixation. They obtained deep orange shades for wool with good colorstrength and fastness properties by using microwave assisted fixation. Al-Mousawi et al. [44] reported synthesis of disperse dyes based on the arylazothienobenzochromene moiety and studied their dyeing properties after application on polyester fabrics using microwave heating. Likewise, Al-Etaibi et al. [45] synthesized pyrazolopyrimidine monoazo disperse dyes for application on polyester fabrics employing microwave irradiation. The dyed fabrics showed satisfactory fastness properties. Al-Etaibi et al. [46] also have prepared a series of 4-hydroxyphenylazopyrazolopyrimidine disperse dyes via one-pot reactions of *p*-hydroxyphenylhydrazone, hydrazine hydrate, and acetylacetone or enaminones using microwave irradiation as an energy source. It was found that shades produced with these dyes after dyeing have acceptable fastness properties. The authors reconstructed the same dyebath for repeat dyeings in order to save water and chemicals and to reduce the quantities of effluent discharged during the dyeing of polyester fibers. Al-Mousawi et al. [47] noticed that the polyester fabrics dyed with thienobenzochromene disperse dyes exhibited relatively excellent washing and perspiration fastness under conventional and microwave heating conditions.

## *3.4 Plasma Technology*

Plasma modifications have created a new approach for remarkable applications in textile industry because of their numerous advantages such as low energy, no chemical requirements, and a green approach over other conventional wet processing techniques [48]. In plasma treatment, the polymer/fiber surfaces are treated with excited and energetic plasma species (ions, radicals, electrons, and metastables) [49]. The plasma introduces new hydrophilic groups into the structure and has been used to achieve adhesion, or reflectivity, wettability, water repellency, dyeability, flame retardancy, and effective antimicrobial properties [50-53]. Recently, Koh and Hong [54] used a plasma sputtering technique to conifer better functional properties to wool dyed with gallnut extract. Yaman et al. [55] investigated the impact of plasma treatment parameters on the surface morphology, physical–chemical, and dyeing properties of polypropylene (PP) using anionic and cationic dyestuffs. They grafted different compounds such as 6-aminohexanoic acid, acrylic acid, ethylendiamine, acryl amide, and hexamethyldisiloxane onto activated polypropylene and found that argon treatment resulted in improved dyeing properties of dyes. Hegemann et al. [56] reported the development of multifunctional textiles by use of nanostructured plasma coatings. Tseng et al. [57] reported the grafting of chitosan oligomer and biopolymer onto nylon textiles previously activated by open air plasma. It was found that nylon grafted with chitosan polymer had better antimicrobial properties than nylon grafted with chitosan oligomer.

## *3.5 Ultrasound Coloration*

The application of ultrasound power is the most important emerging domain in the textile industry and has a significant role in the concept of clean technology for textile processing. Ultrasound technology offers numerous advantages over the conventional chemical processes, mainly by generating cavitation in liquid medium in addition to other mechanical effects such as dispersion, degassing, diffusion, and intense agitation of liquid [13]. 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 effects in the dyebath [12]. When cavitation occurs at a solid/liquid interface (e.g., a fiber/dyebath interface), the resulting asymmetric implosion produces microstreaming towards the solid surface which greatly disrupts the diffusion interlayer and promotes mass transport in that direction [58]. The high rate of mass transfer in textile processing steps has been studied as an alternative to conventional methods [59, 60]. Yachmenev et al. [61] have reported that a combined treatment of enzyme/sonication on cellulosic textiles offers significant advantages such as less consumption of expensive enzymes, shorter processing time, less fiber damage, and better uniformity of treatment. Perelshtein et al. [62] successfully produced antibacterial cotton using an ultrasound technique for coating cotton by MgO and $Al_2O_3$ nanoparticles. The use of an ultrasonic system for continuous washing of textiles in liquid layers has been tried by Gallego-Juarez et al. [63]. Gotoh and Harayama [64] recently showed that the washing of polyester fabric soiled with carbon black or oleic acid as a model contaminant causes little mechanical damage to fabric in the presence of ultrasound. Ultrasonic energy has been used in enzymatic desizing of cotton to improve the desizing efficiency. Wang et al. [65] in their research experiment concluded that use of ultrasound assisted systems in desizing of cotton can save half the processing time and improve the desizing efficiency by about 5 % compared to conventional desizing. Likewise, the use of power ultrasound (26 kHz, 180 W) as an effective technique for improving the bleaching of linen fabric was reported by Abou-Okeil et al. [66]. They found that ultrasound improved the whiteness of laccase–hydrogen peroxide bleached linen and yields results similar to a conventional bleaching process. Khanjani and colleagues [67] have investigated the in situ formation and coating of ZnO nanoparticles on silk fabrics under

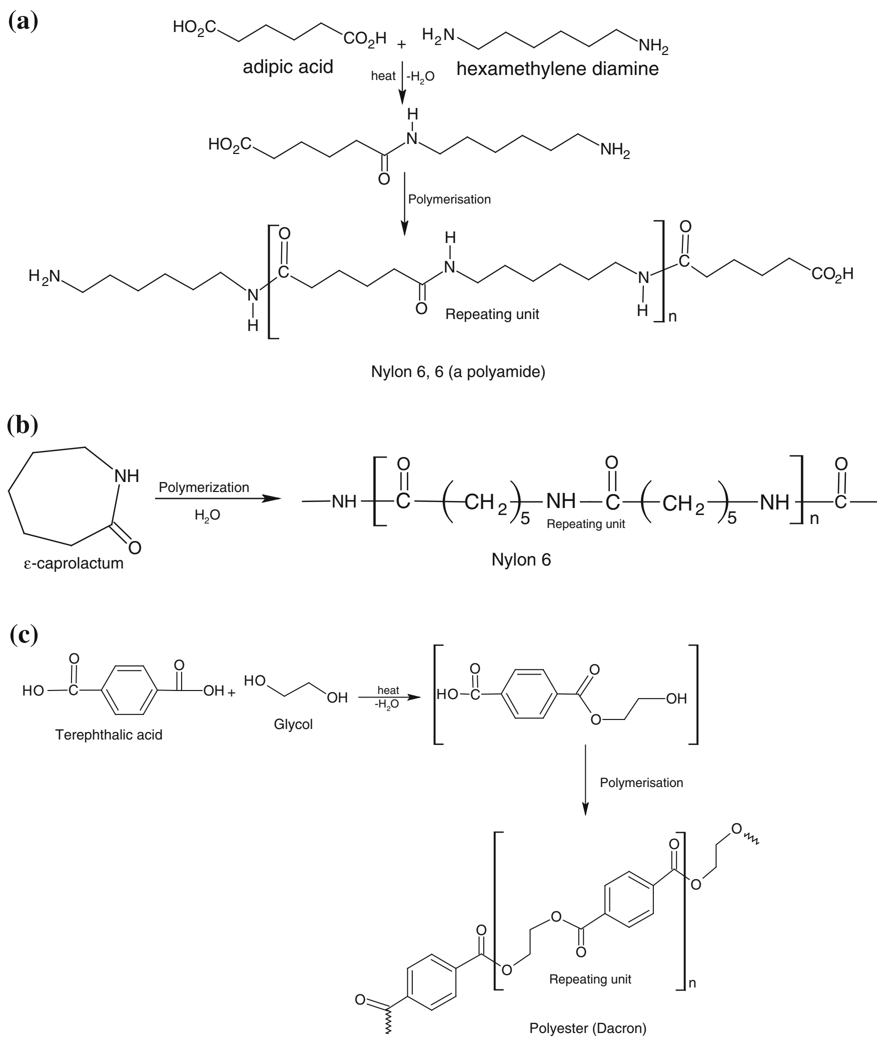



**Fig. 5** Synthesis of **a** nylon 6, 6, **b** nylon 6, and **c** polyester [68]

ultrasound irradiation. The growth of magnesium hydroxide nanostructures and sphere-like trimanganese tetraoxide ($Mn_3O_4$) nanoparticles on silk yarn was achieved by Khanjani and Morsali [69, 70] by using sequential dipping steps in alternating baths of magnesium nitrate and potassium hydroxide under ultrasound irradiation. Recent reports have shown that ultrasound technology provides an easy and efficient route for natural dyeing processes and therefore a certain number of studies on ultrasound assisted natural dyeing and finishing of natural and synthetic fibers were carried out at the experimental level by many research groups [71, 12].

## 4 Application of Environmentally Friendly Materials

The textile processing industry has imposed strict ecological and economic restrictions on the chemicals used, including bans on certain consumer goods containing synthetic agents which are posing challenges to sustainability issues [72, 73]. The worldwide demand for the use of environmentally friendly products in the textile industry is nowadays of great interest, possibly because of increasing concern about the environment, ecology, and pollution control [74, 75]. Textile-related processes such as sizing, scouring, bleaching, mercerizing, dyeing, printing, and finishing are characterized by huge consumption of water, energy, and chemicals [10].

Since time immemorial, natural fibers such as wool, silk, and cotton have been an integral part of human life and society. However, the discovery of cheap and easy-care man-made fibers such as polyamide, acrylic, and nylon became the textile industry's miracle solution. Unfortunately their production from petrochemical sources is a global environmental concern [73]. The methods of synthesis of some commonly used synthetic fibers are show in Fig. 5.

Nowadays, the use of environmentally friendly fibers for textile processing is particularly interesting. Natural fibers, especially cotton, wool, and silk, have been an indispensable part of human existence. The use of formaldehyde- and non-formaldehyde-based agents and the application of enzymes and nanotechnology for cross-linking of cotton in order to overcome its crease resistance were recently reviewed by Harifi and Montazer [76]. Besides cotton, nowadays there is a huge scientific interest in the cultivation of new alternative fibers from crops which require low environment impact conditions, namely jute [77], ramie [78], hemp [79], and flax [80]. Several research projects have also been undertaken to find substitutes for synthetic and non-biodegradable sizing agents for textiles. Poly(-vinyl alcohol) (PVA) is commonly preferred for the effective sizing of synthetic fibers and blends; however, its use has a tremendous environmental impact. For this reason, the use of non toxic and abundantly available natural agents as suitable alternatives for sizing applications has been investigated [81]. Starch in its native form and its modification by grafting with acrylates [82] and methacrylates [83] have been used to make starch more suitable for sizing of cotton, polyester, and polyester/cotton (P/C) yarns in an environmentally friendly way. The use of several other natural polymers for sizing is also well documented in the literature. Hebish et al. [84] examined the use of acid-hydrolyzed and carboxymethylated chitosans as new textile sizing agents. Likewise Stegmaier et al. [85] investigated chitosan as a possible sizing agent in fabric production by appropriate modifications in the textile industry. More recently, Yang and Reddy [81] and Chen et al. [86, 87] are among the researchers who have demonstrated that plant proteins (such as soy proteins and wheat gluten) and chicken feathers used as sizing agents on cotton, polyester and polyester/cotton provide similar performance properties to PVA and are easily degraded in activated sludge. In a subsequent publication, Reddy et al. [88] reported the use of keratin from chicken feathers as a warp sizing

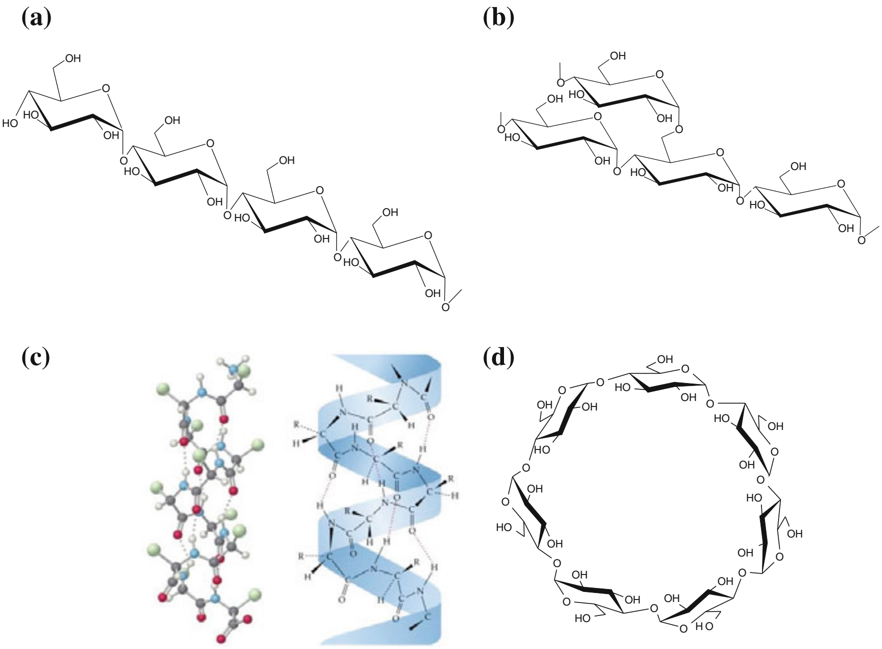



**Fig. 6** Structures of some natural environmentally friendly sizing agents for textiles. **a** Amylose. **b** Amylopectin. **c** Keratin. **d** $\beta$-Cyclodextrin

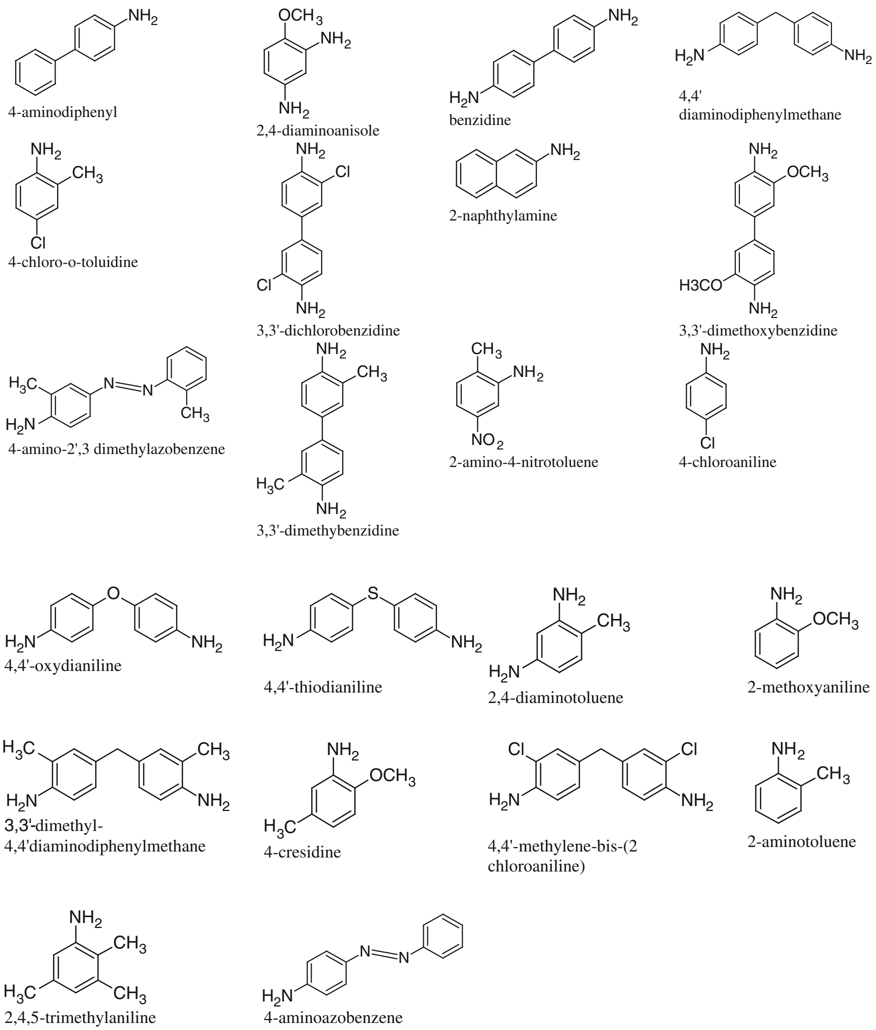
agent on polyester/cotton blends and polyester which can replace PVA and make the textile industry more environmentally friendly (Fig. 6).

Applications of biotechnology to textile wet processes are becoming more popular because of proven reliability, water conservation, and environmental responsibility. Recently published literature indicates that enzymes, mainly cellulases and several non-cellulolytic enzymes (lipases, proteases, and pectinases) are increasingly being used in various stages of textiles processing [89-91].

The development of synthetic dyes and auxiliaries from petrochemical sources and their use in the dyeing industry are now facing serious challenges as they produce large volumes of toxic wastewater [92, 93]. Several synthetic colorants, especially azo and benzidine synthetic dyes, have been banned by many countries owing to their role in the production of any one of the 22 aromatic amines listed in Table 2 [72].

These dyes have detrimental effects on the environment and produce associated allergic, toxic, carcinogenic, and harmful responses [94-96]. Another way to potentially clean up the textile industry would involve the use of natural dyes. Recently, dyes derived from naturally occurring sources such as plants, insects, animals, and minerals have been extensively studied for their dyeing properties [12, 97]. These dyes are obtained without any chemical processing and generally exhibit better biodegradability and compatibility with the environment [98, 99].

**Table 2** Chemical structure of 22 aromatic amines covered by EU Directive 76/769/EEC [3]




Owing to their recently discovered functional and medicinal properties, such as UV protection, antimicrobial and antioxidant activities, and deodorizing ability, they are emerging globally for use in functional textiles [100-102].

Hill [103] has shared his views about the natural dyeing of textiles using colorants from natural sources in his review paper. Apart from Hill's work, a number of review articles concerning the use of natural dyes and pigments have been published by many research groups. Taylor [104] reviewed the use of natural dyes in textile applications. More recently Shahid et al. [12] have collected the dispersed information, from 1998 to 2013, about recent developments in traditional and newly discovered applications of natural dyes. Special focus has been directed on the technological development in natural textile dyeing and use of natural dyes in functional finishing of textiles. Similarly, use of natural product-based bioactive agents such as chitosan, natural dyes, neem extract, and other herbal extracts for antimicrobial finishing of textile substrates was discussed by Joshi et al. [105]. More recently, a novel approach to natural dyeing of cotton fabric with *Hibiscus mutabilis* (Gulzuba) without mordants was examined by Haddar et al. [106]. Their results proved that cationizing cotton with STABIFIX NCC improves its dyeability and leads to good fastness properties. Haddar et al. [107] also investigated the valorization of leaves of fennel (*Foeniculum vulgare*) in the dyeing of cationized cotton. They reported that the optimum dyeing conditions of cationized cotton were found to be a pH of 8.22, a dyeing temperature of 99.83 °C, and a dyeing duration of 59.38 min.

## 5 Use of By-products/Waste from Other Industries

The recycling or reuse of huge amounts of waste materials generated by other industrial sectors in textile processes currently represents a ‘sustainable waste minimization’ strategy, leading to the fulfilment of economic development and objectives of environmental sustainability. Over the past few years, by-products from the agricultural sector and the food and timber industries have attracted much attention for their introduction into the textile industry. Poole et al. [108] have highlighted that protein fibers regenerated from wastes or by-products such as feather keratin and wheat gluten are potentially environmentally sustainable, renewable, and biodegradable, and should therefore be considered for production of safe and novel textiles in the near future. Islam et al. [73] recently published a review paper focused on the use of natural products from industrial plants in textile applications. They reported that by-products from commodity crops could be a readily available alternative source for natural cellulose fibers which could be easily produced in high yields. They concluded that this approach is a worthwhile route for the production of natural fibers which help the fiber industry to be sustainable and also add value to and increase income from agricultural crops. Every year, large amounts of by-products/waste materials produced by the food industry, such as pomegranate peel, walnut shells [109], orange peel [110], onion skins [111], red beet peel [112], and almond shells [113], have been studied to explore their dyeing properties for textile substrates. There is more literature available on other by-products for use in textile processes. Bechtold et al. [114] reported the use of anthocyanin dye extracted from grape pomace for the purpose of textile dyeing. Likewise, it has been shown that olive mill wastewater (OMW), which is a dark brown to black effluent produced during olive oil extraction, has the potential to be used as a natural dye for coloration of wool [115] and polyester fabrics [116]. The depth of shade and fastness properties were found to be very good.

## 6 Conclusion and Future Outlook

This chapter clearly indicates that ecological and economic restrictions imposed on the textile industry have led to its search for ecofriendly and sustainable alternatives. Recently discovered green technologies such as $scCO_2$ methods, electrochemical reduction, plasma treatment, microwave, and ultrasound could technologies considerably reduce the water, chemicals, and energy consumption necessary for different textile processes including scouring, sizing, dyeing, and finishing. Moreover, the coapplication of nano- and biotechnology in the textile and cloth sectors offer much potential in the development of clean, nontoxic, environmentally benign textile and clothing products. However, most of the studies reported in the literature on the use of natural ecofriendly agents in the textile and clothing sectors have been carried out only on a laboratory scale. Further research efforts should be made with these green technologies and sustainable products at pilot plant scale to explore the possibility of their use in the textile industry on the commercial industrial scale.

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# Biodegradation Studies of Textiles and Clothing Products

**Sohel Rana, Subramani Pichandi, Shama Parveen and Raul Fangueiro**

**Abstract** This chapter discusses the biodegradation of textile and clothing products. Various important aspects related to biodegradation such as mechanism, types of microorganisms, factors influencing biodegradation, etc., have been discussed. Different methods and conditions to study biodegradation behavior have been presented, along with the techniques to assess the biodegradation of fibers and textiles. This chapter also discusses the influence of biodegradation on the structure and properties of various types of natural and synthetic fibers as well as their textile products and composites materials.

**Keywords** Biodegradation · Microorganisms · Assessment · Natural fibers · Synthetic fibers · Composite materials

## 1 Introduction

Biodegradation can be visualized as the method used by nature to recycle waste and to break down organic materials into compounds which can be used as nutrients by other organisms. This breakdown of materials is performed through the action of numerous microorganisms such as bacteria, fungi, insects, worms, and many others. Through this biodegradation process it is possible for nature to clean up wastes, to provide nutrients for the growth of new lives, and to produce the energy necessary for various biological processes. Therefore, the biodegradation process is very important for nature and the environment. As a result,

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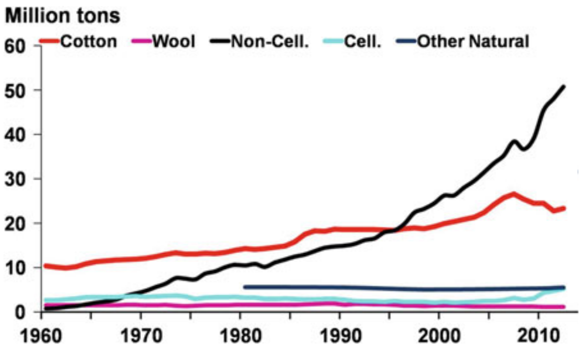


**Fig. 1** World fiber production over last 50 years [2]

biodegradability is an essential requirement for materials used in day-to-day life and is considered to be one of the most important parameters for evaluating their sustainability.

One of the primary needs of human beings is clothing. To fulfil this requirement, tons of textile fibers and products are produced every day all over the world. World production of fibers is rising steadily, reaching over 85,814 thousand tons in 2012 [1]. Figure 1 shows the trend of world fiber production in the last 50 years [2].

It can be seen that the increase in production of synthetic fibers is most significant. From 1990 to 2012, the share of manmade fibers out of total fiber production increased from 37 to 62.6 % [1]. Most manmade fibres are produced from synthetic polymers which are not biodegradable and need to be recycled and reused to a limited extent. At the end of their lifetimes, these materials are disposed of in land or water where they remain forever as waste materials. Over time, non-biodegradable materials release toxic pollutants which can be serious threats for organisms living within the soil or water. These materials can also emit toxic gases to the air, polluting the environment. Burning of non-biodegradable materials also produces harmful toxic gases. Therefore, biodegradability of textile fibers and products is a desirable characteristic. However, while in use, these products should present sufficient resistance against degradation by microorganisms in order to provide a sufficiently long usage period with the desired performance and comfort. Therefore, biodegradation behaviour of textile and clothing products should be appropriate for the type of applications they are used for. This chapter provides a brief overview of the biodegradation process, mechanism, testing conditions, assessment, and also the biodegradation behaviour of various textile fibers, their products, and composites.

## *1.1 Definition of Bio-degradation*

Biodegradation is the process of converting complex matters into simple ones through the action of various microorganisms (bacteria, fungi, virus, etc.). The word biodegradation is the short form of “biotic degradation” which means a

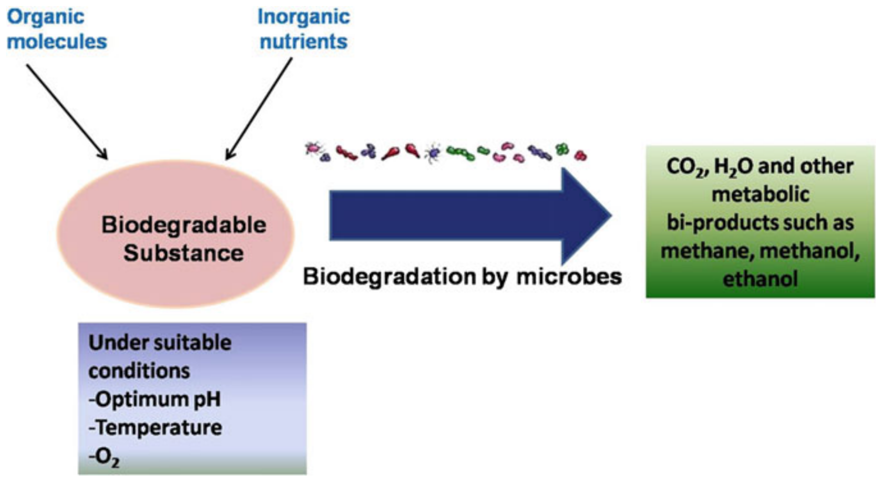


**Fig. 2** Schematic diagram of biodegradation process [5]

biological process that can break down a material into smaller fragments (see Fig. 2) [3]. The biodegradation process has been defined by different organizations over a period of time for different materials as follows:

- *Biodegradation*—"Breakdown of a substance catalyzed by enzymes in vitro or in vivo. This may be characterized for purpose of hazard assessment as:
  - *Primary*. Alteration of the chemical structure of a substance, resulting in loss of a specific property of that substance.
  - *Environmentally acceptable*. Biodegradation to such an extent as to remove undesirable properties of the compound. This often corresponds to primary biodegradation but depends on the circumstances under which the products are discharged into the environment.
  - *Ultimate*. Complete breakdown of a compound either to fully oxidized or to reduced simple molecules (such as carbon dioxide/methane, nitrate/ammonium, and water). It should be noted that the products of biodegradation can be more harmful than the substance degraded."—International Union of Pure and Applied Chemistry (1993) [4].
- *Biodegradation*—"Biotransformation which results in degradation of the pesticide molecule, also called biodegradation, although the latter term sometimes refers to degradation processes in which the pesticide serves as a substrate for growth (e.g., Bollag and Liu 1990)." [4].
- *Biodegradation*—"Transformation of a substance into new compounds through biochemical reactions or the actions of microorganisms such as bacteria".—U.S. Geological Survey (2007) [4].
- *Biodegradation*—"A process by which microbial organisms transform or alter (through metabolic or enzymatic action) the structure of chemicals introduced into the environment".—U.S. Environmental Protection Agency (2009) [4].

- *Biodegradability* (*or biodegradation potential*)—"The relative ease with which petroleum hydrocarbons degrade as a result of biological metabolism. Although virtually all petroleum hydrocarbons are biodegradable, biodegradability is highly variable and dependent somewhat on the type of hydrocarbon. In general, biodegradability increases with increasing solubility; solubility is inversely proportional to molecular weight".—U.S. Environmental Protection Agency 2009 [4].

The biodegradation process involves following steps:

- Degradation, i.e., breakdown of molecules
- Chemical degradation, i.e., breakdown from complex molecules into simpler molecules
- The breaking down of molecules has to be accomplished by microorganisms.

Biodegradable materials are normally organic, i.e., plant and animal matter and other substances obtaining from living organisms, or artificial materials such as plant and animal matter to be put to use by microorganisms. Some microorganisms have a naturally occurring microbial catabolic diversity to degrade, transform, or accumulate a huge range of compounds including hydrocarbons, polychlorinated biphenyls (PCBs), poly aromatic hydrocarbons (PAHs), pharmaceutical substances, radio nuclides, pesticides, and metals. Decomposition of any biodegradable matters may include both abiotic and biological steps. Biodegradable matter breaks down into more than one set of chemicals, which are usually called primary and secondary degradation products [3, 6].

## *1.2 Types of Bio-degradation*

There are three types of bio-degradation:

1. Primary biodegradation
2. Acceptable biodegradation
3. Ultimate biodegradation.

### 1.2.1 Primary Biodegradation

- Biochemical method of catalysis where transformation or alteration in chemical structure of a compound occurs by biochemical reactions
- Results in loss of specific property due to partial biodegradation and leaves molecules mostly intact
- Not desirable because of toxicity issues
- Example: change of toxic halogen groups from para to meta positions.

#### 1.2.2 Acceptable Biodegradation

- Biological conversion of toxic compounds into non-toxic ones by biological means
- Removal of undesirable characteristics occurs
- Complete removal of toxic entity.

#### 1.2.3 Ultimate Biodegradation

- The level of degradation where a compound is totally degraded and results in the production of $CO_2$, water, and mineral constituents
- Molecular cleavage is so extensive that it removes all chemical, biological, and toxic properties.
- The ultimate products are highly stable and cannot be degraded further.

### *1.3 Conditions for Biodegradation*

Biodegradation occurs under different conditions and they are:

- Aerobic biodegradation
- Anaerobic biodegradation.

#### 1.3.1 Aerobic Biodegradation

Defined as "the degradation of a substance by a microorganism in the presence of oxygen. In this type of biodegradation, the microorganism converts oxygen to water during the process of converting other components to simple products" [7].

#### 1.3.2 Anaerobic Biodegradation

Defined as "the degradation of matter by a microorganism in the absence of oxygen. In this process, the microorganism uses a chemical other than oxygen as an electron acceptor. The common substitutes for oxygen are iron, sulfate, and nitrate" [8]. The processes involved in aerobic and anaerobic biodegradation are presented in Fig. 3.

### *1.4 Types of Biodegradable Materials*

There are two main types of biodegradable materials:

*Hydro-biodegradable*. Materials are first broken down through interaction with water (a process called hydrolysis), and are then further broken down by microorganisms.

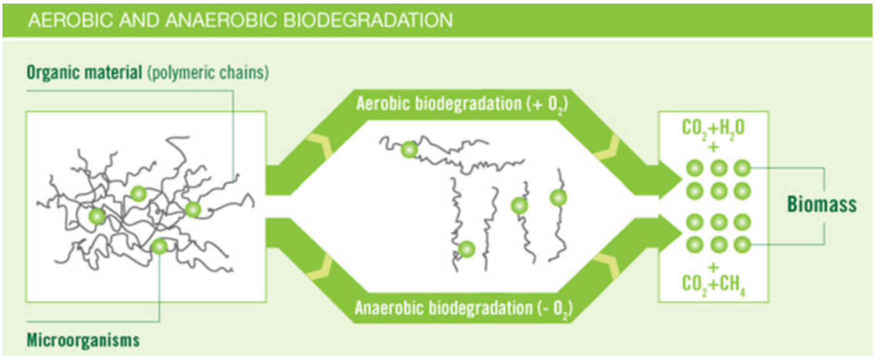


**Fig. 3** Schematic representation of steps involved in aerobic and anaerobic biodegradation [9]

*Photo-biodegradable*. Materials are first broken down through interaction with sunlight (a process called photolysis), and are then further broken down by microorganisms [3].

### *1.5 Measurement of Biodegradation*

There are two commonly used measurement methods for biodegradation.

The first is used to measure "primary degradation." This technique measures reduction of carbon and hydrogen bonds (C–H) in the initial solution. The most widely used test method which measures this decrease is CEC-L-33-A-93.

The second type is used to measure "secondary degradation" or "ultimate degradation." This measures the evolution of $CO_2$ through the biodegradation process. The usual test method for assessing this type of degradation is OECD 301or ASTM D4684. The difference between these two types of measurement techniques is illustrated in Fig. 4 [10].

## 2 Microorganisms

The two major groups of microorganisms associated with the breakdown of organic matter are bacteria and fungi, which are extremely diverse in form, habitat, and activity.

### *2.1 Bacteria*

Bacteria are characteristically simple, unicellular, and have no nucleus (prokaryotic organism) (see Fig. 5). Bacteria are very small in size (1–5 µm), and undetectable to

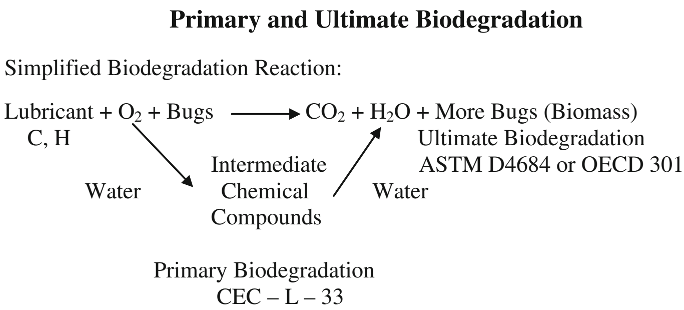


**Fig. 4** Two common measurement methods of biodegradation [10]

**Fig. 5** An example of bacteria [12]

the naked eye. Some bacteria breed in filamentous forms, and these masses of cells can be seen without a microscope. Bacteria are known according to their growing conditions such as strict aerobes, strict anaerobes, and facultative anaerobes. Bacteria which are known as strict aerobes requires $O_2$ for their growth; bacteria known as strict anaerobes die in the presence of $O_2$; and bacteria known as facultative anaerobes can grow in the presence or absence of $O_2$. Many bacteria are heterotrophs which derive energy and carbon from organic matters and these play a major role in nutrient cycling in the environment [11].

## *2.2 Fungi*

Fungi are more intricate microorganisms than bacteria (see Fig. 6). They are typically multi-cellular, and have a nucleus (eukaryotic), making fungi much larger in size than bacteria. Their filamentous growth of hyphae yields structures often large enough to be visible to the naked eye (for example, mold growing on bread). Conversely, soils can contain kilometers of fungal hyphae not visible to the

**Fig. 6** An example of fungal growth [13]

naked eye. Many fungi yields spores which are spread by wind, and, upon landing, these spores can sleep until environments are suitable for their growth and development. This form of dispersal can often be observed as mildew growth on plants or other materials. Fungi are heterotrophs and most are strict aerobes. The ability of fungal hyphae to penetrate rapidly into tissues and other organic materials makes these organisms important decomposers. This invasion puts the hyphae into intimate contact with potential food sources [11].

## 3 Mechanism of Bio-degradation

The mechanism of biodegradation is explained in this section using the example of bio-degradation of polymers. Polymers consist of molecular chains of organic molecules called monomers [14]. Polymers are biodegraded by microorganisms in the following steps.

### *3.1 Formation of Biofilm*

In the first stage, a microbe-rich and moisture-borne biofilm is formed on the surface of the polymer. The biofilm remains adhered to the polymer surface.

### *3.2 Expansion of the Polymer Matrix*

The aggressive accumulation of water expands the polymer matrix, helping in the access of microbes to the entire polymer matrix. The most likely points of attack by microbes on hydrocarbon polymers are near or at the end of molecule chains.

### 3.3 Initial Breakdown of Polymer Chains

The microbes break down the complex polymer chains into simpler organic monomers, thus allowing consumption of the entire polymer matrix. In this process, the microbes secrete some sort of signaling molecules which other microbes can detect. This signaling process, called quorum sensing, is an invitation to other microbes to join the feast. At this stage, volatile organic fatty acids, hydrogen, and $CO_2$ are formed.

### 3.4 Breakdown Continues

As the different types of microbes join the feast, each one uses different elements of the polymer or various by-products of the intermediate biological reactions as their food source. This reaction breaks down the complex polymer chains. Certain enzymes from microbes begin reducing the complex polymer branching, while others look for bulkier chains similar to fatty acids. A syntrophic environment comprising various species of microbes is established to complete the complex chemical steps of biodegradation. Throughout this process, microbes continue to multiply through quorum sensing.

### 3.5 Final Stages of Breakdown

The reduction of molecular weight occurs throughout the chains of the original polymeric material. During the biodegradation process the molecular weight of the polymer decreases and its distribution becomes broader. As the individual polymer chains completely biodegrade, biomass (humus), and biogases (methane and carbon dioxide) are left behind. Carbon dioxide produced in the intermediate steps is consumed in each subsequent step; therefore, not much is left at the end. Methane can then be captured for energy use [14].

## 4 Factors Affecting Biodegradation

The following are the major factors which affect the biodegradation process:

1. Substrate-related factors
2. Organism-related factors
3. Environmental-related factors.

### 4.1 Substrate-Related Factors

The following are the substrate-related factors:

- Nature of pollutants
- Physico-chemical properties
- Concentration
- Biodegradability
- Toxicity
- Chemical nature
- Volatility
- Polarity.

### 4.2 Organism-Related Factors

The following are the organism-related factors:

- Population density
- Composition
- Intra/inter specific interaction
- Enzyme activity
- Turn over number
- Adaptation.

### 4.3 Environmental-Related Factors

The following are the environmental-related factors:

- Temperature
- pH
- Oxygen availability
- Nutrient sources C and E
- Salinity.

## 5 Conditions for Studying Biodegradation

In the ground, fibers can be subjected to aerobic or anaerobic atmospheres. In most aquatic conditions, and in the top few centimeters of soil, sufficient oxygen is present to provide aerobic conditions. In contrast, anaerobic conditions are found in water-logged soils, aquatic sediments, deeper soils, and landfills. As both these conditions are present in real situations, biodegradation studies of fibers and textiles have been assessed under both aerobic and anaerobic conditions.

## 5.1 Aerobic Incubations

Experimental set-up of aerobic incubations is much simpler than that of anaerobic conditions. Consequently, most studies evaluating the biodegradation of fibers and films have been carried out under aerobic conditions. Moreover, fungi play a vital role in the breakdown of polymers, and many of these are strict aerobes. Certainly, oxygen serves as the terminal electron acceptor under aerobic conditions. The main requirements of these aerobic studies are to confirm that the fibers are accessible to the microorganisms and have an adequate supply of oxygen. Thorough evaluation of the biodegradation process requires the experimental set-up to allow the collection of the biodegradation products or residual polymers, and $CO_2$ liberated during the mineralization of the fiber or film.

One of the easiest ways for aerobic culturing (if $CO_2$ is not collected) is to add the fiber or film and microbial inoculum to a container with a liquid medium. This should be covered by means of a sterile foam plug, which allows air to get into the container while stopping foreign microorganisms. The container may be placed on a rotary shaker to increase the rate of aeration. Even without shaking, if the surface area of the liquid is high and the depth of the liquid is low, there is enough oxygen diffusion. The preparation of the medium mainly depends on the aim of the aerobic experiment. In most cases, the medium contains only inorganic salts (including ammonium and phosphate or nitrate), and the polymer is the main source of carbon for the heterotrophic microorganisms. If the fiber contains nitrogen and sulfur, such as in wool and silk, the inorganic nitrogen and sulfur sources may be omitted as the fiber serves as the carbon, nitrogen, and sulfur sources. For example, media devoid of nitrogen salts have been used in study of chitosan-gallen and poly(L-lysine)-gellan fibers by filamentous fungi, and these two nitrogen-containing polymers served as the carbon and nitrogen sources for the fungal growth [11].

## 5.2 Anaerobic Incubations

As mentioned in the previous section, establishing experimental set-up and maintaining conditions suitable for growing anaerobic cultures are more difficult compared to the same for aerobic cultures. However, the use of serum bottle modification of the Hungate technique is now common in many laboratories. As stated previously, the formulation of the medium depends on whether the fiber or fabric is to serve as the sole source of nitrogen, carbon, or sulfur. Moreover, the formulation of the medium for the anaerobic culture depends upon which terminal electron acceptor is to be considered in the study. Terminal electron acceptors include nitrate, Fe(III), Mn(IV), and sulfate. Moreover, bicarbonate ($CO_2$) serves as the terminal electron acceptor for methanogenesis. Fermentation, in which some oxidized organic compound serves as the terminal electron acceptor, also occurs under anaerobic conditions [11].

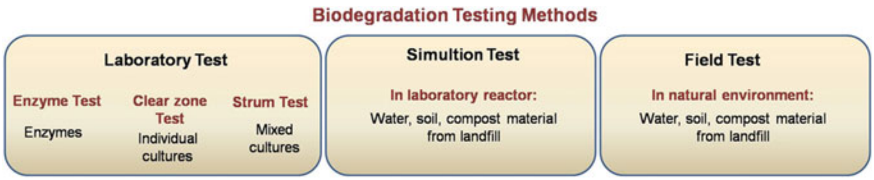


**Fig. 7** Schematic diagram showing different types of biodegradation testing methods [15]

# 6 Assessment of Biodegradation

In general, biodegradation of polymers is determined using three types of testing methods, namely field tests, simulation tests, and laboratory tests [15]. A schematic overview of these testing methods is provided in Fig. 7. In field tests, biodegradability is tested under ideal and practical environmental conditions, for example, burying the sample within soil, placing in the lake or river, or conducting a full-scale composting process. In the simulation test, degradation of the sample is carried out within soil, sea water, or compost in a laboratory under controlled conditions of temperature, pH, and humidity. On the other hand, laboratory biodegradation testing is conducted using defined media, which is mostly synthetic media, inoculated with mixed microbes or individual microbial strains.

The standard test methods for assessing biodegradation of plastics or polymers are detailed in Table 1. A list of test method and standards for assessing biodegradation of chemicals in general can be found in [15]. In the case of fibers, which belong particularly to the polymer group, physical measurements are normally used to evaluate the initial microbial attack on the substrate. These methods are weight loss measurement, measure of the loss of mechanical strength, and microscopic examination. As the biodegradation of the fiber continues, individual small molecules are released and chemical analyses of monomers and products of mineralization can be performed. Frequently, many of these methods are used in a single study to confirm and characterize the biodegradation of the test material.

## *6.1 Detecting Subtle Changes in Fiber Structure or Composition*

The initial reaction during biodegradation of a fiber may produce small deviations in its structure or composition. These are usually detected using very refined instrumental methods. Fourier transform infrared spectroscopy (FTIR) or infrared spectroscopy is often used to detect chemical changes in the fiber. X-ray diffraction (XRD) can be used to study the changes in the crystal structure of fabrics during biodegradation. This method helps to measure changes in the crystallinity. Changes in crystallinity of polymers can also be characterized using solid-state cross-polarization/magic-angle-spinning (CP/MAS) 13C-nuclear magnetic resonance (NMR) spectrometry [11].

**Table 1** Standards for assessing biodegradation of polymers [15]

| Standard | Title |
|---|---|
| ASTM G21-96 | Standard practice for determining resistance of synthetic polymer materials to fungi |
| ASTM G29-96 | Standard practice for determining algal resistance of plastic films |
| DIN IEC 60068-2-10-1991 | Elektrotechnik; Grundlegende Umweltpr, fverfahren; Pr, fung J and Leitfaden: Schimmelwachstum; (Identisch mit IEC 60068-2-10: 1988) |
| EN ISO 846-1997 | Plastics: evaluation of the action of microorganisms |
| IEC 60068-2-10-1988 | Elektrotechnik; Grundlegende Umweltpr, fverfahren; Pr, fung J: Schimmelwachstum |
| ISO 846-1997 | Plastics: determination of behavior under the action of fungi and bacteria. Evaluation by visual examination or measurement of changes in mass or physical properties |

### *6.2 Visual Observation and Microscopy*

The first indication of biodegradation of a fiber or film is the change in its appearance. This change can be viewed with the naked eye as it occurs on a macroscopic scale. Poly (3-hydroxybutyrate) film's appearance after incubation in an anaerobic culture for 10 days is shown in Fig. 8. It shows the obvious change in its appearance; the top strip was incubated in a sterile medium, whereas the bottom strip was incubated in the viable culture.

This type of biodegradation can also be detected by placing a polymer on the surface of an agar plate or an aqueous medium. Microscopy is frequently used to detect physical changes and microbial colonization in fibers. Figure 9a shows the colonization on a poly (L-lysine)-gellan fiber by the fungus *Curvalaria* sp. Prior to microscopic examination, the fibers (1.5–2 cm in length) were incubated with this fungus in aqueous medium for 40 days. In Fig. 9b, the biodegradation led to the breakdown of the fiber at the location indicated by the arrow. Scanning electron microscopy (SEM) is also used to view the effects of biodegradation; this provides much higher magnification than light microscopy. In Fig. 9b, SEM was used to observe the damage to flax fiber incubated for 13 days with the cellulolytic bacterium *Cellvibrio fibrivorans*. This image shows that the fibers remained cylindrical but they were shortened by the microbial activity.

### *6.3 Measuring Weight Loss*

Biodegradation of fibers or films results in the dissolution of part or all of the material, resulting in an overall loss of weight. Actually, measuring weight loss is the common method for detecting biodegradation of films or fibers. Weight loss measurement was one of several methods used to study the biodegradation of flax fibers by two strains of *Cellvibrio*. Measuring weight loss of polymers has also been used to follow biodegradation in anaerobic culture systems [11].

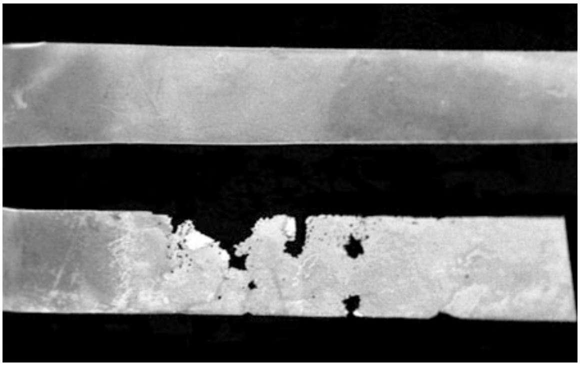

**Fig. 8** Biodegradation of poly (3-hydroxybutyrate) films under methanogenic conditions. The *top strip* was incubated in sterile medium and the *bottom strip* was incubated in anaerobic cultures for 10 days at 35 °C. The original strip dimension was 0.016 mm thick and 1 cm × 7 cm [11]

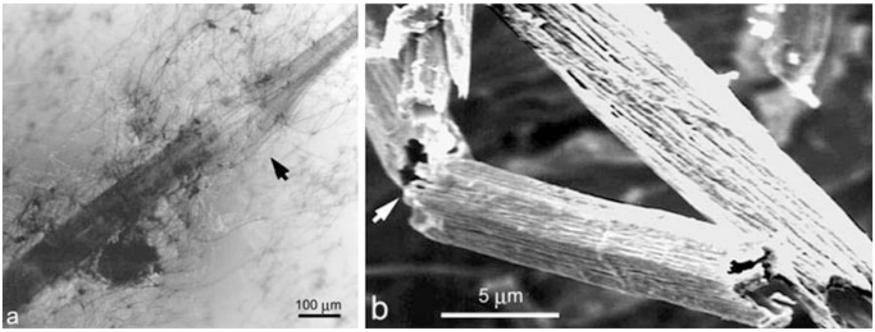


**Fig. 9** **a** Examination of a poly (L-lysine)-gellan fiber by light microscopy showing growth of the fungus *Curvalaria* sp. **b** Scanning electron micrograph of flax fibers after 13 days of incubation with *C. fibrivorans* at 28 °C. The fiber fracture is indicated by the *arrow* [11]

## *6.4 Tensile Properties (Breaking Load)*

Hydrolysis of chemical bonds during microbial depolymerization of macromolecules weakens fibers, and this can be detected by measuring tensile properties. For example, in a research study, the researchers buried pieces of silk fabric (1 cm × 1 cm) in soil and these were incubated for up to 2 months. Then yarns were removed from the fabric and tested under tensile loads. Prior to burial, the mean breaking load of the warp yarn was 297 g-force, whereas after burial, this was significantly decreased to only 2 g-force [11].

**Table 2** Major products of microbial mineralization under aerobic or anaerobic conditions [11]

| Conditions | Substrate | Inorganic products |
|---|---|---|
| Aerobic | Organic-C | $CO_2$ |
| | Organic-H | $H_2O$ |
| | Organic-N | $NH_3$, $NO_3$ |
| | Organic-S | $SO_4^{2-}$ |
| Anaerobic | Organic-C | $CO_2$, $CH_4$ |
| | Organic-H | $H_2$, $H_2O$ |
| | Organic-N | $NH_3$ |
| | Organic-S | $H_2S$ |

### *6.5 Detecting the Products of Mineralization*

The most common products resulting from microbial mineralization are listed in Table 2. As can be seen, products of mineralization from organic carbon as well as sulfur and nitrogen from the substrates can provide excellent indication of microbial degradation [11].

### *6.6 Detection of Intermediates of Biodegradation of Fibers and Films*

Apart from detecting the mineralization products resulting from extensive or complete degradation, detection of intermediates resulting from depolymerization and containing molecules with various molecular sizes can be performed to assess biodegradation. These intermediates are commonly characterized using size exclusion (gel permeation) chromatography, often using high performance liquid chromatography (HPLC) methods.

## 7 Biodegradation Studies of Natural and Synthetic Fibers

### *7.1 Natural Fibers*

#### 7.1.1 Cellulosic Fibers

Cellulose is the main constituent of cotton fibers. It is highly susceptible to hydrolytic and oxidative degradation by microorganisms such as fungi and bacteria which live in the air, water, and soil. The genera of fungi which are most active are *Chaetomium* sp., *Fusarium* sp., *Myrothecium* sp., *Memnoniella* sp., *Stachybotrys* sp., *Verticillium* sp., *Alternaria* sp., *Trichoderma* sp., *Penicillium* sp., *and Aspergillus* sp., and the species of bacteria which lead to considerable biodegradation are *Cytohaga* sp., *Cellulomonas* sp., *Cellvibrio* sp., *Bacillus* sp., *Clostridium* sp., and *Sporocytophaga* sp. Cotton degradation by fungi and bacteria occurs in different ways. Attack by fungi starts at the cracks on the fiber surface or at the fiber ends, and degradation proceeds from the inner to outer layer of the fibers. In contrast, cotton degradation by bacteria starts from the fiber surface and continues to the inner layers of fibers. Cotton fiber is more easily degraded by fungi than bacteria as the later need higher amounts of moisture and saturated cotton fabrics for the entire stages of the degradation process [16].

Depolymerization of cellulose macromolecules is the main reason for the reduced molecular weight and strength, increased solubility, and changed crystallinity occurring because of the cotton biodegradation. Biodegradation of textile materials leads to strength deterioration, staining, discoloration, and bad odor, and causes serious functional, esthetic, and hygiene problems in the products which are still in use or, in the case of historic textiles, that need to be preserved [16]. In a study, cotton samples recovered from a deep-ocean shipwreck site after 133 years of submersion were studied for biodegradation. Two types of cotton samples (dyed and undyed) were studied for morphological and structural changes using optical and SEM and energy dispersive X-ray spectroscopy [17].

Figure 10 shows the optical microscope image of the fiber samples. It was observed that, between these two types of samples, undyed samples were more affected by the microorganisms. Because of the biocidal activity of the tin mordant present in the dyed cotton samples, they were less affected. Biodegradation in the undyed samples occurred because of two types of cellulolytic microorganisms: (1) rod-shaped which resulted in an exposed fiber interior with characteristic grooves having the same dimension as the microorganisms and (2) oval-shaped which penetrated the fiber wall and created holes of their own dimension. When the undyed fiber samples were treated with 18 % NaOH, the localized microbial degradation resulted in fragmentation of fibers, as shown in Fig. 11.

In contrast to the undyed samples, the dyed samples showed less swelling and damage to the primary wall and did not show horizontal surface fragmentation or splitting, which is commonly observed in undyed samples [17].

Park et al. [18] conducted a biodegradability study of natural as well as regenerated cellulosic fibers. Fibers considered for this study were cotton, linen, viscose rayon, and cellulose acetate. Cotton and linen fibers are hydrophilic and also have relatively high crystallinity and orientation, whereas regenerated cellulosic fibers such as cellulose acetate and viscose rayon have more amorphous and less crystalline regions. Viscose rayon is more hydrophilic than most of the natural cellulose fibers, while cellulose acetate is less hydrophilic because of the substitution of acetyl groups ($–COCH_3$) for some of the hydroxyl groups in the molecules [18]. Cotton, linen, viscose rayon, and cellulose acetate fibers all have cellulose but differ in crystallinity, degree of polymerization (DOP), chemical compositions, and manufacturing processes. Moreover, each fibrous material has different non-cellulose content and composition. The biodegradability of these fibers was evaluated by various test methods such as the activated sludge test, soil

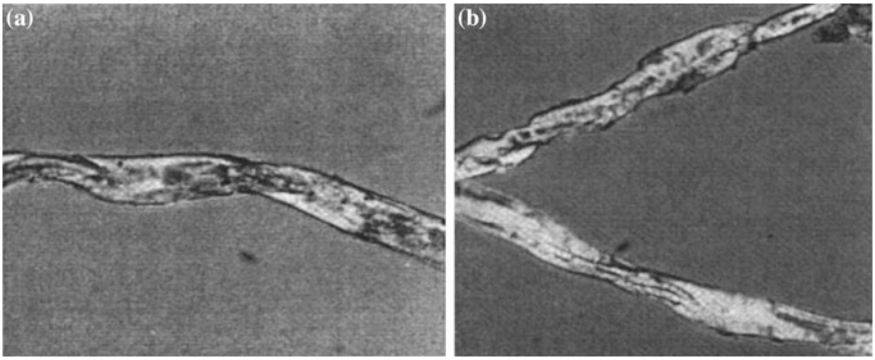

**Fig. 10** Optical microscopic image of historic fibers. **a** Historic dyed cotton. **b** Historic undyed cotton [17]

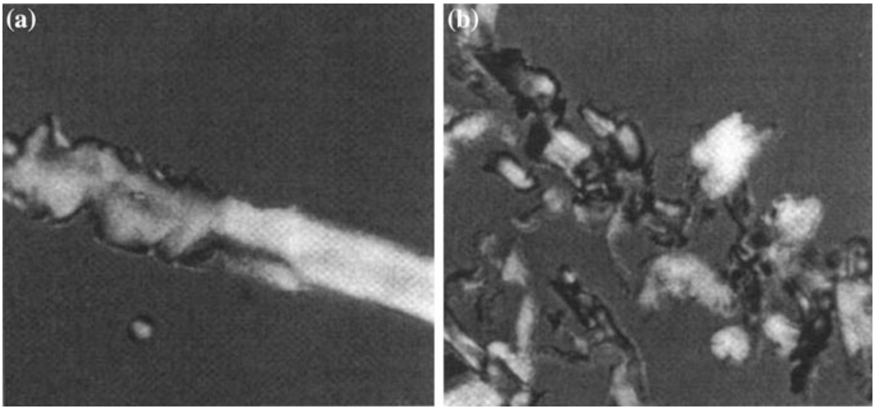

**Fig. 11** Optical microscopic image of historic undyed fiber after 15 min in 18 % NaOH. **a** Intact and degraded fiber segment. **b** Degraded fibers [17]

burial test, and enzymatic hydrolysis test, after which the results were compared. The changes in the internal structure of fiber samples were also observed by XRD. The enzymes used for the hydrolysis test was *Trichodema viride* [18]. The following are the results observed from the various test methods:

- The biodegradability (activated sewage sludge test, soil burial test, and enzyme hydrolysis) was highest in viscose rayon, followed by cotton and cellulose acetate. Linen fiber showed fickle behavior. While showing the greatest biodegradability in the soil burial test, linen showed lower biodegradability than that of viscose rayon and cotton in other tests.
- From the microscopic observations, it was observed that the color of the specimen surface turned brown and black as a result of the action of microorganisms (see Fig. 12).

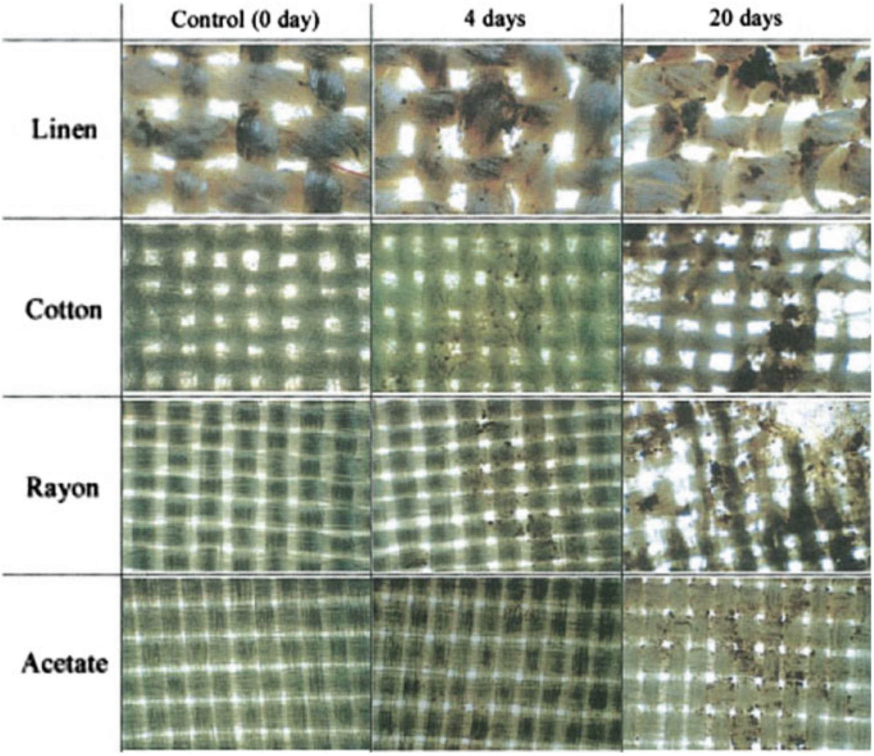


**Fig. 12** Microscopic photos of specimens after burial test [18]

**Table 3** Crystallinity of specimens subjected to soil burial test [18]

| Specimen | Control | 4 days | 8 days | 12 days | 16 days | 20 days | 24 days |
|---|---|---|---|---|---|---|---|
| Linen | 73.7 | 77.8 | 76.4 | 77.6 | – | – | – |
| Cotton | 71.8 | 75.8 | 72.8 | 70.1 | 70.0 | 68.6 | 65.9 |

- Results from X-ray analysis showed that crystallinity of linen and cotton increased a little at the beginning, but decreased continuously thereafter. The crystallinity data is provided in Table 3.
- From the correlation analysis between the properties of cellulose fibers and biodegradability, it was observed that moisture regains and biodegradability were most closely correlated [18].

In another study, the influence of easy-care finishing on the biodegradation of cellulose fibers was investigated. In this study, cellulose fibers were treated with a non-formaldehyde-containing finish based on imidazolidinone [1,3-dimethyl-4,5-dihydroxyethylene urea (DMeDHEU)]. The biodegradability of cellulose fibers (finished and unfinished) was assessed by enzymatic hydrolysis and the soil burial test. The structural changes of the fiber after different period of biodegradation were observed using electron microscopy and spectroscopic analyses, and DOP, crystallinity, tensile strength, and polymer solubility measurements [15].

It was observed that the finishing of cellulose fibers with DMeDHEU enhanced the fiber properties in wear and care, but decreased biodegradability. The results of the soil burial test after different periods of incubation time showed that the rotting process caused by microorganisms was quicker for unfinished than finished samples (see Fig. 13). After 12 days of soil burial, the unfinished cotton sample was degraded severely and broken down into pieces. The less color change in finished cotton samples also proved the lower level of biodegradability [15].

The same trend of results was also observed in other tests carried out for measuring the level of biodegradability. Finishing of cotton with DMeDHEU led to the formation of covalent bonds between the hydroxyl groups of the finish and those present in the cellulose molecules, strengthened the less ordered amorphous regions, and decreased the degree of fiber swelling and hydrophilicity. These were the reasons for reduced biodegradability in finished cotton samples, since the enhancement in macromolecular arrangement and the decreased amount of moisture were less favorable conditions for the development of microorganisms [15].

In another study, Klemencic et al. [19] studied the efficiency of different chemical forms of silver in protecting cellulose against biodegradation using a soil burial test. Cotton fiber samples were treated using a nanopowder of elemental silver with particle size of 30 nm ($Ag^{-1}$), dispersion of AgCl ($Ag^{-2}$), and colloidal silver ($Ag^{-3}$) of various concentrations. The extent of biodegradation was measured by SEM, tensile strength, DOP, color measurements, and FTIR spectroscopy. The results showed that a strong agglomeration of $Ag^{-1}$ led to its inadequate antimicrobial activity, since it was controlled only by $Ag^{+}$ released from the surface of elemental silver by reduction. Even with the agglomeration, the concentration of $Ag^{+}$ released by the alienation of AgCl of the finish $Ag^{-2}$ in the presence of moisture was high enough to offer great protection against fiber biodegradation. The great protective properties of $Ag^{-3}$ were perhaps caused by the synergistic action of Ag nanoparticles and $Ag^{+}$ cations [19].

Warnock et al. [20] studied the biodegradation properties of three cellulosic fabrics, namely cotton, rayon, and Tencel under soil burial tests. The type of soil utilized for this study was Captina silt loam soil (siliceous, active, fine-silty, mesic Typic Fragiudult). Optimum soil moisture of approximately −33 kPa, which is equal to 18 % gravimetric moisture, was sustained through rainfall and supplemented by irrigation during the study [20]. It was understood from the constant decomposition rate of the fabrics in soil over time that the degradation process followed zero-order kinetics in which substrate concentration did not influence the rate. The results showed rapid biodegradation of viscose rayon, intermediate biodegradation of cotton, and slow biodegradation of Tencel. Figure 14 shows the plots of percentage recovery of fabric versus time and this suggests that fabric biodegradation could be by zero-order kinetics. The calculated half life values of

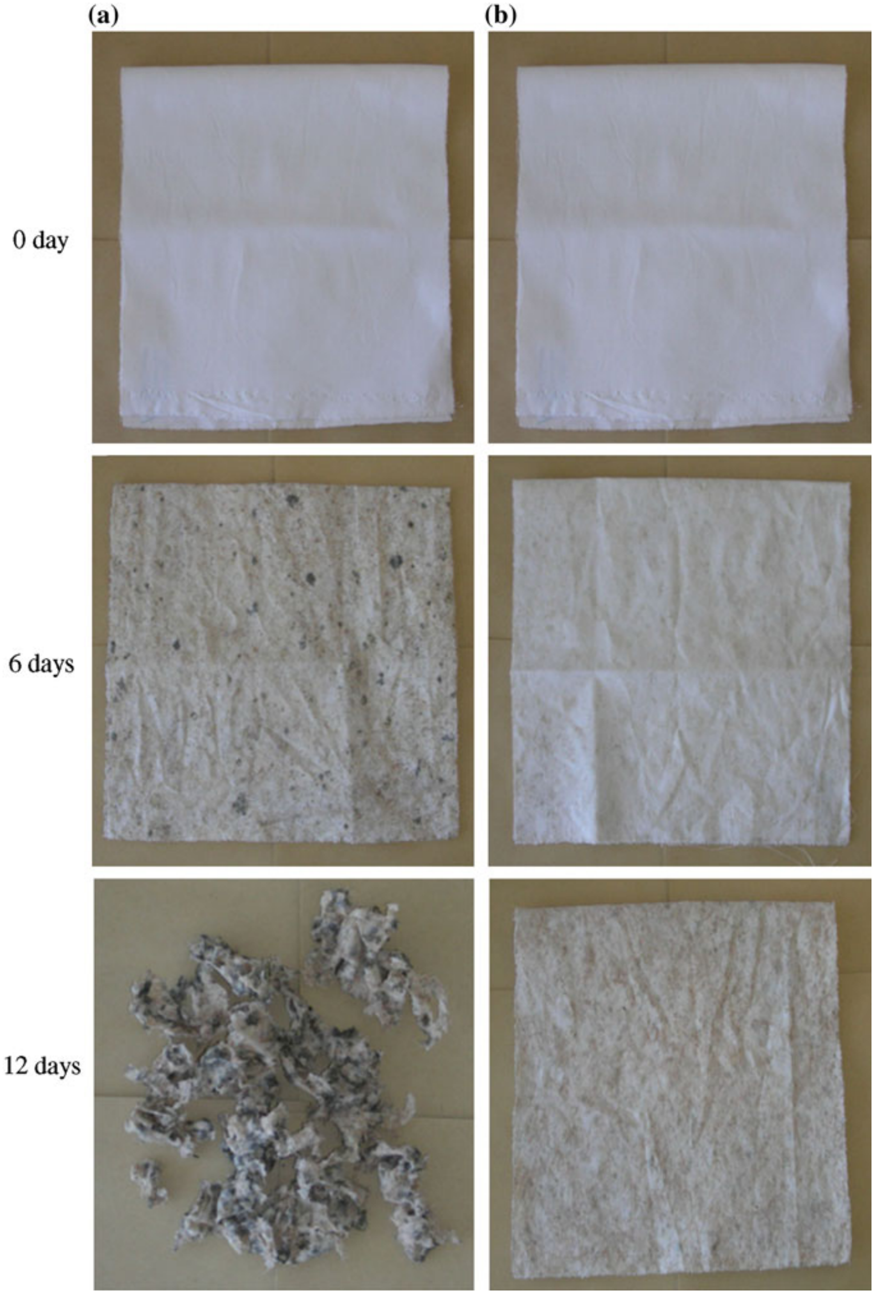


**Fig. 13** Photos of unfinished **a** and finished **b** cotton samples after 0, 6, and 12 days of soil burial [15]

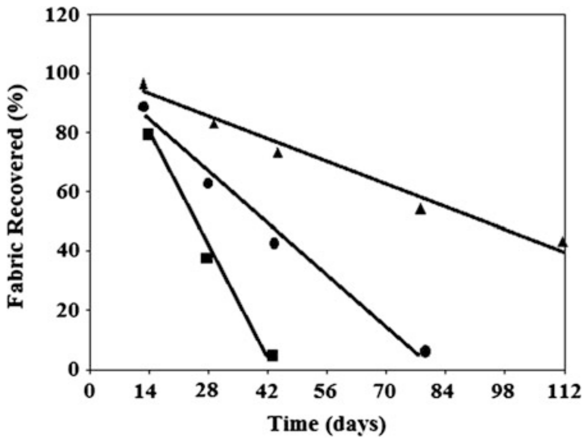


**Fig. 14** Zero-order biodegradation of rayon, cotton, and Tencel® fabrics in a field study [20]

rayon, cotton, and Tencel were 22, 40, and 94 days, respectively. Cotton and rayon were found to be highly susceptible to decomposition [20].

Further, Li et al. [21] carried out a biodegradability study on cotton and polyester fabrics. The biodegradability of fabric was tested in both laboratory and large scale composting environments and results were compared. Cotton fabric used in this study was jersey with three levels of finishing treatments (softener added, resin added, and scoured and bleached), and, in the case of polyester, jersey fabric was used. In the laboratory test, the evolution of $CO_2$ was monitored and integrated to determine the biodegradation rate by ASTM D5988-03 method in natural soil, and the loss of weight was measured after biodegradation in enzyme solutions. The same set of fabrics was buried in the composting environment for 3 months. The loss of weight and fabric morphology after biodegradation was studied to evaluate and compare the biodegradability with that obtained in the laboratory. The cotton fabric with resin showed a comparatively slow degradation rate as compared to the cotton fabric with softener which had an accelerated degradation rate. All cotton fabric samples were considerably more degraded in the compost environment than under the laboratory conditions and were confirmed to be 'compostable.' The polyester fabric exhibited a slight initial degradation, but the fabric stayed undamaged under both compost environment and laboratory conditions [21].

Frisoni et al. [22] studied the biodegradability of steam-exploded flax fibers which are surface modified through acetylation heterogeneously using acetic anhydride and sulfuric acid as catalyst. The level of biodegradation of acetylated fibers was evaluated by measuring their change in weight after a period of exposure to microorganisms. The results showed that after 13 days of exposure with previously secluded cellulolytic *CellVibrio* sp., biodegradation decreases with an increasing degree of acetylation. After biodegradation the fibers show a higher acetyl content than before the experiment, indicating that the bacteria especially biodegrade unsubstituted cellulose [22].

In another study, Modelli et al. [23] studied the level and rate of degradation of flax fibers, both in the pure form and after surface modification of the fibers (acetylation with acetic anhydride or poly ethylene glycol (PEG) grafting). The biodegradation test of the fibers was carried out under laboratory conditions in two different environments. First, the degradation of the fibers under aerobic conditions by the action of microorganisms present in the soil was assessed according to ASTM 5988-96 by monitoring $CO_2$ evolution and, secondly, in vitro biodegradation experiments were carried out by exposing the fibers to pure cultures of *CellVibrio dibroVorans* bacteria and measuring the weight loss as a function of time. The results showed that the level of degradation of acetylated fibers in soil was almost same as that of native fibers, while in the pure culture, acetylated fibers were biodegraded at a slower rate than unmodified fibers. The reverse was the case with the PEG grafted fibers, which degraded at a slower rate than native flax fibers in soil and at a comparable rate upon in vitro exposure to the bacterial culture. The dissimilar biodegradation kinetics observed in the two biodegrading environments resulted from the differences in abiotic factors, biocenoses, and biodegradation assessing methods. However, the final level of biodegradation was the same for unmodified and modified fibers, both in pure culture and in the soil, showing that the surface chemical modifications did not appreciably affect the biodegradability of the flax fibers. Figure 15 compares the SEM micrographs of the three different flax fibers after 13 days [23].

The biodegradability of natural fibers which are used in the automotive industry, such as coir, coir with latex, and sisal, was studied by Salazar et al. [24]. The biodegradation of these fibers was determined by monitoring the production of carbon dioxide ($CO_2$) and fungal growth. The contents of total extractives, holocellulose, carbon, lignin, nitrogen, ashes, and hydrogen of the fibers, were determined in order to discover their actual content and to comprehend the results of the biodegradation tests. The production of $CO_2$ indicated low biodegradation, i.e., about 10 mass%, for all the materials after 45 days of testing. In the same period of ageing the level of sisal fiber degradation was four times greater than that of coir with latex. The fungal growth test showed a higher growth rate on sisal fibers, followed by coir. In the case of coir with latex, it was understood that the fungal growth was not strong, because latex produced a bactericide or fungicide for its preservation during bleeding. After 90 days of ageing, the evaluation of samples showed breaking of the fibers, predominantly in coir without latex and sisal fibers, showing fungal attack and biodegradation processes.

### 7.1.2 Protein Fibers

Wool is a natural and renewable animal fiber and is made solely from keratin. A tough, insoluble protein with an exceptional structure makes it inherently resistant to water, acids, sunlight, mildew, and rotting under normal conditions. Wool fibers and their products have a superior resistance to damage by microorganisms for the following reasons:

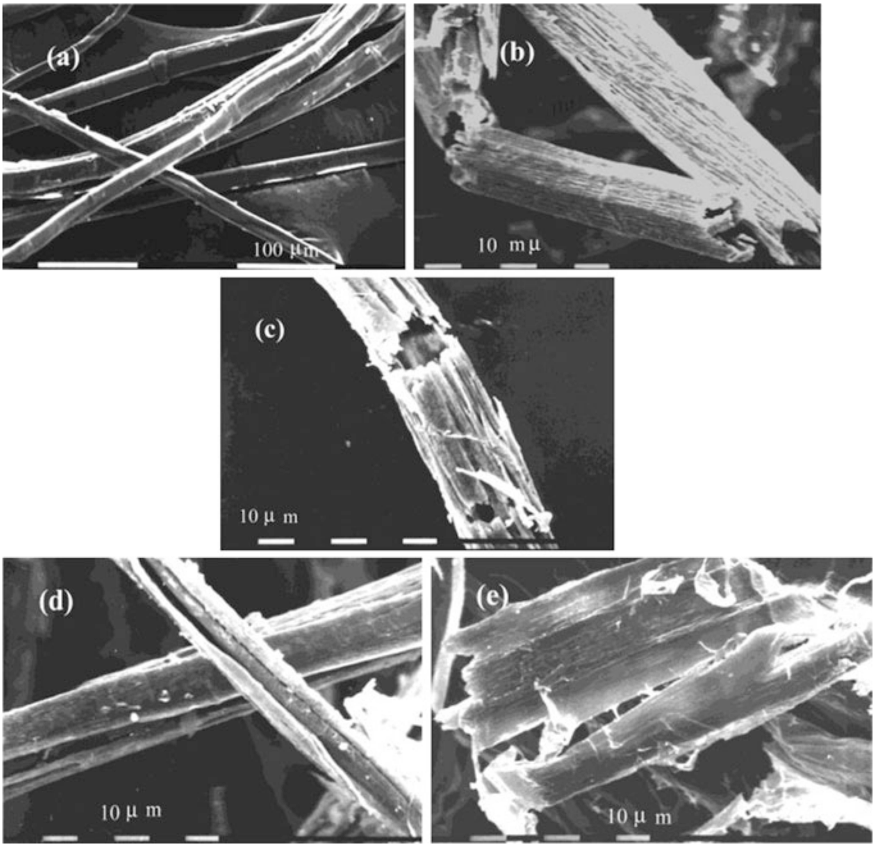


**Fig. 15** SEM micrographs of flax fibers. **a** Fibers before biodegradation. **b** Unmodified fibers after 13 days of exposure. **c** PEG-grafted fibers after 13 days of exposure. **d** Acetylated fibers after 13 days of exposure. **e** Acetylated fibers after 27 days of exposure (in vitro studies) [23]

- Wool fiber surface is covered by a tough, water repelling membrane which prevents access by any microorganisms and enzymes
- Wool-keratin is an extremely cross-linked structure with a high concentration of sulfur links.

Under normal storage conditions, clean dry wool is not attacked by fungi and bacteria. However, if wool materials are kept under wet and warm conditions, or buried under soil, mildew and fungal growth can progress and feed on the lightly cross-linked regions of the fiber, such as the intercellular cement binding the cortical cells together. The fiber starts to fibrillate, and other enzymes can then attack the rest of the fiber. Soil possesses collections of microorganisms which ultimately decompose wool fibers and other keratin materials. Because wool fiber decomposes in soil, it can be used as a slow discharge fertilizer, and acts as a source of nutrients (nitrogen-based) and sulfur over a much longer period than conventional fertilizers. Although slow, the natural biodegradation of wool also suggests that any wool product sent to landfill breaks down over time, unlike synthetic products [25].

Measurement of vulnerability of different types of keratins and fibrillar proteins to digestion by keratinolytic fungus was carried out by Stah et al. [26]. The study was carried out for both normal and modified proteins. The keratins and fibrillar proteins, namely collagen, feather, hoof, wool, horn, horsehair, mohair, and silk, underwent digestion with *Microsporum gypseum* over a period of 21 days. The digestion rate of keratin and fibrillar proteins was in the following order (from highest to lowest): collagen, feather, hoof, wool, horn, horsehair, and mohair. Silk was only very slowly digested. The best pH for the breakdown of wool fiber by *M. gypseum*, as decided by the loss of breaking strength, was between pH 7.0 and 7.5. The acid limit was about pH 3.6 and the alkaline limit was about pH 8.5. The key factor involved in digestibility of keratins was the DOP. The higher was the DOP, the greater was the resistance of keratin to digestion. Primary evidence recommended that the proteolytic enzyme mixture produced by *M. gypseum* includes endo- and exo proteinases, which were involved in the degradation of wool.

Biodegradation study of Merino wool fiber was carried out by Brady et al. [27] with various strains of *Streptomyces* bacteria incubated with basalt salts medium for extended periods. The results showed that, during the incubation period, the degradation of wool fiber in the presence of Streptomyces strains became marked. When the fibers were separated from the basal salts medium and dried, the partially degraded wool fibers were seen to lose their luster and, as compared to the wool fibers from the control flask, they looked dull when viewed using low magnification light microscopy. Wool fibers were considerably degraded by the bacteria. While the original wool fiber was intact, initial enzyme attack on wool fiber caused loosening of the cuticle cells leading to reduced brightness and felting as the raised cuticle cells interlocked. Finally, the cuticle cells totally vanished, the cortex of wool fiber was uncovered, and cortical cells were released. The enzymes degraded the cementing material binding the cortical cells together, leaving only the individual cells. Degradation of wool fiber, as indicated by the decrease in dry mass of filterable solids, was 49 % (*Streptomyces rimosus*), 42 % (*Streptomyces griseus*), 25 % (*Streptomyces fradiae* 3739), 22 % (*Streptomyces S.* 5058), and 17 % (*Streptomyces* TK 64), respectively.

Shrivastava et al. [28] studied the biodegradation of wool fiber by the fungus *Trichophyton simii* extracted from soil and fungus *Aspergillus niger* extracted from decomposing wool (sheep wool) fragments. In this study, the degradation of wool fiber was evaluated based on the amount of protein released into liquid culture medium and weight loss. The results showed that non-dermatophytic fungi can attack and utilize keratinous substrates. The fungus was able to extract nutrients from the substrate, although to a lesser extent than dermatophytes such as *T. simii*. Sulfitolysis studies proposed that the stronger attack of *T. simii* was because of its ability to denature hard keratin. *A. niger* seemed to lack this ability and was restricted to the utilization of non-keratinous components. Both the fungi were found to degrade wool fibers. The amount of protein released by *T. simii* from wool was substantially greater than that released by *A. niger*. *T. simii* caused a weight loss of 62 % in wool as compared to 42 % loss caused by *A. niger* at the end of the 2nd week. In uniculture both the fungi caused release of protein from wool. In dual culture the decomposition of wool was found to be decreased in comparison with uniculture.

A soil burial test of wool textiles was carried out by Solazzo et al. [29] to investigate the biodegradation of woolen textiles found during archaeological excavations. The nature and the length of conservations was mainly dependent on the place of burial and parameters such as soil temperature, composition, pH, oxygen content, and contact with wooden coffins or metals. Dyed wool fabrics which were buried for 8 years in bog-type soils in Denmark (Lejre) and Norway (Rormyra) and in marine sediments in Sweden (Marstrand) were assessed by proteomics analysis. The degradation of wool textiles was found to occur through a range of different mechanisms, mainly because of the complex nature of wool itself with its many families of proteins (keratin and keratin-associated proteins) and structures. The physical deterioration of wool fabrics buried at Lejre and Marstrand was mainly caused by microbial activity. In addition to that, hydrolysis of samples took place at Marstrand, and was influenced by the environmental conditions of the sediment, and in particular the alkaline pH, contributing to the degradation of keratins. In contrast, cross-linking resulted from the long-term preservation of fabrics at Rormyra, where temperature, pH, and vegetative composition of the bog prevented microbial activity, and sphagnum moss could preserve wool by binding with keratins.

Silk is another protein-based fiber and is susceptible to biological degradation by proteolytic enzymes. The rate and level of degradation may be highly variable depending on a series of factors related to morphological and structural features of the polymer (film, fiber, and sponge), processing conditions and characteristics of the biological environment, and the presence of various chemical and mechanical stresses.

Degradation behavior of silk fiber has been investigated through exposure to various proteolytic enzymes for different periods of time. Physical, chemical, and morphological features of biodegraded fiber were examined using various analytical techniques. The results from the biodegradation studies of silk fiber concluded that silk fibroin is susceptible to proteolytic attack, but the level of degradation depends on the morphology and structure of the substrate as well as on the type of enzyme used, i.e., on the cleavage site specificity. The onset of enzymatic degradation of silk fiber has been noticed through tensile measurements, which showed a drop of strength and elongation caused by local degradation randomly distributed along the fibers. The tensile properties of biodegraded silk fibers are given in Table 4 [30].

Seves et al. [31] studied the microorganisms developed on silk fiber materials which were buried under the soil and also in laboratory environment. Attachment and growth of a few bacterial species was noticed on the silk fibers buried in the soil. However, no fungi were observed on silk fibers. The growth of bacteria was more on raw silk containing both sericin and fibroin as compared to the degummed silk containing only fibroin, since these bacteria used mainly sericin for their growth. Formation of biofilm on the fabric was observed using electron microscopy and the mechanical properties deteriorated considerably because of extensive damage to the fibers. The SEM image of degummed silk fabric buried under the soil is shown in Fig. 16.

Only the *Pseudomonas* (Burkholderia) *cepacia* type of bacteria could feed and grow on the fibroin using it as the sole source of carbon and nitrogen, and this was evident from the laboratory experiments, which showed that pure culture of *P. cepacia* could form a well-developed biofilm on fibroin as well as hydrolyze fibroin and produce an extracellular enzyme which can attack fibroin [31].

## *7.2 Biodegradation of Synthetic Fibers*

Biodegradation of synthetic polymers involves following steps:

1. Attachments of microorganisms to the surface of the polymers
2. Growth of microorganism utilizing the polymer as the carbon source
3. Primary degradation of the polymer
4. Ultimate degradation.

### 7.2.1 Factors Affecting Biodegradability

Biodegradability of synthetic polymers is essentially determined by the following important physical and chemical characteristics:

1. Availability of functional groups which increases hydrophilicity
2. Size, molecular weight, and density of the polymer
3. Amount of crystalline and amorphous regions
4. Structural complexity such as linearity or branching in the polymer
5. The presence of easily breakable bonds such as ester or amide bonds as against carbon–carbon bonds
6. Molecular composition (blend)
7. Nature and physical form of the polymers such as films, pellets, powders, or fibers [32].

### 7.2.2 Nylon Fiber

The rate of degradation of nylon 6 and nylon 66 fibers may vary with morphology, surface, structure, and molecular weight, etc. In Table 5, different soil organisms (bacteria) and lignin degradation fungi which have been reported to degrade nylon

**Table 4** Tensile properties of biodegraded silk fibers [30]

| Sample | Breaking load (N) | Elongation at break (%) |
|---|---|---|
| Control | 4.68 ± 0.10 | 32.7 ± 1.6 |
| Collagenase | | |
| Day 1 | 3.86 ± 0.13 | 26.3 ± 1.0 |
| Day 3 | 3.86 ± 0.14 | 25.1 ± 1.6 |
| Day 10 | 3.64 ± 0.13 | 25.7 ± 1.0 |
| Day 17 | 3.60 ± 0.12 | 23.5 ± 1.0 |
| α-Chymotrypsin | | |
| Day 1 | 3.84 ± 0.07 | 28.1 ± 1.1 |
| Day 3 | 3.72 ± 0.11 | 27.8 ± 1.4 |
| Day 10 | 3.98 ± 0.09 | 26.4 ± 0.8 |
| Day 17 | 3.78 ± 0.09 | 25.8 ± 0.7 |
| Protease | | |
| Day 1 | 3.74 ± 0.10 | 21.6 ± 1.2 |
| Day 3 | 3.52 ± 0.16 | 20.5 ± 1.2 |
| Day 17 | 3.14 ± 0.12 | 18.1 ± 1.2 |

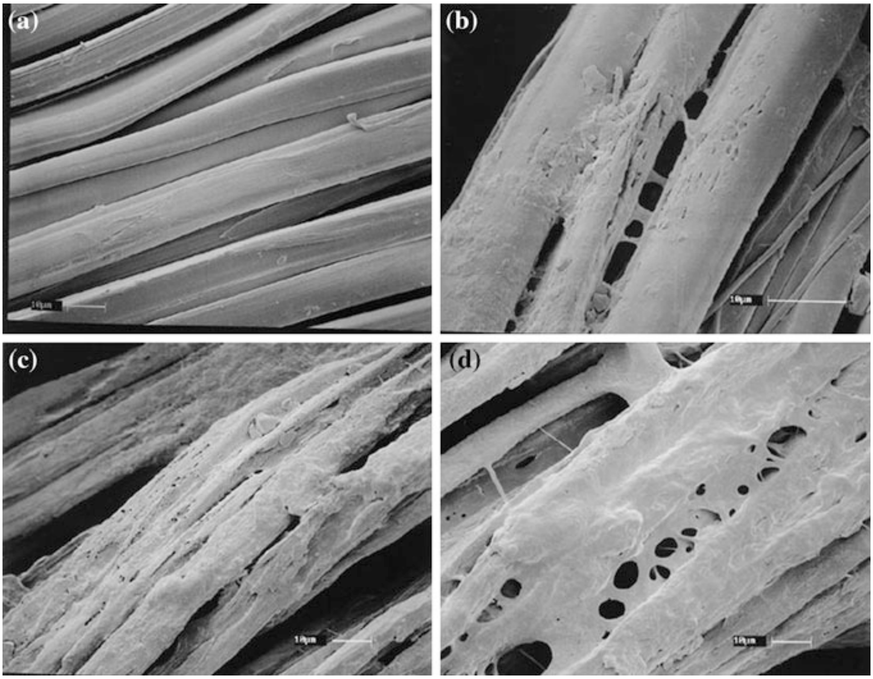


**Fig. 16** SEM micrographs of degummed silk fabric buried in soil. **a**, 0 time. **b**, 30 days of incubation. **c**, **d** 60 days of incubation [31]

fibers are detailed [33]. Biodegradation studies of nylon 6 and nylon 66 fibers by marine microorganisms, namely *Bacillus cereus*, *Bacillus sphericus*, *Vibrio furnisii,* and *Brevundimonas vesicularis*, have been carried out by these researchers [33]. The level and nature of degradation of nylon fibers were assessed using several chemical and physical techniques such as FTIR, DSC, relative viscosity, and EPI-fluorescent microscopy [33].

Degradation of nylon 6 and nylon 66 fibers was confirmed from the weight loss, decrease in viscosity, average molecular weight, and formation of new functional groups, as well as physical damage to the fibers visible under epi-fluorescent microscope over a 3-month period. Also, higher degradation was observed in nylon 66 than nylon 6 and both the fibers experienced the highest level of degradation with *B. cereus*. DSC results showed loss as well as degradation of crystalline region. The results concluded that the marine microorganisms have the potential to degrade nylon polymers [33].

### 7.2.3 Polyester Fiber

Polyester fiber has widespread applications in the textile industry, and its products lead to significant waste generation and environmental pollution, since polyester is highly resistant to biological and atmospheric agents. Recent development in biological techniques for biodegradation of polyester has become a subject of great potential [34]. Zhang et al. [34] studied the biodegradation of PET fiber and diethylene glycol terephthalate (DTP) by lipase and microbes. DTP was considered in this study as the chemical structure is the same as PET and therefore is the best simulating polymer for studying biodegradation of PET fiber. HPCL method was used to study the degradation of DTP. The results showed that more than 90 % of DTP was degraded by microbes in 24 days and 40 % by lipase in 24 h. While the degradation ratio of PET fiber was still weak, it was revealed from SEM images (see Fig. 17) and HPLC analysis that lipase and microbes could act on PET fiber and some cracks were observed on the surface of the fiber [34].

In another study, Mochizuki et al. [35] studied the biodegradability of poly (hexano-6-lactone) (PCL). Poly (hexano-6-lactone) (PCL) is an aliphatic polyester which is vulnerable to digestion by microorganisms such as bacteria and fungi. In this study, the environmental degradation of PCL fibers in activated sludge, soil, and seawater was studied, and the effect of the solid-state morphology of the fiber structure on the level of biodegradation was reported [35]. From the results, it was observed that the degradation of PCL fiber depends on both the fine structure and environmental conditions of the fiber. The half-degradation times of drawn PCL monofilaments are 15–30, 30–40, and 120–150 days for seawater exposure, soil burial, and activated sludge exposure, respectively. The level of microbial degradation decreased with increasing crystalline presence in the fiber resulting from drawing, and with increasing diameter of the fiber. The primary mechanism involved in environmental degradation of PCL fibers was surface erosion with weight loss caused by extracellular degradation enzymes secreted by

**Table 5** Comparison of various soil organisms (bacteria) and lignin degradation fungus for nylon fibers reported in the literature [30]

| Nylon degrading microbes | Bacterial (B)/Fungi (F) system | Nylon 66 or nylon 6 | Reaction conditions | Results |
|---|---|---|---|---|
| *Phanerochaete chrysosporium* | F | 66 | pH—5.0–9.0 Temp. 30 °C. Carbon or nitrogen starvation | CHO, NHCHO, $CH_3$, and $CONH_2$ groups formed in 20 days |
| *Alcaligenes* sp. | B | 6 | Temp. 30–35 °C | Oligomer degradation |
| *Geobacillus thermocatenulatus* | B | 66 | Temp. 60 °C | Decrease in molecular weight from 41,000 to 11,000 in 20 days |
| *Trametes versicolor* | F | 66 | pH—7.0–9.0 Temp. 35–45 °C. Carbon or nitrogen starvation | CHO, NHCHO, $CH_3$, and $CONH_2$ groups formed in 20 days |
| *Flavobacterium* sp. *K172* | B | 66; 6 | pH—7.0–9.0 Temp. 35–45 °C | Oligomer degradation |
| *Pseudomonas aeruginosa* | B | 6 | pH—5.0–9.0 Temp. 30 °C | From activated sludge of nylon 6 factory waste |
| *White Rot Fungus, IZU-154* | F | 66 | With glucose | Decrease in molecular weight from 84,000 to 5,500 in 20 days |

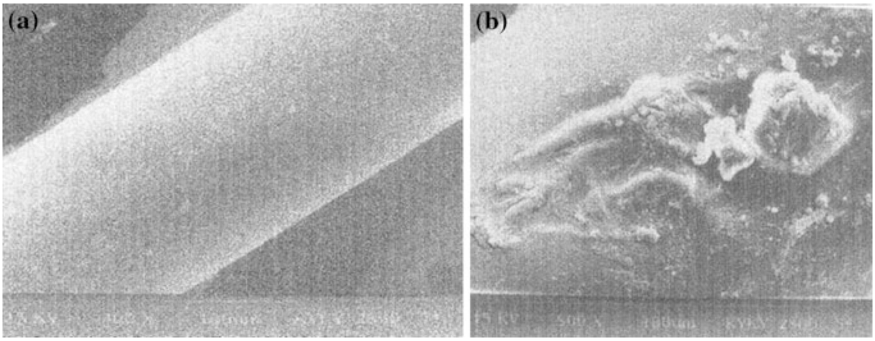


**Fig. 17** SEM images of untreated PET fiber surface (**a**) and PET fiber surface treated with microbes (**b**) [34]

microorganisms. The degradation caused by microbes occurred in two ways: one type was the spherical depression on the fiber surface, which resulted from the localized enzymatic action with colonization and another type resulted from the enzymatic degradation of the amorphous regions, leaving a number of cracks perpendicular to the fiber axis [35].

# 8 Biodegradation of Textile Composites

## *8.1 Banana Fiber Reinforced Biocomposites*

Kumar et al. [36] studied the biodegradability of banana fiber reinforced soy protein composites. The composites were prepared using different volume fractions of alkali-treated and untreated banana fibers with soy protein isolate (SPI) containing various amounts of glycerol (25–50 %) as plasticizer. The biodegradability of these composites was studied using solid media for fungal growth (*A. niger*). The solid media was prepared by dissolving 3.9 g of potato dextrose agar (PDA) in 100 mL of distilled water and the solution was autoclaved for 20 min at 115 °C. Then the solution was poured into a sterile Petri dish under sterile conditions. To observe the fungal growth, some part of the composite was autoclaved at 115 °C for 20 min and put on the PDA media and the remaining part of the composites was used as the nutrients for fungal development. The inocula were prepared by budding the fungi on PDA media at 28 °C for 4–5 days.

The budding of microorganism on the composites is shown in Fig. 18. No microorganism was observed even after 6 months when the autoclaved composite was used as the nutrient for *A. niger* (Fig. 18a) growth. This showed the high resistance of the composites against the fungal growth. In contrast, when autoclaved composites were mounted on solid PDA medium, growth of *A. niger* was noticed after 48 h. Figure 18b shows the budding of *A. niger* on the composite mounted on PDA media. The maximum growth of fungus was noticed after 72 h.

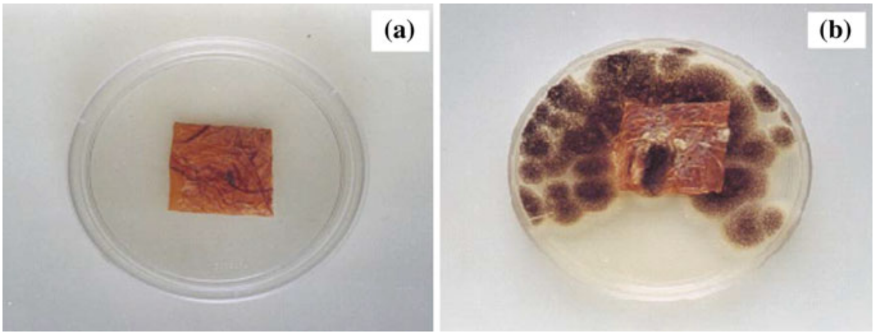


**Fig. 18** **a** No growth of *A. niger* on autoclaved composite and **b** growth on autoclaved composite mounted on PDA media after 48 h [36]

Further, Zaman et al. [37] studied the biodegradability of banana fiber-reinforced LDPE unidirectional composites through a soil burial test. In this study, banana fibers were treated with 2-ethylhexyl acrylate (EHA) mixed with methanol (MeOH) under UV radiation. The treated fiber reinforced composites showed better mechanical properties than untreated fiber reinforced composites. To obtain enhanced properties, optimized banana fibers were again treated with aqueous starch solution (3–7 wt%) for 2–8 min. Degradation tests of starch (6 %) treated and untreated banana fiber/LDPE composite samples were performed in non-calcareous soil (the moisture content of soil was 3.7 % and the pH was 5.5) for different periods of time. After a certain period, the samples were carefully taken out, washed with distilled water, and dried at 105 °C for 6 h and kept for 24 h at room temperature. After drying, the samples were tested to check their mechanical properties to evaluate the degradation. Tensile properties of composites are provided in Table 6. The results showed that the tensile properties (tensile strength, TS and tensile modulus, TM) of starch-treated banana fiber reinforced composites decreased by around 15 % after 120 days of soil degradation, but untreated banana fiber composite lost around 30 % of TM and 37 % of TS. During soil burial tests, water penetrated from the cutting edge of the composites and degradation of cellulose occurred, significantly reducing the tensile properties of the composites.

### *8.2 Abaca Fiber Reinforced Biocomposites*

Shibata et al. [38] prepared biodegradable composites from biodegradable polyesters and surface treated and untreated abaca fibers. Poly (butylene succinate) (PBS), polyester carbonate (PEC)/poly (lactic acid) (PLA) blend, and PLA were used as biodegradable polyesters. Biodegradability of the composites was evaluated by measuring the weight loss after soil burial tests. The composite samples were buried in a 1:1 mixture of black soil and leaf mold soil, and kept at room temperature of 25–30 °C and RH of 80 %. The water content of the soil was

**Table 6** Degradation of tensile strength and tensile modulus of composites during soil degradation tests [37]

| Materials | Degradation time (days) | Degradation in soil | |
|---|---|---|---|
| Untreated banana/LDPE composite | 0 | 19.3 ± 0.5 | 633 ± 25 |
| | 10 | 18.7 ± 0.7 | 611 ± 43 |
| | 30 | 17.5 ± 0.5 | 579 ± 33 |
| | 60 | 15.3 ± 0.9 | 530 ± 51 |
| | 90 | 13.6 ± 1.3 | 493 ± 35 |
| | 120 | 12.2 ± 0.7 | 449 ± 42 |
| Treated banana/LDPE composite | 0 | 26.4 ± 0.5 | 1032 ± 32 |
| | 10 | 25.6 ± 0.9 | 1012 ± 56 |
| | 30 | 24.7 ± 0.6 | 988 ± 39 |
| | 60 | 23.8 ± 1.2 | 953 ± 63 |
| | 90 | 22.5 ± 0.8 | 920 ± 41 |
| | 120 | 21.6 ± 0.6 | 893 ± 67 |

maintained (at about 40 %) by repeated watering. The test was carried out for 4, 8, 12, and 24 weeks. After the soil burial test, the composite samples were removed carefully and washed and dried to a constant weight in a vacuum oven at 40 °C. The weight loss was measured and averaged. The results showed that untreated fiber composites experienced the highest weight loss, demonstrating high biodegradability. The composites containing treated abaca fiber exhibits lower biodegradability than untreated abaca composites. Figure 19 shows SEM images of the composite film surface after being buried in soil for 24 weeks. For composites with untreated fiber, rough surfaces enclosing many cavities were detected. In PBS/untreated fiber composites, both PBS and fiber were biodegraded. For PLA/untreated fiber and PEC/PLA/untreated fiber composites, parts of the fibers were preferentially degraded.

### *8.3 Kenaf Fiber Reinforced Biocomposites*

Anuar et al. [39] studied the biodegradability of kenaf fiber reinforced PLA biocomposites through soil burial tests. The samples were incubated in pots containing soil at almost constant temperature of 26 °C for more than 30 days. The soil moisture content was maintained at 40–50 %. The pots were protected with plastic film to avoid water evaporation from the soil surface. Biodegradation was measured by monitoring changes in weight as a function of burial time. The samples were taken out from the soil in every 5 days. The samples were washed and dried in an oven at 70–90 °C for 2 h. After drying, the samples were weighed and noted. The results showed that the higher the percentage of kenaf fiber, the higher the degradation. Photomicrographs of the composites before and after 40 days in soil burial tests are shown in Figs. 20 and 21.

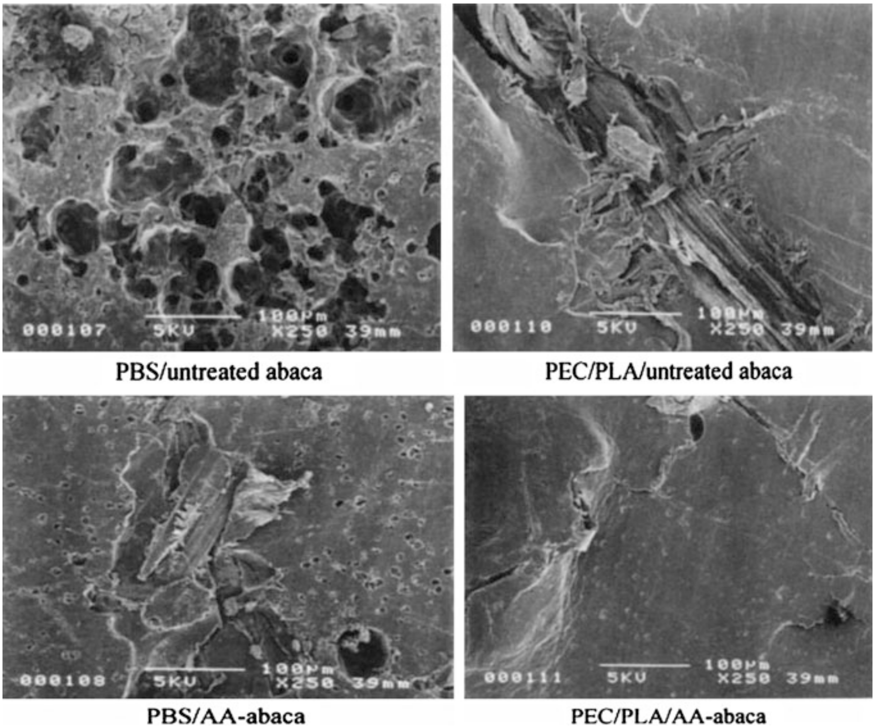


**Fig. 19** SEM micrographs of the film surface of neat resin and composites with 10 wt% fiber loading after 24 weeks in soil [38]

Hidayat and Tachibana [40] studied the degradation of kenaf fiber reinforced PLA biocomposites based on changes in mass and mechanical properties as well as visual and SEM observations. The degradation characteristics were analyzed through enzymatic activity. A natural isolate, *Pleurotus ostreatus*, was used as a degrading agent via entrapment of mycelia in immobilized Ca-alginate beads. This fungus degraded the PLA-kenaf composites by 12, 21, 30 and 48 % in 1, 2, 3, and 6 months, respectively. This was evident from mass change (Fig. 22) and SEM observations. The degradation caused shortening of fibers and decreased mechanical properties by about 84 %.

## 8.4 Cotton Fiber Reinforced Biocomposites

Calabia et al. [41] prepared biodegradable composites using cotton fiber (CF) as a filler in PBS and the biodegradability of the composites was studied with and without silane treatment of cotton fiber. Biodegradability of the composite was monitored under controlled compost conditions at 58 °C based on testing standard ISO 14855-2 using microbial oxidative degradation analyzer (MODA) apparatus.

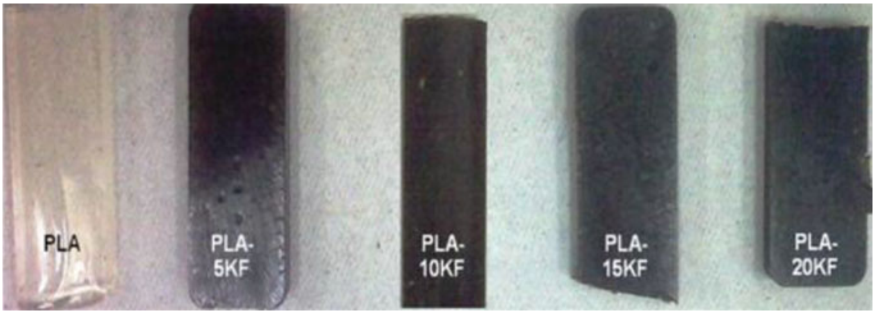


**Fig. 20** Photomicrographs of kenaf fiber reinforced PLA composite (PLA-KF) before soil burial test [39]


**Fig. 21** Photomicrographs of kenaf fiber reinforced PLA composite (PLA-KF) after soil burial for 40 days [39]

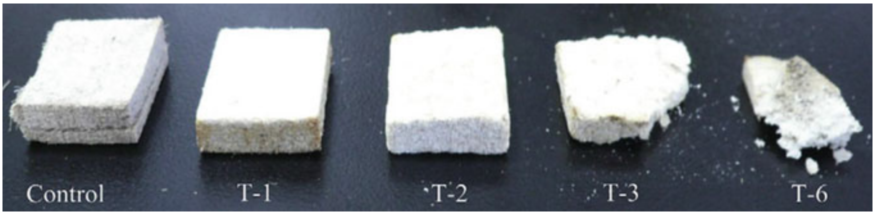


**Fig. 22** PLA/KF composite before (control) and after degradation by *P. ostreatus:* 1, 2, 3, and 6 months' incubation [40]

The biodegradability was also studied for neat PBS for comparison with PBS/CF composites. The results showed that during the first stage of biodegradation, i.e., at 0–30 days, the degradation of neat PBS was slower compared to PBS/CF composites, reflecting that cotton fiber enhanced the degradation of PBS. Also, when the degradation of PBS/CF composites with and without silane treatment was compared, the treated one showed lesser degradation than untreated composites. This was caused by the enhanced interfacial adhesion between PBS and cotton fiber after silane treatment, reducing the penetration of water and microorganisms or enzymes (i.e., cellulase and lipase). In contrast, during the second stage of biodegradation, i.e., at 30–50 days, the results were the opposite. At the end of first stage degradation, the surface of the composite was already collapsed because of the extended exposure to the composting environment and this made the composites more susceptible to microbial access. In the last degradation stage, i.e., at 90–100 days, the levels of biodegradation of both treated and untreated composites were the same. This study concluded that silane treatment of cotton fiber did not affect the biodegradation rate of composites [41].

## *8.5 Flax Fiber Reinforced Biocomposites*

Kumar et al. [42] studied the biodegradability of biocomposites prepared from woven and nonwoven flax fiber reinforced PLA composites with amphiphilic additives as accelerators for biodegradation. The biodegradation of the composites was studied through soil burial tests. The composites were prepared with and without additives. The composite samples prepared from nonwoven fabrics were designed as PFB-NW, PFM-NW, PFD-NW, PFZ-NW, and PF-NW, where B, M, Z, and D represents benzilic acid, mandelic acid, zein, and dicumyl peroxide, respectively. PF-NW represents composites without any additives. Similarly, the composites produced from woven flax fiber were designed as PFB-W, PFM-W, PFD-W, PFZ-W, and PF-W. For the biodegradation test the composite sheets were cut into 40 × 20 mm rectangular specimens and were buried under farmland soil (kept in flower pots) having a pH of 7.5–7.7 and soil humidity of ~98 % maintained by sprinkling water. All specimens buried in soil were kept in a flower pot at room temperature. The composite specimens were dug out from the soil after 20, 30, 40, 50, 60, 70, 80, and 90 days. After that, the specimens were washed and dried at 60 °C in an air oven for 48 h. Then the specimens were weighed to evaluate the biodegradation. SEM images were also taken to observe the surface morphology of the composite specimens. The results showed that, with mandelic acid, the composites showed faster biodegradation with 20–25 % of weight reduction after 50–60 days. In contrast, with dicumyl peroxide additive, the biodegradation of composites was moderately slow and this was confirmed from low loss in weight (5–10 %), even after 80–90 days. This was also confirmed from the SEM images of surface morphology of the biodegraded composites.

In another study, Barkoula et al. [43] studied biodegradability of composites produced from flax/polyhydroxybutyrate (PHB) and its copolymer with hydroxyvalerate (HV). The composites samples were produced using injection molded technique and contained 8 wt% of HV with 20 vol.% of flax fiber. The composite samples were buried under soil openly at a depth of 25 cm to study the effect of biodegradation. At periodic intervals of 4 weeks, a tensile bar was


**Fig. 23** Pictures of different stages of biodegradation of flax/PHB/HV (8 wt%) composites with 20 vol.% fiber after burial in soil [43]

removed from the soil, washed and dried for 3 days at 80 °C and stored for 3 days at room temperature. Then the samples were weighed and tensile tests were performed at a speed of 4.8 mm/min. Figure 23 shows the images of tensile bars after several week of burial under the soil.

The tensile results of the specimens removed after 2 weeks burial showed that the tensile property decreased sharply, but after this period the properties of the composites became constant. In contrast to this, the mass decreased continuously during the first 20 weeks, indicating biodegradation of composites even in these non-optimized surroundings. The sharp drop in the initial modulus and strength of the composites was probably attributed to the debonding caused by moisture absorption in the first 2 weeks. After this initial drop, further effects of degradation on tensile properties were steadier [43].

## *8.6 Jute Fiber Reinforced Biocomposites*

Liu et al. [44] prepared PBS/jute composites and studied the effects of fiber diameter, fiber content, arrangement, forms, and surface modification on the biodegradability using compost-soil burial tests. The composition of compost soil was: water 20 %, organic substance 20 %, rotten leaves 30 %, urea 5 %, and others (sawdust, wastepaper) 5 %. Specimens were removed from the soil after 30, 60, 90, 120, 150, and 180 days and then washed and dried in a vacuum oven at 60 °C. The effect of fiber content on the biodegradability of PBS/jute fiber composite was evident from the weight loss which occurred in the following order: PBS/10 % jute > PBS/20 % jute > PBS/30 % jute > pure PBS film > bulk jute fiber. The PBS/10 % jute specimen lost 62.5 % of its weight after 180 days of burial. On the other hand, weight loss of the specimen was found to decrease with the decrease of fiber diameter because the finer fiber has a better inner structure. The order of weight loss after surface treatment was: PBS/untreated jute > PBS/alkali treated jute > PBS/coupling agent treated jute. This was attributed to the fact that hydrophilicity of jute was reduced by surface modification enhancing the compatibility of jute with hydrophobic PBS. PBS/woven fabric composites also exhibited higher weight loss than PBS/nonwoven composites [44].

In another study, Siddiquee et al. [45] studied the optimum method of biodegradation of jute fiber reinforced PP and PE composites. The biodegradation methods utilized in this study were compost, soil burial tests, and weather degradation. PE and PP were reinforced with 5, 10 and 15 % of fiber. The results showed that the biodegradation rate was highest in compost and lowest in soil burial tests. In the compost, the composites lost 60 % of their weight. In compost conditions the rate of biodegradation was influenced by water, air, and temperature. The microorganisms mostly consumed the fiber portions in the composites and no change was observed in pure polymers. This was because of the non-biodegradability characteristics of pure polymers. Composites with longer fiber lengths showed faster degradation rates caused by large surface areas available for microorganisms. PE showed a slightly higher degradation rate than PP [45].

It can be noted that the biodegradation studies conducted by various researchers mainly followed one of three different types of test methods mentioned in Sect. 6. The field tests used to study biodegradation are realistic, but proper monitoring of the degradation process and full understanding of degradation mechanism are not possible. It is also not easy to understand the influence of various external parameters such as temperature, pH, or humidity, as these parameters are not well controlled. In the studies using field tests, biodegradation has mostly been assessed through characterization of visible changes of fibers or weight loss, which is also very difficult to quantify correctly in cases where the sample breaks into small fragments and needs to be recovered from soil, water, or compost. Because of the complex and undefined environmental conditions, the intermediates formed by biodegradation cannot easily be analyzed. On the other hand, biodegradation studies which have been performed in the laboratory simulating the real conditions are better in the sense that external parameters can be controlled and analytical tools can be more easily used to analyze the residues and intermediates, to determine $CO_2$ evolution or $O_2$ consumption, etc. Therefore, understanding the biodegradation process and mechanism is easier in the laboratory simulation tests. In this case, experimental times can also be shortened by addition of nutrients to enhance microbial activity. However, among the various test methods studied, the most suitable method to investigate the biodegradation mechanism is the use of defined media (enzymes, individual culture, or mixed cultures) in the laboratory environments. Although this test method is suitable for investigating the basic mechanism of biodegradation of fibers or polymers, it cannot simulate the real conditions and only provides limited information about the biodegradation rate of polymers in natural environments. Therefore, each of these assessment techniques has their own limitations but may be used in combination to draw important conclusions about various important aspects of biodegradation, i.e., biodegradation rate, mechanism, influence of parameters, etc. Moreover, in many of the above research studies, no specific standard was followed for evaluating biodegradation of fibers and composites. This makes it really difficult to compare their results with those obtained in other studies for similar as well as different materials. Therefore, it is also necessary to choose the most suitable standard to study biodegradation of fibers and textiles, depending on the research objectives and type of materials to be studied.

## 9 Summary and Conclusions

Biodegradation is the process involving breakdown of complex materials into simple materials by microorganisms available in air, water, and soil. The most common microorganisms involved in biodegradation process are bacteria and fungi. Biodegradation of any materials occurs in two different conditions, namely aerobic and anaerobic, according to their chemical nature. In aerobic conditions, biodegradation of materials is carried out in the presence of $O_2$, while in anaerobic conditions, biodegradation of materials occurs in the presence a few compounds such as sulfate, nitrogen, and iron. The evaluation of biodegradation of materials (fibers and films) is important for measuring the levels of biodegradation. The measurement techniques involve assessment of weight loss after degradation, loss of tensile properties, and microscopic observation of surface and structure with suitable techniques.

Textiles fibers which are manufactured from natural resources are biodegradable and their level and extent of biodegradation vary according to their chemical compositions. Cotton fibers are highly vulnerable to microorganisms (bacteria and fungi) available in soil, water, and air. Some of the most active fungi are *Chaetomium* sp., *Fusarium* sp., *Myrothecium* sp., etc., and a few of the most active bacteria are *cytohaga* sp., *cellulomonas* sp., *CellVibrio* sp., etc. Biodegradation study of cotton showed that cotton fibers after dyeing and finishing processes exhibited higher resistance to biodegradation than raw cotton fabrics. Other vegetable fibers such as flax, sisal, and coir fibers are also biodegradable as are cotton fibers. The surface treatment (acetylation) used with these natural fibers reduced their biodegradability.

Animal fibers such as wool and silk are also biodegradable by bacteria and fungi. In a clean and dry environment, normal wool fiber has good resistance against microorganisms, while in wet and warm conditions the fibers are vulnerable to mildew and fungal growth. The biodegradability study of wool fiber showed that the best pH for wool biodegradation with *M. gypseum* was 7–7.5. The biodegradation of wool fiber also occurs with the bacteria Streptomyces. Wool can be biodegradable with fungus extracted from soil and decomposing wool. On other hand, silk fiber was found to biodegrade only by bacteria but not by fungi.

Among the synthetic fibers, nylon 6 and 66 fibers were found to biodegrade by marine microorganisms such as *B. cereus*, *B. sphericus*, *V. furnisii*, and *B. vesicularis*, resulting in decreases in viscosity and average molecular weight, and formation of new functional groups as well as physical damage to the fibers. While comparing nylon 6 and nylon 66, nylon 66 showed higher degradation. Studies also revealed that lipase and microbes could act on the PET fiber leading to formation of some cracks on the fiber surface, although the degradation was not so significant. However, poly (hexano-6-lactone) (PCL), which is an aliphatic polyester, was found vulnerable to digestion by microorganisms such as bacteria and fungi. The degradation of PCL fiber was dependent on both fine structure and environmental conditions and the level of microbial degradation decreased with increasing crystalline region and with increasing diameter of the fiber. The primary mechanism involved in environmental degradation of PCL fibers was surface erosion with weight loss caused by extracellular degradation enzymes secreted by microorganisms.

Biodegradability of fiber reinforced composites is also a subject of considerable interest, as composite materials are being widely used today for various applications. Studies revealed that biocomposites made from banana fibers exhibited strong resistance to fungal growth. However, banana fiber reinforced HDPE composites showed considerable biodegradation and loss of tensile properties (30 and 37 % in tensile modulus and strength, respectively) when buried in soil for 120 days. Similarly, abaca fiber reinforced biodegradable polyester composites showed considerable biodegradation when buried in soil. In the case of kenaf fiber reinforced PLA biocomposites, levels of biodegradation increased with increase in the Kenaf fiber content. Moreover, the fungus *P. ostreatus* degraded the PLA–kenaf composites by 12, 21, 30 and 48 % in 1, 2, 3 and 6 months, respectively, leading to a decrease in mechanical properties by 84 %. Similar to Kenaf fiber reinforced biocomposites, cotton fiber reinforced PBS also showed higher biodegradation by microorganisms or enzymes with higher cotton fiber content. The use of amphiphilic additives as accelerators for biodegradation was found to have a strong influence on the biodegradation of flax fiber reinforced PLA composites within soil. With mandelic acid, the composites showed faster biodegradation with 20–25 % of weight reduction after 50–60 days. In contrast, with dicumyl peroxide additive, the biodegradation of composites was moderately slow, resulting in a weight loss of only 5–10 %, even after 80–90 days. Flax biocomposites with polyhydroxybutyrate showed a sharp drop in the initial modulus and strength of the composites in the first 2 weeks after burial in soil and any further effect of degradation on tensile properties was steadier. Jute/PBS biocomposites also showed considerable biodegradation depending on the fiber diameter, fiber content, arrangement, forms, and surface modification. The PBS/10 % jute specimen exhibited maximum weight loss of 62.5 % after 180 days of burial, and biodegradation decreased with increase in fiber content. On the other hand, weight loss of the specimen was found to decrease with decrease in fiber diameter and also with surface treatments with alkali and coupling agents. Composites of jute fiber with PE and PP polymers can also be biodegraded and the biodegradation rate was found to be the highest in the case of compost with a loss of weight of 60 % and lowest in soil burial tests.

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# Responsibility Without Means

**Kirsi Laitala, Marthe Hårvik Austgulen and Ingun Grimstad Klepp**

**Abstract** The sustainability challenges facing the textile and clothing industry are substantial, but both the international and the national regulations of the textile industry are low. Consumers have, therefore, been passed a significant share of the responsibility for ensuring the sustainability. In this chapter, we present and discuss the results on *how* consumers can reduce the environmental impact of their own behaviour, and *whether* consumers are capable of and willing to change their own behaviour. Results are based on data retrieved through two research projects on environmental challenges connected to textiles and clothing, and are thus based on a triangulation of methods. Data from desktop studies, in-depth interviews in combination with wardrobe studies and from consumer surveys are used to elucidate the research questions posed. We find that consumers show limited knowledge, as well as limited engagement related to the environmentally preferable textile and clothing consumption. There is little information available to the consumers and environmentally friendly consumption is not facilitated. To place the responsibility for change on consumers is thus to give the responsibility to those without the means to take it. Therefore, solutions based on political consumption alone are insufficient and should be supported with additional regulatory instruments.

**Keywords** Consumerism · Responsibility · Laundering · Maintenance · Lifespan · Use phase · Disposal

## 1 Introduction

Over the past 50 years, the textile industry has moved to new areas where production costs are low. At the same time, the amount of textiles produced has exploded, and prices have dropped dramatically. Just since 2001 the import of

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clothing to Norway has almost doubled and it now amounts to 16.6 kg/capita [90], while the current prices of clothing are the same as they were in 1980 [89]. To the extent that Norway is different from other Western countries, this development is even more evident. Both this high level of production and consumption of textiles and clothing, and the way the textiles and clothing are produced, are connected with significant environmental problems.

In the absence of an international regime regulating environmental challenges connected to the production and consumption of textiles, consumers have been passed a significant share of the responsibility for the sustainability of textiles and clothing. It is often claimed in the literature on political consumption that consumers have the potential to influence (the environmental impact) through their own consumption choices (e.g. [70]). However, these claims have also been contested by critics who argue that this transfer of responsibility towards consumers ignores the fact that consumption is an embedded part of the systems of provision and thus in social, cultural and institutional framework conditions (e.g. [88]). Sustainable consumption usually refers to a level and pattern of consumption which meets the needs of the present without compromising the ability of the future to meet future needs [99], and environmental sustainability is defined by Goodland [32] as "the maintenance of nature capital". In this chapter, the understanding of sustainable textile and clothing consumption is limited to concerns related to environment and climate change, and we thus exclude concerns related to working conditions, which is another important aspect concerning economic sustainability and ethics. The aim of this chapter is to present and discuss results on *how* consumers can reduce the environmental impact of their own behaviour, and to consider *whether* consumers are capable of and willing to alter their own behaviour according to environmental considerations. We answer these questions through the presentation of data retrieved from two research projects[1] on environmental challenges connected with the textile industry which have been focusing on the perspectives and the role of the consumers. These results are presented and discussed within the analytical frame of self-regulation and regulation through consumption.

## 2 Regulation Through Consumption

Since the 1980s, increasingly powerful Western retailers have sourced their produced and manufactured goods from low-wage countries [38, 77]. During the same time period, both the amount of textiles traded and the cleaning frequency of the

[1] The relevant projects from which we will present results are the following:

1. From Textile Waste to Material Resources in a Grave to Cradle Approach
2. A Study of Environmental Standards and the Trade Impact on Indian Textiles and Clothing Sector.

textiles has increased. Together, these developments lead to several intertwined problems. Examples of these are the lack of control of the use of hazardous chemicals, conflicts regarding alternative uses of agricultural land and water, exploitation of labour, and growth of energy consumption in the textiles' use phase.

In the developing countries, the regulations of environmental hazards connected to textile production are extremely limited. In Europe, the most relevant regulation which applies to textiles is REACH—the Regulation on Registration, Evaluation, Authorization and Restriction of Chemicals. REACH applies both to products produced in Europe and to products imported into Europe. The regulation is, however, limited to the use of certain chemicals and products. Nevertheless, content declaration on textile products is not mandatory, neither in Norway nor in the EU. This also applies to undesirable chemicals.

The identities and the amounts of chemicals used in relation to textiles represent both an environmental as well as a health problem, for both producers and consumers. Still, the environmental problems connected with the textile industry are much larger in scope. In a life cycle perspective, the major environmental hazards are the extensive use of water and pesticides required for growing many natural fibres, especially cotton, emissions to air and water arising from producing synthetic and cellulosic fibres, and the significant use of non-renewable fibres [1, 29]. In addition, according to several Life Cycle Assessment (LCA)-studies, garments' use-phase is the most energy-demanding stage [66]. Thus, only a minority of the environmental risks connected with the textile industry are covered by national and transnational legislation and control. In the absence of national and international regulation, alternatives which privatize responsibility have been highlighted and promoted. The alternatives include industry self-regulation [98], corporate social responsibility [97], public-private partnerships [16], and political consumerism [70]. Instead of direct state intervention, strategies are being developed to mobilize and include business, civil society organizations and individuals in implementing the society's goals [35, 43, 68].

In all the above-mentioned alternatives, and especially in political consumption, the role of the consumers is stressed as crucial. It is important that the consumers feel they are responsible, they have the necessary information and tools available, they feel empowered, and they are willing and able to take responsibility, both through their own consumption and by placing pressure on governments and industries. In fact, according to Siegle [87], the textile industry's enemy is "the intelligent fashion consumer who asks the right questions and buys more carefully". However, in a sustainability perspective, it is not only the clothing purchase which is of importance. The garment's use-phase is also important, both because it is very energy-demanding and because it determines how long the garment is used and how it is disposed of [55].

Through information campaigns, eco-labelling, eco-friendly collections, and other information tools, consumers are encouraged to use market-based actions such as boycotts, buycotts, demonstrations, investment decisions, and opinion formation to raise their concerns publicly [12, 70], as well as to change their own consumption behaviour. Through these channels, consumers are claimed to be able to influence companies to take the necessary steps in a more environmentally friendly direction.

Consumerism has been especially emphasized in the field of environmental policy, as it has been argued that the old model of regulation, which stipulates mandatory product or process standards, is unable to deal with diffuse, complex, large-scale and transboundary risks and problems [7, 8, 31], of which the textile industry serves as a good example. On the other hand, belief in this privatization of the responsibility and regulation through consumption and market-based mechanisms has also been subject to criticism from several sources. Some argue that political consumerism is highly dependent upon economic sources, and is therefore reproducing patterns of marginalization, powerlessness and disembeddedness nationally and globally [6]. Others argue that consumers as agents are unreliable and capricious, and they drop their ethical and environmental concerns as soon as their economy slumps and when other concerns becomes more important [63]. A final group points to the way production, manufacturing, distribution and marketing are functioning as barriers because consumers lack the necessary information and autonomy to make unbiased choices [39, 88].

In this chapter we seek to contribute to this discussion by studying *how* consumers can reduce the environmental impact of their own behaviour, as well as *whether* Western consumers are willing and able to alter their own behaviour according to environmental considerations. The main focus is placed on how consumers can influence the production process through their procurement of textiles, the energy used throughout the use-phase, and the waste generated through disposal of textiles. The answers to these questions may function as a good starting point for a discussion on the potential effect of (political) consumerism as a tool to influence the sustainability of the textile industry.

## 3 Data and Methods

The results presented in this chapter are based on data retrieved from two research projects on environmental challenges connected with textiles and clothing, and are thus based on a triangulation of methods. From the project "From Textile Waste to Material Resources in a Grave to Cradle Approach" we employ data collected in 2010 through a survey about sustainable textile consumption with 546 respondents and through in-depth interviews. The qualitative part of the study consisted of a strategic sample of 16 households. The sampling criterion was to find individuals with different life situations, age, gender, civil status and family size. The background variables of the main respondents are listed in Table 1. A semi-structured interview guide was used, where the topics were fixed, but not the exact order or wording of the questions. A majority of the interviews took place at the homes of the informants and lasted on average between 1 and 2 h. The interviews were

**Table 1** Background variables of main informants

| Property | Variables | No. of informants |
|---|---|---|
| Sex | Female | 13 |
| | Male | 3 |
| Age | 20–34 | 8 |
| | 35–49 | 6 |
| | 50+ | 2 |
| Family | No children | 7 |
| | Small children | 7 |
| | Adult children | 2 |
| Relationship status | Single/living alone | 6 |
| | Living with partner | 10 |
| Area of living | Oslo | 8 |
| | Other cities | 8 |
| Nationality | All Norwegian | 12 |
| | Foreign household member(s) | 4 |
| Education | Vocational | 1 |
| | Bachelor level | 6 |
| | Graduate level | 9 |
| Employment situation | Working[1] | 12 |
| | Student[2] | 3 |
| | Retired | 1 |

[1] Three of them only work part time
[2] All three students had part time jobs

recorded, transcribed, coded and analysed with ATLAS.ti software. All quotations from the interviews are given with age and a respondent pseudonym.

In addition to interviews, these households participated in wardrobe studies. A wardrobe study is an approach combining methods such as qualitative research interviews, field work, inventories, and laboratory testing based on all or some selection of clothes of a person or a household. This method has been described and discussed in more detail by Klepp and Bjerck [49]. The participating households collected all clothing which went out of use during a 6-months period. Afterwards, they were interviewed to find out what the user had to say about the individual garment and its history of use, especially related to the specific reasons for disposal. This way of acquiring information on clothing to be disposed of gives rich empirical data. Kvale and Brinkmann [51] point out that it is an important aspect of qualitative interviews to get specific descriptions by the informant instead of only general opinions the informant has about a theme, and keeping the focus on clothing items is one way to do this. A total of 620 garments were taken out of use and registered.

The quantitative survey data was collected in 2010. The recruitment of respondents was done in several steps and through different channels. The main recruitment was done by mailing a paper questionnaire to randomly selected addresses from the telephone directory. As the response rate was rather low (10 %), additional respondents were recruited through personal and professional networks, and through publicity in media. The project was presented in several newspaper and magazine articles which included the address to the online version of the questionnaire. A total of 546 responses were received. The sample has preponderance of female respondents (77 %). The age distribution is not representative for the Norwegian population, because the youngest age group (respondents below the age of 24) and oldest age group (respondents above the age of 60) are underrepresented. So although the sample is not representative of the population, it still gives a large number of respondents which can be used as examples of consumers in Norway, and which can be compared with each other to some extent. The preponderance of women in the sample also has some benefits, because women often take responsibility for a larger portion of tasks related to a family's clothing consumption such as acquisition, laundering and repair [59]. It is also argued that young women purchase more clothing than other consumer groups, and therefore focusing on them may generate information on certain volumes of clothing [11, 41, 69]. The cases are not weighted.

From the project "A Study of Environmental Standards and the Trade Impact on Indian Textiles and Clothing Sector" we employ data on Norwegian consumers collected through a cross-national consumer survey regarding consumer perspectives on eco-labelling of textiles. The data was collected through a TNS' web panel in March 2012, and the sample includes 1,004 respondents from Norway. The Norwegian panel consist of approximately 50,000 respondents, and the panel samples are pre-classified by age, gender and residence. Respondents are randomly selected within these groups. The size of the panel indicates that it is possible to draw representative samples, and the final sample is weighed according to age and gender [3]. The questionnaire was developed though a thorough process which includes a piloting of the questionnaire in Norway. The data received from both surveys was analysed with the help of SPSS software (IBM, USA).

In addition to these sources, we employ data from desktop studies in this chapter. Surveys and interviews are appropriate tools for studying attitudes and intentions, and registrations, observations or more direct methods are more suitable when detailed information on behaviour is needed. This triangulation of data and data collection methods are therefore important in order to strengthen the validity of our findings. This need for data validation is also emphasised by Devinney et al. [22] in their research on ethical consumerism.

## 4 Environmental Impacts of Consumer Behaviour

Clothing consumption includes several stages. Usually the focus of sustainable clothing consumption research lies in the acquisition phase, but the use, maintenance, and disposal are also important from an environmental point of view. What we choose, how we take care of it, how long we keep it and what we do with the garments after we stop using them can affect the magnitude of the environmental impacts. In the following, the alternatives that consumers have for reducing these impacts are presented for the different consumption phases.

### *4.1 Acquisition*

Clothing can be acquired in many ways and from many different sources. The different possibilities include options such as getting the product permanently or temporarily through buying, inheriting, borrowing, renting, receiving a present, making it, finding it or altering an existing product. The most studied topic in previous research has been the acquisition process where consumers buy new products. Sustainability is one of the aspects the consumer may consider in this process, among a great variety of other aspects, such as price, colour, style, fit, and intended use areas. The alternatives which are somehow favourable from an environmental point of view include products made of specific fibres (such as recycled or organic), are eco-labelled, are pre-owned, are made of materials which needs less laundering during use, or have good quality, fit and design which enables extensive use or long lifespan [3, 28, 29].

In environmentally sustainable product acquisition, the first consideration should be whether or not the acquisition is necessary, followed by the selection of products with long lifespan, potential for reuse, minimum packaging and minimum toxicity [64]. Buying or inheriting pre-owned clothing is one of the sustainable clothing acquisition options readily available for most Norwegian consumers. Informal clothing exchange such as inhering items from family members or friends seem to be occurring on a larger scale than sales through formalised markets [54]. Private exchanges are also the environmentally preferable solution because less transport and sorting are needed [27].

There is great interest among textile stakeholders to be able to compare the environmental impact of different fibres. Several tools that try to evaluate and compare fibres in a cradle to gate perspective (fibre manufacturing phase only) have been developed, including Made-By [65], Higg index 1.0 [92], Eco-metrics calculator [20], Environmental Impact index (EI) and Ecological Sustainability Index (ESI) [73] as well as a new mobile phone application called Making, launched by Nike in 2013 [76]. These tools rate the fibres based on several environmental indicators, and then weight the impacts in an attempt to compare effects such as greenhouse gases, human toxicity, eco-toxicity, energy and water consumption, and land use. However, they are criticized for being too inaccurate, using wrong grounds for the comparison, employing misleading underlying assumptions, being non-transparent, or for the fact that they exclude the garment manufacture, use and disposal phases, which can have major implications as different materials have different impacts, especially during dyeing and use[2] [52, 81]. The Department for

[2] Not all criticism is directed at all the given tools.

Environment Food and Rural Affairs (DEFRA) has also presented a study where the environmental impacts of different fibres are compared, but without attempting to make a general weighed score [93]. Based on the selections and assumptions of production used in the evaluations, the results between different fibres vary greatly. In general, different fibre groups often have their own specific environmental impact areas. The growth of conventional cotton requires high water, pesticide and fertilizer consumption [34], merino wool production requires large land areas [83], and polyester requires non-renewable resources and high energy consumption during fibre production, which contribute to increased $CO_2$ emissions [66]. This makes it difficult to give advice to producers or consumers related to which fibre type to select. However, there are some general rules that most of the above-mentioned tools agree on, such as that recycled fibres in general have lower environmental impact than virgin fibres of the same material (most commonly available recycled fibres are polyester and wool), and that organic fibres are preferable to conventionally grown. Use of organic cotton instead of regular cotton is estimated to reduce the toxicity by 92 %, and the reduction of climate change impact and total environmental impact is estimated to be about 6 % [1].

Even more importantly, one has to take into account that the different materials vary in their properties, which makes them more suitable for some uses than others. It is important to make garments with high utility value which are suitable for the intended use area, and which can tolerate being used and maintained.

### *4.2 Laundering and Maintenance*

Clothing maintenance which includes processes such as laundering, drying, ironing and dry-cleaning have significant environmental impact, mainly because of the consumption of energy, water and chemicals, but also because of the wear effects they have on the textiles. LCA studies on clothing and products used in laundering, such as detergents and washing machines, show that the use period is usually the most energy-demanding period during these products' life cycle [66, 79, 85]. Depending on the energy sources, this phase can also produce the largest greenhouse gas (GHG) emissions. Calculations of energy consumption and $CO_2$ emissions in the use phase vary from about 12–82 % of the total clothing life cycle [18]. However, the potential variation is much greater depending on how much the product is used. In addition to the length of the clothing use period, the environmental impact of use is highly dependent on the selected maintenance frequency and methods. In the UK, washing textiles at 30 °C instead of 40 °C would save 0.5 Twh, equivalent to 0.22 Mt $CO_2$ yearly [5]. It has been estimated that one day's use of jeans in France requires in total 17.5 L water, 1.49 MJ primary energy and 4.41 g $CO_2$e[53].[3] Consumption figures per use time decrease when garments

[3] Calculation based on jeans that are used once a week during 4 years and washed at 40 °C and ironed after every third wash, which equals to 208 use days and 69 laundering cycles.

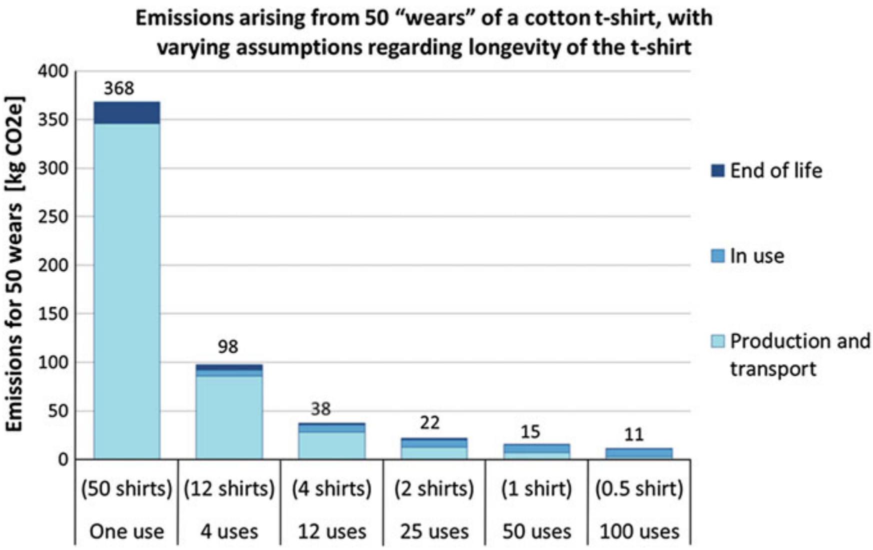


**Fig. 1** Emissions arising from 50 wears of a cotton T-shirt, with varying assumptions regarding longevity of the T-shirt [17]; based on Allwood et al. [1]

are used longer, washed less frequently or at lower temperature. Figure 1 shows the total $CO_2$e emissions and the relationship between the different life cycle stages for 50 "wears" of a cotton T-shirt. Each pillar indicates different lengths of lifespans, starting from the very short lifespan of one wear per T-shirt, when no laundering is needed, up to 100 wears per T-shirt, with assumed laundering after each wear [1, 17]. The figure indicates that greatest savings can be achieved through increased lifespan, but also that the use phase starts to dominate the GHG emissions when the T-shirt is used for a longer period, in this case a minimum of 50 times. If T-shirts were to be used as disposable single-use-only garments, the environmental impacts would be magnified tremendously. The figure also highlights how the effects of laundering and lifespans are related, and why knowledge of both aspects is important when evaluating the environmental effect of clothing consumption. Depending on the use area, sometimes single-use textiles could be a preferable option to reusable textiles, for example surgical textiles in hospitals where hygiene is of extreme importance [84].

Technological and behavioural changes can be used to reduce the environmental impacts of clothes' maintenance. The alternatives consumers have include washing at lower temperatures or with eco-programs, decrease washing frequencies, using full capacity of the washing machine and correct detergent dosing, avoiding dry cleaning, reducing the need for ironing, and line drying clothes whenever possible [5, 60]. The further potential within technical improvements include improving textiles so that they require less maintenance, such as using anti-crease fabrics, materials which do not easily get dirty, using lighter weight materials, or developing appliances to reduce energy and water use and increasing washing machines' spin drying efficiency.

Washing at 30 °C uses about 30 % less energy than washing at 40 °C [60]. A cleaning effect test of laundering at different temperatures with various detergents showed that the cleaning effect can actually be better at 30 °C than at 40 °C, if a more efficient detergent is chosen, and that, in any of the cases, the difference between the results from the two temperatures was not large, at least when detergents suitable for low temperature laundering were used [60]. Moreover, some textiles show less signs of wear and tear or colour change when washed at lower temperature, thus giving additional environmental benefits in the form of potentially prolonging the lifespans of clothing.

Current alternatives to regular compact detergents such as laundry balls and pellets did not deliver additional cleaning effect compared to laundering with water only [50, 56]. However, these studies showed that water has rather a high cleaning effect on its own, and that cleaning effect with reduced detergent dosage for many stain types is close to that of full dosage. Therefore, reduced detergent dosage may often be sufficient, if the laundry is not very soiled (ibid).

### *4.3 Mending*

Mending, re-design and altering are alternatives users have for prolonging the use period of clothing already in their wardrobe. Textiles age through different mechanisms, such as mechanical stress, photochemical degradation, thermal degradation, physical structural changes or chemical attack [13]. These mechanisms can cause holes, rifts, broken seams, loose buttons and faded colours which consumers can try to mend by various techniques. In addition, consumers may alter garments' original appearance for several reasons, such as for improving the fit, changing unwanted colours, adding personal characteristics, or just to remove unwanted decorations.

### *4.4 Lifespans, Amount of Use*

Prolonging the use period is one of the possibilities consumers have for increasing sustainability within the field of textiles and clothing [29, 45]. Theoretically, if the use period could be doubled and one garment fewer was produced, the environmental effects from the production and discarding phases could be reduced significantly. Klepp [45] has developed a framework for the lifespan of clothing (Fig. 2). It shows that, throughout the whole lifespan, the garment can go through different phases between active use and resting periods. Active use means that the garment is worn regularly. The number of times it is worn before cleaning varies greatly. Clothing can also go out of use at several stages. First, the user or caretaker either makes a conscious choice of not using the garment any more, or just does not select it for use as there are other, and more preferable, alternatives

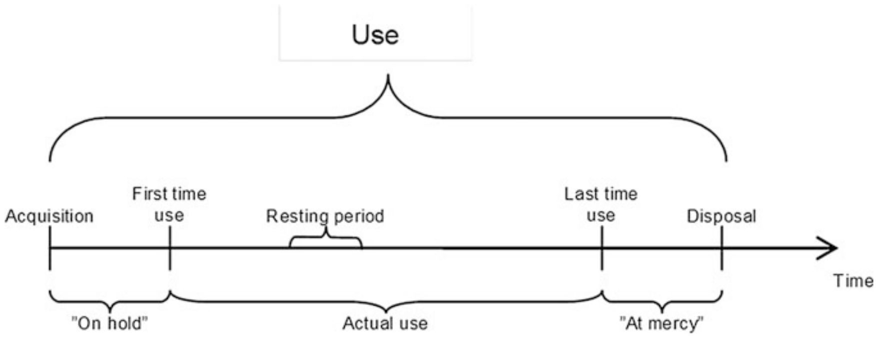


**Fig. 2** Clothing lifespans [45]

available. After a while, s/he has to make a choice of what to do with it. While waiting for this decision, the garment is "at mercy" [45].

Lifespans of clothing vary greatly and there is very little reliable information available on this topic [74]. For example, some reports estimate that garments have an average lifespan of 1–3 years [9, 33], while other studies estimate the average lifespans to be up to 7 years [45] or even much higher for specific garments, such as skirts and dresses that are used for up to 15.2 years [94]. Most studies estimate the lifespans to be somewhere in between these results, such as 3.3 years [62], or 5.4 years, out of which 4 years are with the current owner [58]. There are several reasons for these variations in results, including the variations in measurement methods, garment types and selected samples. For example, children's clothing in general has shorter use period per user, as the child grows out of the garments regularly. The accuracy of the method used is important, and the above-mentioned studies were based on various methods including survey, wardrobe studies, interviews, and correlation studies related to the amount of purchases. In addition, the results are affected by the way the active use period and potential resting periods are separated. Lack of data leads to incomplete LCA studies and the fact that we do not know enough about what contributes to clothing longevity.

The clothing consumption stages affect each other and the length of clothing lifespans, which, in turn, have environmental impacts. An example of this is that making an environmentally preferable acquisition decision based on material choice may not always have the lowest total environmental impact. Selecting an organic cotton product instead of regular cotton gives savings in pesticide, fertilizer and water consumption in the fibre production stage [1]. However, because of the lack of standards and knowledge of organic production, fibre quality can be rather low when it is introduced to the market [82]. The lower quality may lead to shorter lifespans, and in total contribute to higher environmental impacts, although the impact categories would be different [1]. On the other hand, if the garment is chosen based on material choice rather than other important considerations such as size and fit, the garment might be hanging in the closet rather than replacing another garment.

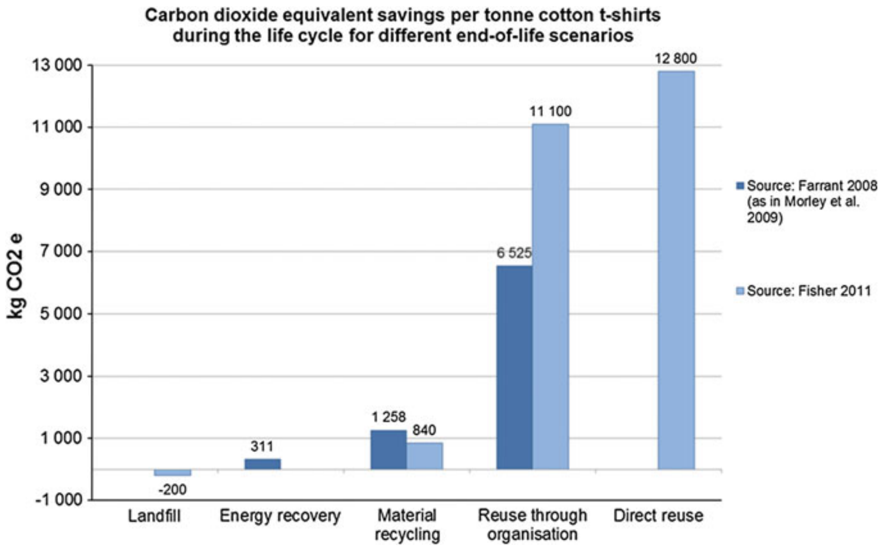


**Fig. 3** Comparison of different end-of-life scenarios of cotton T-shirts and the potential saving of kg $CO_2$ equivalent per tonne textiles during the lifecycle

## *4.5 Disposal*

The EU's Sixth and Seventh Environment Action Programmes set waste prevention and management as one of the top priorities. Waste Framework Directive enforces the targets and gives a hierarchy of environmentally preferable waste management systems [25]. This is called waste hierarchy, and it sets out five steps for dealing with waste, ranked according to environmental impact, where the best solutions are given first:

1. Prevention of waste occurring, e.g. using less materials or keeping products for longer
2. Preparing for re-use; can include, for example, cleaning, sorting and repairing so that the product can be used again
3. Material recycling, i.e. turning waste into a new product
4. Other forms of recovery, e.g. incineration with energy recovery
5. Disposal, e.g. landfilling or incineration without energy recovery

As illustrated in Fig. 3, for textiles and clothing it has been shown that the greatest energy and $CO_2$e savings are achieved through longer lifespans and direct reuse, followed by reuse through organisations, material recycling, and finally energy recovery, which are all better solutions than landfilling [26, 27, 72]. In addition to environmental sustainability, recycling and reuse is beneficial for the economic and social aspects of sustainability, such as employment and earnings from resold textiles [21].

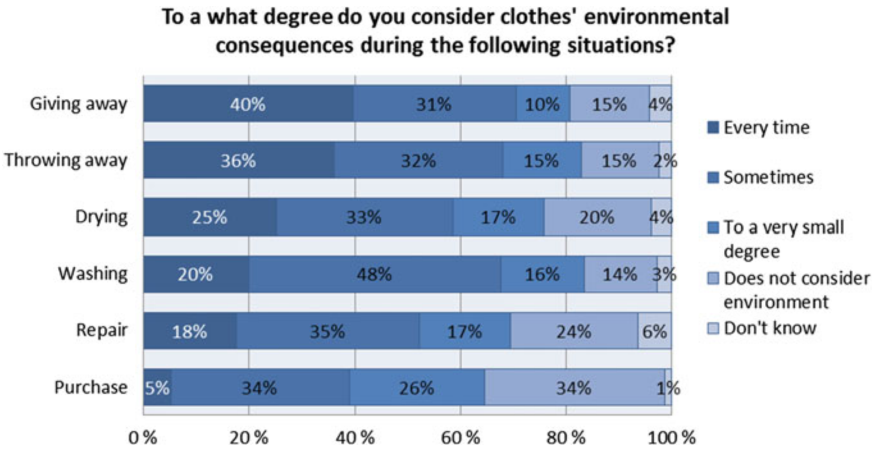


**Fig. 4** Consideration of clothes' environmental consequences during the different use stages in percentage (Survey 2010. $N = 285$)

## 5 Ability, Knowledge and Willingness to Change

In the previous section we have presented literature and evidence on how consumers can reduce the environmental impact of their own clothing consumption behaviour. In the following section we focus on whether Norwegian consumers are both willing and able to alter their behaviour according to environmental considerations. In order to be able to change their consumption behaviour and practices, the consumers must have the necessary knowledge on the environmentally preferred alternatives. In addition, the structural obstacles for the environmentally preferred behaviour and practices must be limited. For the consumption patterns to change in a more environmentally friendly direction, the consumers must also be willing to change their own behaviour. As illustrated in Fig. 4, the survey results from 2010 show that consumers state that they are taking the environment most into account in the disposal phase, followed by the use phase. Less consideration is given to environmental issues at the moment of clothing purchase when the opportunity to influence, both production conditions and concerns about use and disposal, is at its greatest. In other words, the willingness to act in an environmentally correct manner is highest in the phase where the potential environmental impact of the changed behaviour is lowest.

In the following we present evidence on Norwegian consumers' knowledge, willingness, and ability to take environmentally sound choices in the clothing consumption phases presented in the previous section, namely acquisition, use-period and disposal.

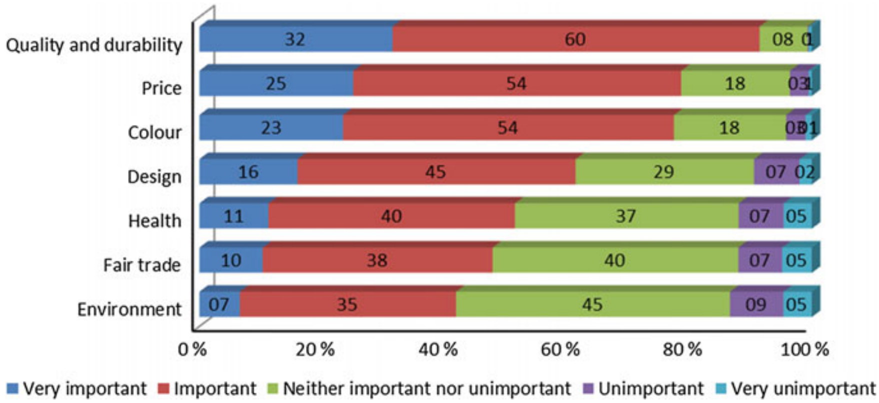


**Fig. 5** Considerations when buying textiles. Per cent proportions. Respondents answering "don't know" have been excluded (Survey from 2012, *N* ranging from 968 to 995)

## 5.1 Acquisition

As illustrated in the previous section, there are many considerations which the consumer can take into account before and when s/he chooses if, and if so, what, to purchase. About 20 % of the Norwegian respondents in the 2012 survey state that they try to think of the environment when they buy clothes and textiles [3]. However, as illustrated in Fig. 5, environment still comes out as the least important consideration when compared with other considerations such as colour, price, design, quality and durability, health and fair trade.[4] Only 6.6 % of the respondents state that this is "very important" and 35 % state that it is "important".

This finding is also evident when the respondents are asked to rank the considerations from one (most important) to seven (least important). The result of the ranking of 'environment', relative to the other considerations, is illustrated in Fig. 6. The figure clearly shows that environment is very seldom ranked as the most important consideration. Indeed, environment is typically ranked as the second least or the least important consideration.

As illustrated in Fig. 5, a majority of the respondents emphasize quality and durability. In these areas, as discussed in Sect. 4, there is a great potential to reduce the environmental impact. However, also in this field, the consumers lack information and tools. There is no quality or durability labelling of the clothing and the consumers' ability to recognize quality in the purchase situation are limited. The opportunities remaining are to place trust in prices and brands, and neither of these are reliable sources regarding the products' technical quality. These results indicate that environmental considerations are not very prominent in

[4] The data originates from the same survey.

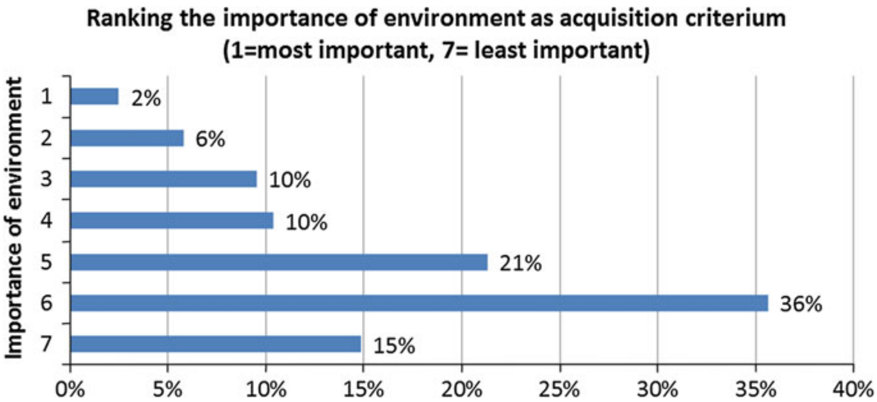


**Fig. 6** "Think about the last time you were buying clothes for yourself or someone in your household. How concerned were you about the following aspects?" This figures show the ranking of 'environment' in per cent. Respondents answering "don't know" have been excluded (Survey from 2012, $N = 853$)

the clothing acquisition phase. However, this phase is often emphasised when sustainable textiles and clothing consumption are discussed by the consumers themselves. In addition to a focus on consumers' knowledge and attitudes, studies on sustainable clothing consumption often concentrate on consumers' acquisition behaviour related to selection of products which are somehow more sustainable than other alternatives. In general, such studies have identified a "knowledge-to-action" gap [67]. It has been shown that neither environmental attitudes nor knowledge directly translate into sustainable clothing acquisition behaviour, although sometimes a weak or indirect connection is found [14, 15, 30, 42]. The discrepancies between attitudes and behaviour are mainly explained by the fact that shopping for clothes can be a complicated process where several criteria must be taken into account simultaneously, including price, fit, style, colour, cultural and social aspects, in addition to sustainability. It may be difficult to find products satisfying all the desires at the same time [71, 75]. From an environmental point of view, it is also important that consumers select clothing which satisfies their different needs, so that the garments are used, preferably for a long time.

This brings us to the other considerations, rather than just willingness to assume environment as a basis for the procurement, that the consumer can take in the clothing acquisition phase. As mentioned in Sect. 4.1, the clothing's fibre content can be an important indicator of sustainability. Nevertheless, there is a significant degree of confusion in the Norwegian population regarding which fibres are the most sustainable ones. Previous studies have shown that consumers have a low level of knowledge on the environmental impacts of different fibres [57]. Cotton and other natural fibres are often emphasized as environmentally sustainable, as expressed here by 59-year-old Pia in an interview: *Well, I know that cotton, for example, pure cotton, is more environmentally friendly than blend products or*

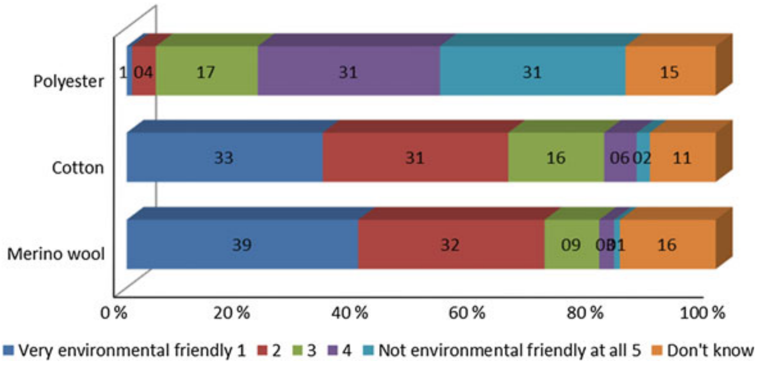


**Fig. 7** How environmentally friendly do you think the different fibres are? Total $N = 1004$

*100 % synthetic … Environmentally-friendly clothing consumption … hmm … it must be that it is made mostly of wool and cotton*. This belief in natural fibres as always environmentally preferable to man-made materials has been confirmed by other studies in several other countries [4, 37]. This finding is also confirmed though the consumer survey from 2012 where the respondents were asked to indicate the degree of environmental friendliness of three different fibres. The results, illustrated in Fig. 7, show that both cotton and merino wool are considered as much more environmentally friendly than polyester.

Action based on such false knowledge, and unrefined grounds, may lead to acquisition of products with higher environmental impact than necessary [65]. The unrefined knowledge in the population on the importance and meaning of fibre content indicates that, even though the consumers try to take environmental considerations into account in the clothing acquisition phase, the result may be an even higher environmental impact.

Apart from care instructions and fibre content, there are no mandatory requirements to the labelling of clothing and textile products in Norway. Nevertheless, voluntary labelling schemes for clarifying environmental and/or ethical perspectives of the products do exist, such as the Nordic Swan, the EU Flower and the Fair Trade label. The number of textile products covered by these schemes are, however, limited, and few textiles with these kinds of labels are available on the Norwegian market [3, 91]. Some clothing made of organic cotton, and clothing with health label Oeko-tex 100 can be found [78]. Some eco-labelled clothes for children can also be found on the Norwegian market. The limited amount of eco-labelled textiles in the market became evident in the interviews undertaken during the Textile Waste Project [57], here exemplified by 27-year-old Diana: *Because another thing with sustainability … one thing that I absolutely associate with that is the production of clothes […] It would perhaps be a good idea to have a kind of labelling system for clothing so that you can be assured that they are produced under certain conditions. Actually, it is a bit strange that it does not exist for clothing when it exists for food and recycled glass and stuff like that*. In general, global eco-labels for textiles are not very well known among Norwegian consumers, and very few know where to shop if they want to buy eco-labelled clothing and textiles [3].

## *5.2 Maintenance, Laundering and Mending*

As demonstrated in a previous section, the use-phase, which includes maintenance, laundering and mending, is a consumption phase where it would be possible for consumers to take measures with significant environmental impact. This has, however, not been given much attention. A positive note is the desire for quality and durability, but before this desire can contribute to improvements the consumer need the tools to recognize quality. This applies both to technical quality and/or durability, the clothes' usability in terms of fit and social and aesthetic flexibility.

Laundering practices are constantly changing and are influenced by social, cultural and moral norms [86]. These changes occur relatively fast through different mechanisms and have been affected by new technologies, available information, as well as changes in society and its norms [46, 48]. Washing technologies have improved as new compact and less toxic detergent formulations functioning better at lower temperatures have been introduced, as well as more efficient washing machines which consume less water and energy [60, 80]. Despite the great improvement in cleaning technologies, the time consumers use for washing clothes has not been reduced. Today, body odours are considered appalling, and daily washes and use of perfumes is almost a norm [2]. These changes in social norms have led to increased washing frequency for our bodies and clothing [86]. We own more clothing, and wash it more frequently [47]. This increased washing can counteract the technological improvements which have occurred in laundering. Steering these processes of change requires a consideration of integrated socio-technical systems. Research on consumer behaviour shows that people seldom measure the detergent dosages, and are unaware of some aspects which should affect the dosage, such as water hardness [61].

Some positive trends in consumer behaviour during the past decade have been observed, such as reduction in average laundering temperature, in addition to an indication of reduction in the laundering frequency of jeans [61]. However, the laundering frequency of many other types of garments, especially those that are close to the body, has been even higher than before. Results also confirm that consumer behaviour is prominent for environmental effects from laundering, and frequent laundering especially should be studied more thoroughly. It is common that consumers choose to launder clothing in order to reduce the pile of clothing used, even if they themselves would have considered the clothing clean enough to be used for longer [61].

The possibility of getting the clothing clean is also a determining factor for potential lifespans. Stains or odours which are not removed in laundering are important disposal reasons, and stains especially reduce the lifespans and reuse possibilities of children's clothing. Laundering clothing at low temperature reduces the energy consumption, but if the stain or odour is not removed, the laundering has not fulfilled its purpose. It should be possible to launder clothing efficiently enough to remove the dirt. Other material properties such as shrinkage is also affected by treatment, as many tumble dried test materials show a higher level of shrinkage than hung dried materials. Garments disposed of because of shrinkage have 1.5 years shorter average lifespans than other garments [58]. In this phase, both the opportunity and willingness to act in an environmentally friendly manner is greater, but a growing focus on body odour and cleanliness is currently driving development in the wrong direction. Technical improvements of appliances and detergents are negated by the consumers' increased laundering frequency.

The scale, focus and techniques in clothing mending has changed over the past few decades from very specialised, time consuming and invisible mending methods based on economic reasons to far simpler techniques where the potential for creativity and unique aesthetic expression has become more important [40, 44]. Time spent on repair, handicrafts and making one's own clothing has reduced significantly in the past few decades, but at least some repairs are still performed [28, 33, 96]. The main reasons for not repairing are lack of time, equipment and skill, as well as the low cost of new clothing related to the cost of professional repair. A survey from the UK shows that about 62 % of respondents own clothing which could have been used if it was repaired [33].

## 5.3 *Disposal Phase*

The majority of studies on which end-of-life solutions consumers choose for their clothing give a positive picture, as they usually prefer to deliver the clothing for reuse rather than binning [10, 19, 36, 45]. The preferred reuse channel varies to some extent, but in general donating and giving to friends/family are more frequent than selling garments. However, a lot of garments are still binned if the user feels that they are of no use to others, either because of wear and tear, stains, other damages, or because of change in fashion trends [24, 95]. Studies of clothing disposal reasons have shown that wear and tear, size and fit issues, taste related issues, as well as fashion are the main drivers for clothing disposal, although the importance of these reasons varies between the different studies [23, 45, 55, 95].

Two Norwegian studies on disposed clothing show that about every fifth garment is unused or only used once or twice [45, 58]. It is also evident that the way clothes are acquired has an impact on whether they are used or not. Most of the unused clothes were gifts or inherited clothing items from family and friends. This means that the receiver has very little control over what s/he is given. In addition comes clothing which was not tried on before purchase, and/or which was bought in a sale.

As shown in Fig. 4, consumers are most aware of environmental issues at the disposal phase. In the 2010 survey we find a clear link between the respondents' answers as to whether they take environmental aspects into account when giving or throwing away clothing and whether they say that they give clothing to charity or friends. We also find a link between the interest areas of environment, fashion and clothes, and whether the respondents are likely to let changes in fashion reduce the use-period and lifespan of the clothing. Survey respondents who are not particularly concerned about the environment are slightly more likely to let fashion changes affect their clothing life time than respondents who are interested in environmental questions. However, self-reported behaviour and what the respondents think their behavior should be may have had an effect on their responses. As expected, respondents who have a higher interest in fashion or clothing are more likely to say that they let fashion changes affect their clothing use-time than respondents who are not very interested in fashion. This finding is evident in interviews and studies on disposed clothing even though fashion as a disposal reason was not often mentioned. Markus, 42, is one of the respondents who dispose of clothing because they feel some items are no longer modern. He describes how his interest in fashion had changed over the years: *Well, I'm quite averagely interested in clothes. It's not like I only buy something to keep me warm (laughs a little). A little more than that. […] I was more interested before we got children. Now you don't have time for that. […] I was maybe more fashion conscious before. I felt that clothes went out of fashion. I do not feel that things are going out of fashion now. So now I rather buy clothes that might remain in a way longer than… I do not buy the most fancy, the trendiest. Because I'm 42 years old, so… That would be more pathetic*. Still, Markus would mainly buy brand clothing and he said that the oldest clothes he used were only about 3–5 years old. Heidi, 32, describes her opinion of fashion in these words: *No. I am not interested in fashion other than that I follow to see when clothes that I like come into fashion again (laughs a little). […] It can go 2 years without me buying anything, aside for underwear, because everything is just awful colour and everything (laughs a little). Could be a long period in between when my style is in fashion*. She described using a lot of clothes that are 10–15 years old, and mentioned several concrete examples. These results show how fashion interest can affect the life time of clothing.

Analyses of disposed clothing confirms that, in the majority of cases, material changes were visible, although at the same time a large proportion of clothing appeared very little used or almost new. In interviews with the previous owners it became evident that they were unaware of what happens to textiles after they are delivered to clothes collectors. They assume that most would go to reuse either in Norway or other countries, but don't know about the massive sorting processes, the material recycling possibilities, and have not thought too much about the environmental benefits, as they concentrate more on the moral norm of non-wastefulness. Most informants say that they give clothes to charity or friends, and seldom throw usable garments in with the garbage. Norway's two largest clothing collection organisations (Salvation Army's Fretex and UFF-Humana people to people) are the ones most commonly used. Camilla (29) likes to give usable clothing for reuse, but she admits that it doesn't always happen: *Often it is a bit cumbersome to deliver clothes anywhere. That is why it happens that you do not get it done anyway, and then they are just lying around… And eventually I throw them in the trash. […] At least in Norway, second-hand clothes have to be so good standard, that if I do not want it for some reason, it is often very likely that not many others will want it either.* Other informants also talked about these same constraints for delivering clothing to charity, mainly the inconvenience, but also considered that clothing may not have been of good enough quality for the recycling organisation or for the potential new users. The respondents are often unsure whether they should give clothes to charity or throw them away as waste. Some choose to give almost everything to charity. Erik (30) describes his jeans with a 15-cm wide split in the crotch: *I had given it to Fretex, because some people like pants with holes in, which are worn. Fretex can choose if they want to have it.* Others were more selective: *This would have gone in the trash. The poor Salvation Army gets more than enough garbage* (Karl 46). Many respondents assume incorrectly that, if there are only small faults in clothing, the charity organisations would repair them before it was sold. However, the two largest charity organisations do not repair, but they might sell these items at a lower price.

In the disposal phase the consumers have a greater opportunity to make good environmental choices, and it is thus perhaps not surprising that it is in this phase that they think about the environment. The deciding factors can of course be discussed, but, either way, the environmental impact is limited. The fast growth in textiles which are reused and transported around the world is more a symptom of rather than a solution to the problem. In Norway we also lack systems for collection of textiles which are not perceived as usable by the owner. Because knowledge about textiles is limited, much clothing which could have been better exploited ends up in residual waste. It therefore becomes important both to improve the systems and to minimize waste production.

## 6 Discussion

At the beginning of this chapter we argued that this way of presenting evidence, both on *how* consumers can reduce the environmental impact of their own consumption behaviour as well as evidence on *whether* consumers are willing and able to change their behaviour in an environmentally friendly direction, is a fruitful way to contribute to the discussion on political consumerism in the textile industry. The rationale for this is that, both in academic literature as well as in de facto consumer policies, the role of consumers is stressed as crucial. It is important that the consumers are empowered, that they feel responsible and that they have the necessary tools and information available.

In this chapter we show that there is a significant discrepancy between knowledge about how the consumers can contribute in order to make their textile consumption more environmentally friendly and knowledge as well as willingness among the consumers which are necessary for these changes to happen. The results indicate that environmental behaviour is most prominent in the end-of-use period when the clothing is either to be disposed of or recycled, and is present to a lesser degree during acquisition- and use-phases. If the respondents consider the environment during acquisition, they most often consider purchasing second-hand, ethically produced clothing, organic cotton and/or not to make unnecessary purchases. Eco-labels are not a prominent purchase criteria, most likely because they are not readily available on the Norwegian market. Most consumers do not make a direct connection between their own clothing purchase behaviour and environmental impact, and seldom change their clothing consumption behaviour based on environmental interest. However, results show that they sometimes act according to what is environmentally beneficial, although the main motivation behind the act is not always sustainability and/or environmental considerations. Another important finding is that many consumers lack environmental knowledge in several areas when it comes to clothing consumption. We find the same faulty perception as Hiller Connell [37], relating to the assumption that natural fibres are environmentally preferable to man-made materials. When it comes to recycling, most respondents mainly donated only clothing they thought suitable for reuse in Norway. They lack knowledge of the potential for material recycling of textiles, as well as export of clothing to reuse in other countries. In this area, the lack of knowledge contributes to a lower textile recycling rate.

The main finding presented in this chapter it thus that there is both limited knowledge, as well as limited engagement, among the consumers regarding the environmentally preferable behaviour and practices related to textile and clothing consumption. This finding has important policy implications, as the main regulatory strategies connected to the environmental challenges facing the textile industry relating to textile consumption are voluntary and private by nature. These regulatory alternatives to national (and international) strong regulation, which includes industry self-regulation, corporate social responsibility, public-private partnerships and political consumerism, are to various degrees dependent upon consumer engagement. The findings presented in this chapter indicate that these alternatives may be necessary, but they are insufficient to improve significantly the environmental impacts of textile consumption. An important goal for consumer policy is to empower consumers to make informed choices in the market, and an important tool for implementation of these kinds of policies is the provision of information. Still, efforts to influence the moral decision processes and consumer behaviour are likely to have a limited effect when other structural processes, such as the prices of clothing and textiles, point in the opposite direction—towards increased consumption of cheap textiles and clothing.

## 7 Conclusion

The starting point for this chapter was two questions. How consumers can reduce the environmental impact of their own behaviour and whether consumers are capable of and willing to alter their own behaviour according to environmental considerations. The answer to the first question is to buy fewer clothes, to choose clothing which is frequently used, seldom washed, have low environmental impact in the production phase, and to dispose of the textiles in a more environmentally friendly manner. We find that the consumers' knowledge about clothes and textiles is fairly poor and that the information provided to consumers about how they can take the necessary measures are not available. These findings make the answer to the second question less encouraging, because even though the consumers might have been willing and motivated to take environmental considerations into account, they would not know how to proceed. This is especially the case for the clothing acquisition phase where the impact of the choices is at its greatest, but both the willingness and the abilities to take environmental considerations are low.

When studying the different phases of clothing consumption, it becomes evident that the challenges we are facing are varying. In the disposal phase it is the systems which need to be improved. In this phase the consumers are willing to act according to environmental concerns, but there is a lack of systems for collecting used clothing which the consumers perceive as unsuitable for reuse. Consequently, much clothing which could have been better exploited ends up as residual waste. In the use-phase we have seen great technological improvements in appliances. Consumer practices have, on the other hand, steadily deteriorated from an environmental point of view. Improvements in this phase could come through a combination of attitude changes among consumers and qualitative improvements of clothing and textiles so that laundering becomes simpler and less frequent. The main challenges, however, are found in the acquisition phase. Here, there is a lack of will, opportunities and knowledge to make changes. The enablers which could have contributed, such as eco-labels, are limited and, in addition, the information they provide is too limited to function as a good guidance tool. Important information, such as the durability of the clothing, and its physical and mechanical properties, is not included in the schemes. The schemes also do not say how much of the environmental impact the use-phase is accounting for. Nevertheless, the most important aspect of acquisition is that the consumer finds clothes which cover their needs and which are well adapted to the body's size and movement pattern, as well as the occasions for which the user needs the clothes. Knowledge, both of the technical and social aspects, of clothes are low and there are no systems for providing consumers with the information needed for them to make informed choices in both these aspects.

To place the responsibility for change on consumers is to give the responsibility to those without the means to take it. The most important reason for this is that the textile industry is characterized by its large-scale and diffuse value chains and its complex products. As presented in Sect. 2 of this chapter, the old model of regulation, which stipulates mandatory product or process standards, is unable to deal with problems such as environmental factors in the textile value chain. Regulation through consumption, and other forms of voluntary regulation has, therefore, been presented as one solution. Based on the findings presented in this chapter, we argue that these alternatives may be necessary, but that they are insufficient to improve significantly the environmental impacts of textile consumption. This does not mean that the consumers should not play an important role in the restructuring processes, but that the combination of an increasingly condensed knowledge about clothing and textiles and the dramatic fall in clothing and textile prices is hardly a good recipe for success.

Future research should thus concentrate on areas where the potential for environmental benefits are greatest and where knowledge is at its lowest. This applies in particular to how we can ensure that more of the clothing's technical lifespan is extracted by the clothing's first owner, or by the first owner's closest circle, and how consumers can make informed acquisition choices both with regard to technical and social usability and the environmental impact in the production and use-phase. We need greater knowledge about how this international industry can be regulated and managed in order for both environmental and ethical concerns to be accounted for. In this work, it seems evident that the main responsibility must lie with the countries and actors who earn money from production and who are using textiles, and not with the countries and people who produce them. We need clothes to take part in society and to stay warm and beautiful. Nonetheless, we need to ensure that this can be done without leaving dirty tracks.

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# Environmental Analysis of Textile Value Chain: An Overview

**T. Karthik and D. Gopalakrishnan**

**Abstract** Clothing is something required by all human beings. It is one of the most fundamental requirements needed to survive. It is the biggest economic activity the textile industries are involved into satisfy the ever growing demands in terms of quality, variety and other technical requirements. Increasing public awareness and sense of social responsibility related to environmental issues have led the textile industry to manufacture products with improved environmental profiles. In recent years, environmental benefit claims such as environmentally friendly, environmentally responsible, eco-safe, recycled and green materials have often been used to describe and promote products which supposedly have minimal negative environmental impacts. Sustainability does not just mean ecologically sustainable, although that is often the part of sustainability focused on today. This chapter aims to give an insight into the comprehensive details relating to the various processes in the value chain of textile and clothing manufacturing such as fibres, yarn and fabric production processes, textile chemical processing and their influence on the environment.

**Keywords** Sustainability · Eco-friendly · Textiles · Clothing · Processing

## 1 Introduction

Sustain means "to maintain" or "to uphold" and, with regard to industrial processes, sustainability means establishing those principles and practices which can help to maintain the equilibrium of nature, in other words, to avoid causing irreversible damage to the Earth's natural resources.

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Living in an environmentally conscious era, consumers have demanding requirements in many areas. Being aware of environmental issues, nowadays consumers seek eco-friendly products. Today, people have started looking for "Green Products" everywhere. In terms of textile products, the purchasing decisions of consumers were previously based upon comfort, style, aesthetic appeal, etc., but now more on eco-friendliness of products. Many clothing companies have started providing clothes made from eco-friendly fabrics, and the demands for these green products are increasing [6]. The criteria to judge any material as "environmental friendly" are renewability, an ecological footprint of the resource, and the usage of any chemical to grow/process to make the product ready for use. If textile producing companies embrace these trends, they not only capitalize by increasing profits but also sleep better, knowing that they are playing their part in protecting our environment. Adopting friendly practices such as reusing and recycling wastewaters is a great start for accomplishing these goals. At present, business models are linked to the volume of sales and production alone. Therefore, more sustainable consumption is seen merely as leading to reduced volumes and decreasing profitability in production, not as an opportunity for a new kind of green business [7].

## 2 Textile and Clothing Industries

With the increasing consumption of manufactured goods all over the world, product manufacturing systems have come under intense scrutiny with regard to their impact on the environment. The consumption of natural resources has increased dramatically in the last 40 years with little regard for the resulting environmental degradation, particularly in the rapidly industrializing countries [12]. It is only relatively recently that we have come to recognize the unintended consequences of this carefree attitude towards the natural environment. Problems such as global warming, caused by increasing atmospheric carbon dioxide levels from the burning of fossil fuels, natural resource depletion, toxic waste disposal, and increasing air, water, and soil pollution from both agriculture and industry are becoming issues of global importance, requiring concerted international action to solve them. In such a scenario, it becomes every individual's responsibility to contribute proactively and participate in the solving of these problems. Every industrial sector and the leading companies in each sector are also now being held to account for their impact on human health and the environment [2].

The textile industry is a significant contributor to many national economies, encompassing both small- and large-scale operations worldwide. In terms of its output or production and employment, the textile industry is one of the largest industries in the world. The demand for sustainable clothing from "ethical" consumers, significant improvements in enforcement of environmental laws by regulatory authorities, and better compliance by manufacturers clearly demonstrate a growing recognition of the importance of moving towards a more sustainable model for the textile and clothing industries [9]. The clothing industry is intensive and offers basic level jobs for unskilled labour in developed as well as developing countries. Moreover, it is a sector where relatively modern technology can be adopted, even in poor countries, at relatively low investment costs. At the same time, the textile and clothing (and fashion) industries have high-value added segments where design, research, and development are important competitive factors. The high end of the fashion industry uses human capital intensively in design and marketing. The same applies to market segments such as sportswear where both design and material technology are important [8].

Textiles provide the major input to the clothing industry, creating vertical linkages between the two. At the micro level, the two sectors are increasingly integrated through vertical supply chains which also involve the distribution and sales activities. Indeed, retailers in the clothing sector increasingly manage the supply chain of the clothing and textiles sectors [3].

The textile and clothing industries involve:

- Obtaining and processing raw materials, i.e. the preparation and production of textile fibres. 'Natural' fibres include, among others, cotton, wool, silk, flax and hemp. 'Manufactured' fibres include fibres resulting from the transformation of natural polymers (cellulosic fibres such as viscose, modal, Lyocell) or synthetic polymers (fibres from organic material such as oil, i.e. polyester, nylon, acrylic, polypropylene) and fibres from inorganic materials (such as glass).
- Production of yarns and fabrics.
- Finishing activities which give textiles visual, physical and aesthetic properties which consumers demand, such as bleaching, printing, dyeing and coating.
- Transformation of textiles into garments which can be either fashion or non-fashion garments (the so-called 'clothing industry').

The textile manufacturing process is characterised by the high consumption of resources such as water, fuel and a variety of chemicals in a long process sequence generating a significant amount of waste. The common practices of low process efficiency result in substantial wastage of resources and severe damage to the environment. The main environmental problems associated with the textile industry are typically those associated with water body pollution caused by the discharge of untreated effluents. Other environmental issues of equal importance are air emission, notably Volatile Organic Compounds (VOCs) and excessive noise or odour as well as workspace safety [10].

Figure 1 provides a brief outline of the social, environmental and economic impacts at each stage in the life of an item of clothing.

## 3 Environmental Impact Areas in the Textile and Clothing Industries

The broad classification of environmental impact areas of the textile and clothing industries is shown in Fig. 2.

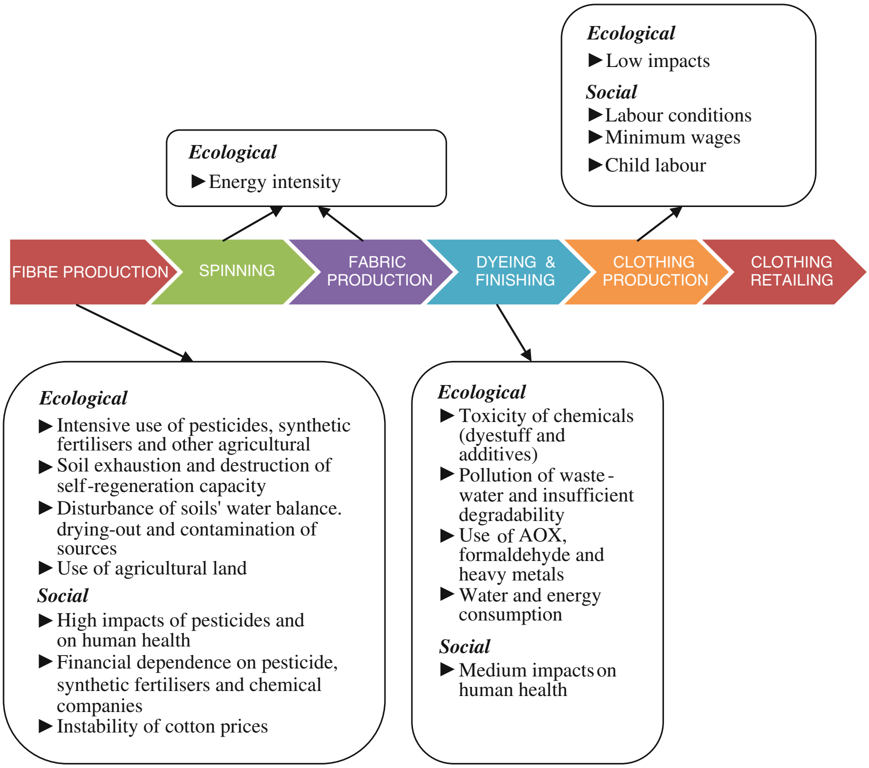


**Fig. 1** Environmental and social impact of textile manufacturing processes

## *3.1 Raw Materials*

The choice of raw materials for clothing has large impacts on the environment. Natural fibres such as cotton are often assumed to be a more environmentally responsible choice, but this is not necessarily true. Cotton is notorious for its intensive use of water and pesticides. The same goes for "natural" dyes, which depend on the harvest of millions of insects or plant bark to achieve colour the "natural" way. These dyes often also require the use of supplementary chemicals containing toxic metals [11]. Fibre choice also drives consumer-care requirements, which can indirectly impact the consumption of water, energy and toxic chemicals.

## *3.2 Manufacturing*

Textile dyeing and finishing mills are particularly high-volume, high-impact producers of water pollution and carbon dioxide emissions. Through extensive

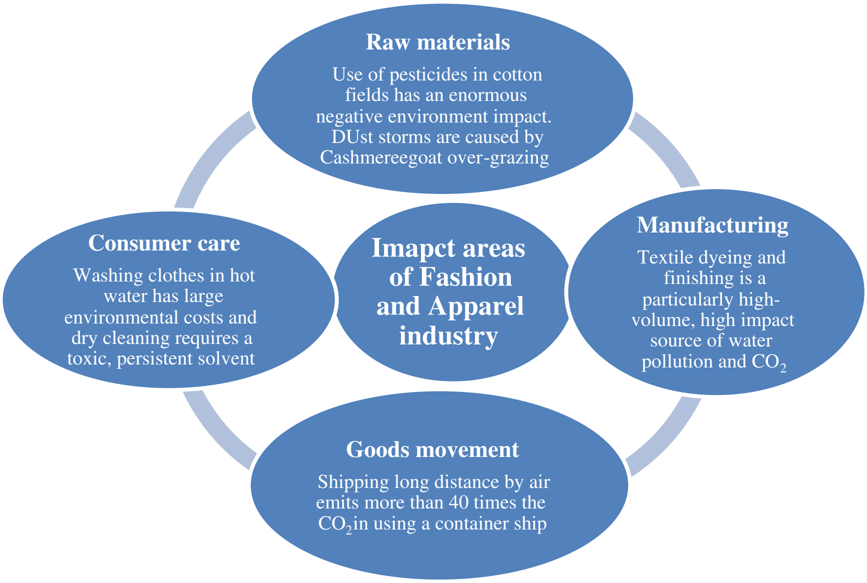


**Fig. 2** Impact areas of the fashion and apparel industry

hands-on research in China, NRDC (Natural Resources Defense Council) has developed ten practical, easy-to-implement best practices for textile mills which significantly reduce water, energy and chemical use, thereby improving manufacturing efficiency. In fact, all of NRDC's best practices for responsible sourcing pay themselves back in less than a year. Designers, retailers and brands can reduce the footprint of their global supply chain by encouraging or requiring mills to adopt these improvements and reward those who do so with more business [10].

## 3.3 Transportation

The apparel industry is a global enterprise, where raw materials, manufacturers and retailers are routinely on opposite sides of the globe. Each designer and retailer must choose among container ships, railroads, trucks and airplanes to move their garments from factory to market. Each mode of transportation sends different levels of pollution into the environment and affects different populations and ecosystems around the world. However, there are many choices a retailer can make to decrease the impact of global transport and to help protect public health.

### *3.4 Consumer Care*

Once purchased, the way a consumer cleans and cares for garments can have a surprisingly large impact on water and energy use. In fact, clothes frequently laundered or dry-cleaned make their biggest environmental impact once they leave the store. Washing in cold water and minimizing dry cleaning (even so-called "organic dry cleaning") can reduce impacts substantially.

## 4 Environmental Impacts of Fibres

Recently, with increase in consumer interest and establishment of third party certification systems, a greater focus has been given by the textile companies to the production of sustainable fibres. New alternatives have been investigated, developed and introduced to the market. The comprehensive analyses of impact of important natural and synthetic fibres and environmental benchmark of fibres are shown in Tables 1 and 2, respectively.

### *4.1 Cotton*

Cotton is the most important apparel fibre around the world. Cotton is a natural cellulosic fibre, comes from a renewable resource, and is intrinsically biodegradable. Therefore, many consumers believe it is an environmentally responsible product. In fact, cotton plants are very prone to attack by certain insects and fungi. Cotton is the most pesticide intensive crop in the world: these pesticides injure and kill many people every year. It also takes up a large proportion of agricultural land, much of which is needed by local people to grow their own food. Herbicides, and also the chemical defoliants which are sometimes used to aid mechanical cotton harvesting, add to the toll on both the environment and human health. These chemicals typically remain in the fabric after finishing, and are released during the lifetime of the garments [5].

Before the fibres can be processed into textile products, the waxy outer layer on cotton must be dissolved in aqueous sodium hydroxide through a process called "scouring" so that dyes can penetrate. The same chemical is also used in the mercerization of cotton to improve performance characteristics. Furthermore, most of the cotton is bleached before dyeing or printing to yield a better colouration [32]. Formaldehyde or related products have been used on cotton in the durable-press finish to improve the wrinkle recovery of the fabrics. The carcinogenic property of formaldehyde has been a major concern with using the chemical on cotton. Despite its "natural" image, cotton production has become increasingly associated with severe negative environmental and social impacts. The environmental impacts from cotton production include the use of chemicals and the generation of waste. Social costs of cotton production include, for example, severe

**Table 1** Environmental impacts of important natural and synthetic textile fibres

| Textile fibre | Non-polluting to obtain, process and fabricate | Made from renewable resources | Fully bio-degradable | Reusable/recyclable |
|---|---|---|---|---|
| Cotton | No<br>Fertilizers, herbicides, pesticides, dyes and finishing chemicals used can pollute air, water, and soil | Yes<br>Cotton comes from cotton plants which are renewable | Yes | Yes<br>However, it is difficult to recycle cotton from postconsumer products because of the presence of dyes and other fibres |
| Wool | No<br>Runoff contamination, chemicals used for cleaning, dyeing, and finishing can cause pollution | Yes<br>Wool comes from sheep, which are renewable | Yes | Yes<br>Wool has been recycled |
| Rayon | No<br>Harsh chemicals used to process wood pulp, and dyes and finishing chemicals can cause pollution | No<br>Wood pulp used for rayon comes from mature forest | Yes | Yes<br>However, rayon fibres have not been recycled |
| Tencel® | No<br>Chemicals used for dyeing and finishing can cause pollution | Yes<br>Trees used for Tencel® are replanted | Yes | Yes<br>However, Tencel® has not been recycled |
| Polyester | No<br>Chemicals used for dyeing and finishing can pollute air and water | No<br>Petroleum sources are not renewable | No | Yes<br>100 % polyester has been recycled |
| Nylon | No<br>Chemicals used for dyeing and finishing can pollute air and water | No<br>Petroleum sources are not renewable | No | Yes<br>100 % nylon has been recycled |
| Leather | No<br>Livestock production and chemicals used for tanning and dyeing can cause pollution | Yes<br>Leathers come from animal skins and hides | Yes | Yes<br>Leather products can be reused |

health problems related to the heavy use of toxic pesticides, especially in countries where regulatory systems are weak or lacking [13].

Efforts have recently been made to find substitutes for toxic chemicals used in textile processing. Citric acid, for example, which causes no adverse effects to humans or the environment, has been introduced to replace formaldehyde,

**Table 2** Environmental benchmarks of textile fibres

| Class A | Class B | Class C | Class D | Class E | Class F |
|---|---|---|---|---|---|
| • Recycled cotton | • Tencel® | • Conventional hemp | • Virgin polyester | • Conventional cotton | • Silk |
| • Mechanically recycled nylon | • Organic cotton | • Ramie | • Poly-acrylic | • Virgin nylon | • Organic wool |
| • Mechanically recycled polyester | • Chemically recycled polyester | • PLA | • Generic modal | • Cupra | • Leather |
| • Recycled wool | | • Conventional linen | | • Bamboo viscose | • Spandex |
| • Organic hemp | | | | • Wool | • Acetate |
| • Organic linen | | | | • Generic viscose | • Cashmere wool |
| | | | | | • Alpaca wool |
| | | | | | • Mohair wool |
| | | | | | • Bamboo linen |

a possible carcinogen, for durable-press-finished cotton fabric. An effort made to improve cotton dyeing is the introduction of covalently bound cationic dye sites into the cotton fibres so the affinity of the dyes for fibres is improved and the rinsing and after-washing steps of the conventional processes can be eliminated, thus reducing environmental pollution. In recent years, a few nonconventional strains of cottons have been grown under more environmentally responsible conditions and marketed as naturally coloured cotton, organic cotton and green cotton. Naturally coloured cottons, available in various shades of green and brown, have been developed through selective breeding from natural mutants, and the fibres can be processed into coloured or patterned fabrics without the use of dyes [26]. Furthermore, naturally coloured cotton plants have better resistance to pests and disease than conventional white cotton, which can reduce or eliminate the need for pesticides and fungicides.

## *4.2 Organic Cotton*

Organic cotton is produced without the use of synthetic fertilizer, herbicides and pesticides. The cotton is grown by using natural fertilizers (manure) and by replacing pesticides with beneficial insects to prey on insects harmful to the plants. Once it is harvested, certified organic cotton is stored without the use of rodenticides or fungicides. Green cotton is used to describe cotton fabric washed with mild natural-based soap, and the fabric is not bleached or treated with any chemicals, except possibly natural dyes. Despite the fact that a few types of environmentally responsible cottons have been introduced to the market, conventional white cotton still accounts for the majority of cotton products.

## *4.3 Wool*

Wool is the most important animal fibre used in textiles. The fibres are the hair of animals, most often sheep. Of course, this is a renewable resource. Although the production of wool does not involve the use of fertilizers or herbicides as in cotton production, wool cannot be produced without some negative impacts on the environment. For example, soil erosion can occur from overgrazing by sheep if not controlled properly. Also, excess sheep manure can create runoff contamination. The processing of wool requires the use of soap and alkaline solutions to clean the fibres and to remove grease and impurities. Chemicals are also used on wool fabrics to prevent shrinkage, to ensure machine washability, and to provide resistance to moths and stains. Through selective breeding, coloured wool can be obtained from sheep with natural pigmentation. The use of coloured wool can eliminate the need for colouring the fibres. However, the amount of coloured wool used still is minuscule compared to conventional wool [24].

## 4.4 Organic Wool

Organic wool is different from conventional wool in at least two major ways: (1) sheep cannot be dipped in insecticides to control external parasites such as ticks and lice, and (2) organic wool farmers are required to ensure that they do not exceed the natural carrying capacity of the land on which their animals graze [14].

The term “organic” doesn’t only cover management of the livestock according to organic or holistic management principles but also (1) processing of the raw wool, using newer, more benign processes rather than harmful scouring and descaling chemicals; and (2) wastewater treatment from scouring and processing according to Global Organic Textile Standard (GOTS).

## 4.5 Rayon

Rayon, the first regenerated cellulosic fibre, was produced and sold as “artificial silk” until the name “rayon” was adopted in 1924. Historically, rayon was produced by two methods: the viscose and the cuprammonium processes. The production of viscose rayon still poses a threat to the environment; the wood pulp used comes from mature forests, and the processing of wood pulp into fibre and cleaning it after extrusion uses large quantities of harsh chemicals which can contribute to water and air pollution. Recently, some rayon producers have been working to recover and recycle the chemicals used in order to reduce the pollutant emissions and waste water effluent.

## 4.6 Lyocell

Tencel® (with the generic name lyocell) is another regenerated cellulosic fibre made from wood pulp. It was first introduced in the early 1990s and was marketed as a type of rayon without negative environmental impact. The wood pulp for Tencel® comes from wood harvested from trees grown specifically for this end use. During the synthesis of the polymer, the wood pulp is dissolved in a weak bath of amine oxide, a low-toxicity and low-skin irritation solvent, and the solution is spun into a bath of diluted solvent where Tencel® filaments are solidified and produced. All the solvents used in the production of Tencel® filament are then recovered, purified, and recycled. In general, Tencel® is biodegradable and from a renewable resource. In addition, the chemicals used in the production of Tencel® fibre are significantly less hazardous to the environment. Although compared to rayon the production of Tencel® poses much less adverse impacts on the environment, it is still a relative new fibre and is not as widely used as rayon [25].

The manufacturing process for lyocell is different from that of other regenerated cellulosics such as rayon in that it proceeds without the formation of intermediate compounds and there is no curing or ripening stage, therefore the whole process is completed in 3 h. The minimal use of chemicals means that the pure cellulose pulp used to feed the lyocell process remains chemically unchanged by processing. No aggressive chemicals are used for this spinning process, only an organic solvent. Therefore no regeneration of the cellulose is necessary.

Additionally, the production process for lyocell is characterized by an almost completely closed solvent cycle. The spinning bath is cleaned, the excess water is removed by evaporation and the solvent is then recovered for re-use. The water generated during evaporation is used in the washing process. On account of the closed-loop process, the solvent necessary for the production process is recovered almost completely. The remaining minimal emissions are treated before disposal.

### 4.7 Nylon

Nylon and polyester are among the most widely used synthetic fibres in the United States. Both fibres are produced from polymer solution obtained from the by-product of nonrenewable petroleum resources and are essentially non-biodegradable. There are concerns about the use and disposal of hazardous chemicals in the production of nylon resin solids. However, the raw material for nylon is melted in an autoclave without the use of solvents, and the polymer solution is extruded through a spinneret. The filaments are then solidified in air on cooling. After spinning, the fibres are ready to be used without cleaning or washing. However, the manufacture of nylon emits nitrous oxide, which is a substance partly responsible for depleting Earth's ozone layer. In addition to dyes, chemicals are often added to the spinning solution to change the physical and chemical properties of the filaments before the fibres are formed. Once the fibre is formed, nylon does not require any finishing processes similar to those used on cotton or wool [34].

Nylon is the major fibre used in carpets, but there are problems associated with nylon carpet recycling. The problems arise from the presence of dyes or chemicals added to the polymer solution during fibre manufacturing, the wide variety of nylon polymers, and the adhesives used in nylon carpet backings. Recently, the industry has been working on recycling nylon from carpet by converting nylon fibres into caprolactam, which is used as raw material for Nylon 6.

### 4.8 Polyester

Polyester is the most widely used synthetic fibre and is sometimes referred to as the workhorse fibre of the industry. The production process of polyester is similar to nylon. Similar to all other synthetic fibres, polyester can be dyed at the solution stage before the fibres are formed. However, when the colours are to be added to polyester fibre products at later stages, polyester is difficult to dye. The dyeing of polyester must be achieved under pressure or in the presence of a carrier. Some disperse dyes used on polyester have been shown to cause allergic contact dermatitis. Unlike nylon, polyester is extensively recycled to reduce landfills. Polyester is being produced by recycling soda bottles made of polyethylene terephthalate [34]. The other advantage of producing fibres from recycled polyester is that significantly less environmental pollution is generated compared to the production of polyester fibres made from new raw materials; it is estimated that air pollution is reduced by as much as 85 %. However, the quality of recycled polyester may not be as good as that of the virgin polyester.

## *4.9 Bamboo*

Bamboo's eco-friendly positioning in the market has been based on the following properties:

1. A natural (that is, non-synthetic) fibre
2. A quick-growth plant (it belongs to the grass family) which sequesters greenhouse gases
3. A renewable plant which can grow back after its 3–5-year harvesting period
4. A plant which doesn't need pesticides or fertilizers during its growth phase

The manufacturing of bamboo fibre is where the debate really gets heated. There are three methods by which bamboo may be processes into fibre for fabric production. The first is a mechanical process similar to that used to process flax or hemp; the stalks are crushed and natural enzymes break them down further, allowing fibres to be combed out. This is an expensive process but it is eco-friendly. The second method follows the process by which rayon is made where the fibres are broken down with aggressive chemicals and extruded through mechanical spinnerets. A third method follows the closed solvent spinning loop which is used for the production of Lyocell fibres. Today the majority of bamboo on the market is processed as rayon. As long as it is manufactured by the rayon process, bamboo fibre and fabrics are no more sustainable than conventional rayon [31].

True bamboo fabric is known for its softness and boasts strong absorbency and anti-microbial properties, but the chemical process in bamboo rayon destroys this anti-microbial effect. Bamboo fibre can be dyed with all dyes recommended for cellulosic fibres. As usual, the dye class selection depends mainly on fastness, requirements. However, as always when producing a sustainable fibre, sustainable products in pre-treatment, dyeing and finishing should also be selected.

## 4.10 PLA (Ingeo$^{TM}$)

Ingeo$^{TM}$ is a polylactide acid fibre (PLA fibre) made from 100 % annually renewable resources and was introduced by Cargill Dow LLC to the textile market in January 2003. The name Ingeo literally means “ingredients from the Earth”. Ingeo$^{TM}$ is produced by fermentation of dextrose obtained in this case from corn starch. Other potential feedstocks could be rice and potatoes and even grass or straw. The fermentation products are subsequently transformed by condensation and vacuum extraction into a high-performance polymer called polylactic acid from which the branded Ingeo fibres and filament yarns are extruded [30].

Ingeo combines the comfort properties of natural fibres with the performance of man-made fibres such as breathability, moisture management, crease resistance, no support of bacterial growth, inherent flame retardancy and UV resistance. In addition, the fibres have environmental benefits resulting from using renewable resources as their feedstock, including reduced $CO_2$ emissions and less fossil fuel usage than other materials (estimated at up to 50 %). In textile applications Ingeo is used for fibre fill, knitted apparel, furnishings, carpets and denim.

## 4.11 Recycled PET

Two kinds of recycled PET are available on the market. One is mechanically recycled PET (only melting of PET) which has a strong yellowish shade and is not suitable for white or pale shades. To get a better degree of whiteness, a bleaching process has to be carried out, and even then the OBA has to be tinted with some dyes to get close to the required level of white. The bleaching process is not eco-friendly at all and adds additional cost to the process. This kind of recycled PET should only be used for dark shades (mainly navy + black). The other type of recycled PET is a full chemically recycled PET. This has a similar shade to “virgin PET” and can be used without any problems for all shades. It is claimed that the cost of recycled PET can be twice the cost of virgin PET.

Regarding dyeing, both recycled PETs behave the same as “virgin PET” but careful dye selection is necessary to ensure the highest levels of exhaustion compatibility and fastness. As part of its econfidence® program, DyStar has recently launched a range of “green” Dianix dyes which are ideally suited for the processing of recycled PET. A comprehensive screening program covering raw materials and intermediates as well as sophisticated dye manufacturing controls ensures that no harmful chemicals are carried through onto the fibre.

## 4.12 Leather

Leather is obtained from the skins and hides of a variety of mammals, notably cattle, pigs, goats and sheep. Most skins and hides are by-products of animals raised primarily for their meat or, in the case of sheep, their meat and wool. Because leather comes from animal skins and hides, it is renewable and is fully biodegradable. However, similar to wool, the raising of animals for their skins and hides creates problems such as manure-containing runoff, which poses a threat to the environment [34]. To make leathers, the skins and hides are first salted, then cleaned to remove hair, tanned, coloured or dyed, and finally finished to achieve a certain appearance or performance properties. Tanning is the process used to make skins and hides pliable and water-resistant. The most common method of tanning leather uses solutions composed of chromium-based salts and oils. The tanning process is the most environmentally controversial among all stages of leather manufacturing. In addition, leather products require dry cleaning using chemicals such as perchloroethylene, trichlorofluoromethane, or trichlorotrifluoroethane, which are toxic to humans and harmful to the environment.

In recent years, washable suede or leather garments have been commercially available. These washable leathers have been coated with an environmentally safe enzyme followed by prewashing so they can resist stains and can be machine washed and dried. The International Cooperation (1999) has developed a research project called Leather Production of the Future to minimize pollutants and to reduce negative environmental impacts from the production of leather worldwide. In addition, the United Nations Industrial Development Organization (2003) has developed a series of methods to help leather producers worldwide reduce the ecological impact of leather production. These methods include treatment of effluents, efficient use of chemicals, new biodegradable chemicals for tanning, and modern equipment which can reduce effluents or decrease solid waste discharge. Furthermore, these clean technologies can lead to an improvement in the quality of leathers produced.

## 4.13 Milk Yarn

Cyarn milk protein fibre dewaters and skims milk, and manufactures the protein spinning fluid suitable for a wet spinning process by means of a new bio-engineering technique, and new high-grade textile fibre is made by combining them. In April 2004 it passed Oeko-Tex Standard 100 green certification for international ecological textiles. Cyarn milk protein fibre is healthy for skin, comfortable, with bright colours because of good dyeability, etc. The milk protein fibre can be spun purely or spun with cashmere, silk, spun silk, cotton, wool, ramie and other fibres to weave fabrics with the features of milk protein fibre [16]. It can also be used to create top grade underwear, shirts, T-shirts, loungewear, etc. to satisfy people's pursuit of comfortable, healthy, superior and fashionable garments. The milk protein fibre is a fresh product as a superior green, healthy and comfortable fibre, and milk protein fibre will certainly become popular goods in the market as a new favorite for textiles.

## 5 Environmental Impact of Textile Processes

It is a fact that the textile industry has grown many times during the last decades to meet global and domestic demand. This tremendous growth has also led to a parallel growth in environmental problems, which remained unnoticed. Any industrial activity produces pollution in one form or the other, and the textile industry certainly released a wide spectrum of pollution into the environment. The textile manufacturing process is characterised by the high consumption of resources such as water, fuel and a variety of chemicals in a long process sequence which generates a significant amount of waste. The common practices of low process efficiency result in substantial wastage of resources and severe damage to the environment [18, 19]. The practice of age-old processes ranging from raw material input to final products compounded major environmental impact. As well as the old techniques, the chemicals used, unskilled labour, logistics employed, untreated effluent disposal, erroneous working methods and improper sanitation are generating wastewater, noise, dust, toxic waste, gaseous waste, hazardous chemicals and heaps of solid waste [35]. The main environmental problems associated with the textile industry are typically those associated with water body pollution caused by discharge of untreated effluents. Other environmental issues of equal importance are air emission, notably volatile organic compounds (VOCs) and excessive noise or odour as well as workspace safety. An overview of the amounts of waste generated within textile processes is presented in Table 3.

### *5.1 Environmental Impact of Spinning*

During spinning, fibres are subjected to various mechanical processes which comb, align and spin them to produce a yarn. In some cases two or more yarns are then twisted together to form a twine. Chemical auxiliaries are used to provide lubrication, allowing high speed processing. Traditionally mineral oils were used, a source of poly aromatic hydrocarbons (PAHs). PAHs are prevalent pollutants in both terrestrial and aquatic environments which can cause a wide range of toxic effects; some are known human carcinogens. Today they have been largely replaced by synthetic oils (silicone oils, polyglycols) and ester oils (esterified fatty acids) [17]. These offer better performance and have more uniform properties. As the oils are applied as aqueous preparations and are not generally water soluble, emulsifiers are required. Generally these are non-ionic surfactants such as alcohol

**Table 3** Wastes generated during textile manufacturing

| Process | Emission | Waste water | Solid wastes |
|---|---|---|---|
| Fibre preparation | Little or none | Little or none | Fibre waste and packaging waste |
| Yarn spinning | Little or none | Little or none | Packaging wastes; sized yarn; fibre waste; cleaning and processing waste |
| Slashing/sizing | VOCs | BOD; COD; metals | Fibre lint; yarn waste; packaging waste; cleaning waste, size unused starch-based sized |
| Weaving | Little or none | Little or none | Packaging waste; yarn and fabric scraps; off-spec fabric; used oil. |
| Knitting | Little or none | Little or none | Packaging waste yarn and fabric scraps; off-spec fabric |
| Tufting | Little or none | Little or none | Packaging waste yarn, fabric scraps; off-spec fabric |
| Desizing | VOCs from glycol ethers | BOD from sizes lubricants; biocides; anti-static compounds | Packaging waste; fibre lint; yarn waste; cleaning and maintenance materials |
| Scouring | VOCs from glycol ethers and scouring solvents | Disinfectants, insecticide residues; NaOH; detergents, oils; knitting lubricants; spin finishes; spent solvents | Little or none |
| Bleaching | Little or none | $H_2O_2$, stabilizers; high pH | Little or none; even if little, the impact could be considerable |
| Singeing | Small amounts of exhaust gases from the burners | Little or none | Little or none |
| Mercerising | Little or none | High pH; NaOH | Little or none |
| Heat-setting | Volatilization of spin finish agents synthetic fibre manufacture | Little or none | Little or none |

(continued)

**Table 3** (continued)

| Process | Emission | Waste water | Solid wastes |
|---|---|---|---|
| Dyeing | VOCs | Metals; salt; surfactants; organic processing assistants; cationic materials; colour; BOD; COD; sulfide; acidity/alkalinity; spent solvents | Little or none |
| Printing | Solvents, acetic acid drying and curing oven emissions combustion; gases | Suspended solids; urea; solvents; colour; metals; heat; BOD; foam | Little or none |
| Finishing | VOCs; contaminants in purchased chemicals; formaldehyde vapors; combustion gases | COD; suspended solids; toxic materials; spot solvents | Fabric scraps and trimmings; packaging waste |

ethoxylates and alkylphenol ethoxylates. The aqueous preparations must be protected from degradation during storage so preservatives such as bactericides and fungicides are also added. As discussed later, these end up in finishing plant effluent streams.

Synthetic oils do not contain the same levels of impurities (no metals, etc.) as mineral oils and some biodegrade. Ester oils are also biodegradable and easier to emulsify than mineral oils (therefore a lower surfactant loading is required). For the spinning of synthetic fibres, silicon oils predominate and account for up to 7 % of the yarn by weight. Though these are non-toxic and bio-eliminable, emulsification is difficult and so large amounts of surfactant are employed.

## *5.2 Environmental Impact of Weaving*

Weaving interlaces two or more perpendicular yarn systems. On a loom, weft yarn is woven between taught, parallel warp yarns (the *shed*). The warp yarns are under tension and are subjected to stress during weaving as the weft yarn is inserted between them at great speed. In order to reduce damage caused by the many abrasive contacts the shed must endure, a chemical preparation, size, is applied to warp yarn prior to assembly on the loom. The size forms a film, rendering the yarn more slippery, supple and stronger. Thus it reduces friction, the number of free fibre ends which may interfere with the weaving process and the number of warp yarn breakages.

**Table 4** Natural- and synthetic-based starches for sizing

| Polysaccharide based | Fully synthetic |
|---|---|
| • Starch | • Polyvinyl alcohols |
| • Starch derivatives | • Polyacrylates |
| • Cellulose derivatives | • Polyvinyl acetate |
| • Galactomannans | • Polyester |

Size preparations fall into two broad classes; natural and synthetic (Table 4). Natural sizes (of which starch dominates) are currently still the most widely used. The source of starch varies geographically; in Europe both native and modified starches originate from potatoes, in the US corn starch (from maize) is employed, whereas in Asia starches originate from rice, sago, maize and tapioca. Starch is increasingly often chemically treated to produce depolymerised derivatives such as carboxymethyl cellulose (CMC). This improves its performance and renders it water soluble (recyclable).

Warp yarns typically account for 60 % of the fabric and therefore sizing agents represent a significant use of auxiliaries. As can be seen in Table 5, cotton is the most heavily sized fibre with loads of up to 200 g/kg applied to the warp yarn. This is because starch/starch derivatives are usually employed, for which loadings are significantly higher than for synthetic sizes.

A range of additional agents are generally present in most size preparations for cotton. These include:

- *Viscosity Regulators*—agents that interact with the starch to alter its physical properties. For example, borax (sodium borate) increases viscosity by complexing (binding to) the starch, whereas peroxysulphates may be used to cleave chemically the starch macromolecule, reducing viscosity.
- *Antistatic Agents*—phosphoric acid esters may be used; these are water soluble and difficult to degrade, resulting in their passage through common waste water systems unscathed.
- *Wetting Agents*—improve size penetration of the yarn.
- *Defoaming Agents*—if PVA size is used it is necessary to add an agent to prevent the formation of foam. Oils (paraffin or silicone) or fatty acid esters are often used.
- *Preservatives*—to prevent degradation of sizes such as starch, biocides are often added.

Sizes for fibres other than cotton do not contain such a range of auxiliaries and generally only a preservative is added (as is the case with all aqueous preparations that are stored for long periods of time). It was not possible to find out what percentage of the size additives typically account for.

Spinning and weaving auxiliary chemicals are generally left on the fabric by producers. Removal is carried out by finishing houses prior to dying as an impure fabric would result in poor dye take-up and inconsistent results. For this reason, the effects of sizes upon waste water streams shall be discussed in full as part of the

**Table 5** Size loading of different fibres

| Fibre | Loading(g/kg yarn) | Size used |
|---|---|---|
| Cotton/cotton-polyester | 80–200 | Starch/ starch derivatives often in combination with others |
| Polyester | 40–60 | Mainly polyester, also small amounts of PVA |
| Nylon | 20–50 | Polyacrylic acid |
| Viscose | 40–120 | Normally combinations of all types |

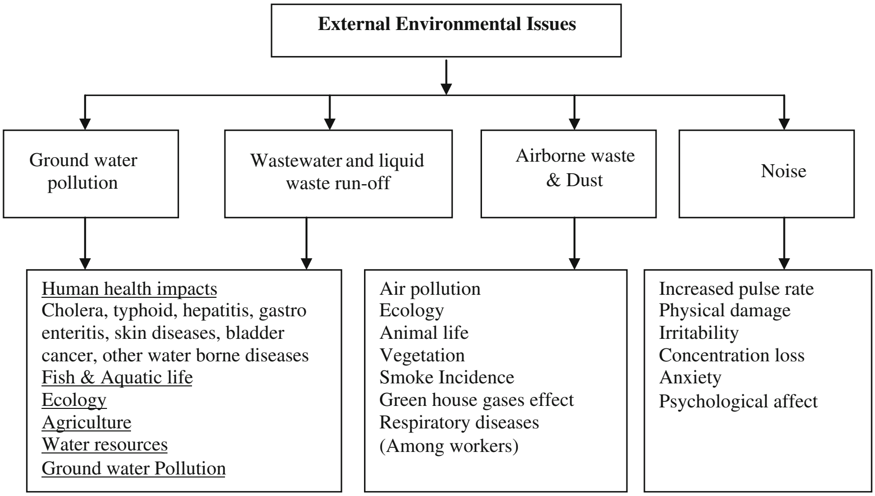


**Fig. 3** External environmental issues and their impacts

pre-treatment section. Most of the substances are relatively benign in terms of direct environmental toxicity. It is because of the quantity of these substances used that they burden the environment.

### 5.2.1 External Environmental Issues

The external environmental issues relating to the textile processes are given in Fig. 3

### 5.2.2 Air Pollution

Most processes performed in textile mills produce atmospheric emissions. Gaseous emissions have been identified as the second greatest pollution problem (after effluent quality) for the textile industry. Speculation concerning the amounts and types of air pollutants emitted from textile operations has been widespread but, generally, air emission data for textile manufacturing operations are not readily available [1]. Air pollution is the most difficult type of pollution to sample, test and quantify in an audit. Air emissions can be classified according to the nature of their sources:

Point sources:

- Boilers
- Ovens
- Storage tanks

Diffusive:

- Solvent-based
- Wastewater treatment
- Warehouses
- Spills

Textile mills usually generate nitrogen and sulphur oxides from boilers. Other significant sources of air emissions in textile operations include resin finishing and drying operations, printing, dyeing, fabric preparation, and wastewater treatment plants. Hydrocarbons are emitted from drying ovens and from mineral oils in high-temperature drying/curing. These processes can emit formaldehyde, acids, softeners, and other volatile compounds [18, 19]. Residues from fibre preparation sometimes emit pollutants during heat setting processes. Carriers and solvents may be emitted during dyeing operations depending on the types of dyeing processes used and from wastewater treatment plant operations. Carriers used in batch dyeing of disperse dyes may lead to volatilisation of aqueous chemical emulsions during heat setting, drying, or curing stages [29]. Acetic acid and formaldehyde are two major emissions of concern in textiles. The major sources of air pollution in the textile industry are summarized in Table 6.

Gaseous wastes from the textile industry, containing solvent vapours such as ammonia and formaldehyde, are normally diffused into the atmosphere. Another form of air waste originates from boilers. Most textile mills use coal or gas as fuel, and large amounts of gases are liberated into the atmosphere, making the air quality heavily chemical and poisonous. The release of cotton dust to the air from spinning operations can be a health hazard. It can cause acute respiratory diseases. The average levels of suspended particulate matter in metropolitan cities exceed 360 g/$m^3$ while the WHO standard is 150 g/$m^3$. Thus, there is growing concern about this increasing air pollution resulting in strict environmental legislation [20–22].

### 5.2.3 Water Pollution

The textile industry uses high volumes of water throughout its operations, from the washing of fibres to bleaching, dyeing and washing of finished products. On

**Table 6** Summary of wastes generated during textiles manufacturing

| Process | Source | Pollutants |
|---|---|---|
| Energy production | Emissions from boiler | Particulates, nitrous oxides (Nox) sulphur dioxide ($SO_2$) |
| Coating, drying and curing | Emission from high temperature ovens | Volatile organic components (VOCs) |
| Cotton handling activities | Emissions from preparation, carding, combing, and fabrics manufacturing | Particulates |
| Sizing | Emission from using sizing compounds (gums, PVA) | Nitrogen oxides, sulphur oxides, carbon monoxide |
| Bleaching | Emission from using chlorine compound | Chlorine, chlorine dioxide |
| Dyeing | Disperse dyeing using carriers Sulphur dyeing<br>Aniline dyeing | Carriers $H_2S$<br>Aniline vapours |
| Printing | Emission | Hydrocarbons, ammonia |
| Finishing | Resin finishing heat setting of synthetic fabrics | Formaldehyde carriers—low molecular<br>Polymers—lubricating oils |
| Chemical storage | Emissions from storage tanks for commodity and chemicals | volatile organic components (VOCs) |
| Wastewater treatment | Emissions from treatment tanks and vessels | Volatile organic components, toxic emissions |

average, approximately 200 L of water are required to produce 1 kg of textiles (Table 7). The large volumes of wastewater generated also contain a wide variety of chemicals, used throughout processing. These can cause damage if not properly treated before being discharged into the environment. Of all the steps involved in textiles processing, wet processing creates the highest volume of wastewater [23].

The aquatic toxicity of textile industry wastewater varies considerably among production facilities. The sources of aquatic toxicity can include salt, surfactants, ionic metals and their metal complexes, toxic organic chemicals, biocides and toxic anions. Most textile dyes have low aquatic toxicity. On the other hand, surfactants and related compounds, such as detergents, emulsifiers and dispersants are used in almost every textile process and can be an important contributor to effluent aquatic toxicity, BOD and foaming.

The manufacturing of textiles involves the use of water, chemicals and other solvents. The wastewater generated during these processes is highly polluted and dangerous, especially when it gets mixed with other chemicals and is disposed of untreated. The characteristics of wastewater generated from Indian textile processing is highly polluted with high pH, biochemical oxygen demand (BOD) and chemical oxygen demand (COD), and high concentrations of total dissolved solids (TDS), suspended solids (SS), chlorides, sulphates and phenols. Liquid wastes from textile mills arise mainly from wet-finishing treatments, where large volume of water and chemicals are used in textile baths. If the bath is discharged directly to the surroundings, it becomes a major source of pollutants. Most dyes and chemicals used are synthetic and are not readily biodegradable [20–22].

**Table 7** Average water consumption for various types of fabric

| Processing subcategory | Water consumption ($m^3$/ton fibre material) | |
|---|---|---|
| | Minimum | Maximum |
| Wool | 111 | 285 |
| Woven | 5 | 114 |
| Knit | 20 | 84 |
| Carpet | 8.3 | 47 |
| Stock/yarn | 3.3 | 100 |
| Non-woven | 2.5 | 40 |
| Felted fabric finishing | 33 | 213 |

### 5.2.4 Environmental Impact of Textile Wet Processing

The major pollution problems presented by textile wet processing are water pollution problems. There are a few air pollution problems caused by chemicals, lint, etc., but these are minor. The largest impact, especially with respect to water pollution, may be made in the wet-processing operations, primarily those steps taken after the construction of unfinished fabric (commonly called grey goods), because these operations are the most water- and energy-intensive and potentially the greatest waste-generating part of the textile industry. Since there is such a range of diverse products and applications of textiles today, the type of processing used is highly variable and depends on site-specific manufacturing practices as well as the type of fibre used and the final physical and chemical properties desired. Even for a constant product type, no two textile mills use exactly the same methods of production. The textile industry consumes a vast quantity of water and the amount of wastewater generated is also very high [28].

### 5.2.5 Pollutants Associated with Sizing, Desizing and Scouring

Size is a mixture of primary and auxiliary chemicals. Three main types of sizes are currently used:

- Natural products (starch)
- Fully synthetic products (PVA, PVAc, PAA, PEs, etc.)
- Semi synthetic products (blends)—modified starch, starch ether, starch ester, carboxy methylcellulose (CMC), hydroxy ethyl cellulose (HEC), carboxy methyl starch (CMS), etc.

Auxiliaries used in sizing mixture include:

- Adhesives and binders: natural gum, (locust bean gum, tragasol, gelatin, soya protein casein, acrylates, PVA, CMC, etc.)
- Antistatic agents: to suppress static in high speed weaving

- Anti sticking agents: to reduce fouling of dry cans and guide rollers (waxes, oil, tallow, pine oil, kerosene, Stoddard solvent, etc.
- Biocides: (preservative) *o*-phenyl phenol (OPP)
- Defoamers: zinc and calcium chloride, light mineral oil, isooctyl alcohol
- Deliquescent: zinc and calcium chloride, polyalcohols (PEG), glycerin, polypropylene glycol, diethylene glycol (DEG), urea, etc.
- Emulsifier, dispersants and surfactants: non-ionic ethylene oxide compounds
- Humectants: to protect against drying
- Lubricants and softeners: fats, waxes, oils, tallow, sulphated tallow, butyl stearate, glycerin, mineral oil, etc.
- Thinning agents: enzymes, oxidisers, perborates, persulphates, peroxides, chloramides, etc.
- Tints: to identify warps
- Weighers: clay

Any of these additives present in the size mixture are removed later in wet processing, and thus all of these materials appear in waste streams from desizing operations. Most of these additives have very high BOD values and the sizing agents are also responsible for up to 80 % of the total COD load in the wastewater [11]. The toxicity of a few of these additives has been recorded. In addition to size and desize chemicals removed from textiles, sizing and desizing operations generate additional wastes which deserve attention, including the following:

- Packaging material for size
- Dumps of unused portion of size mixes
- Machine cleaning and maintenance
- Fibre lint and yarn waste

### 5.2.6 Desizing

Manmade fibres are generally sized with water-soluble sizes easily removed by a hot water wash or in the scouring process. On the other hand, natural fibres such as cotton are most often sized with water insoluble starches or mixtures of starch and other size materials. Enzymes are used to break these starches into water-soluble sugars. Bacteria in waste treatment can easily attack the water-soluble sugars; these are very degradable and have high BOD.

### 5.2.7 Scouring

Scouring is a cleaning process which removes impurities from fibres, yarn or cloth. The impurities include lubricants, dirt and other natural materials, water-soluble sizes, antistatic agents and fugitive tints used for yarn identification. Scouring uses alkali to saponify natural oils, and surfactants to emulsify and suspend non-saponifiable impurities in the scouring bath.

### 5.2.8 Bleaching

Bleaching is a chemical process which eliminates unwanted coloured matter from fibres, yarns or cloth, Bleaching decolourises coloured impurities not removed by scouring and prepares the cloth for further finishing processes such as dyeing or printing. The most common bleaching agents include hydrogen peroxide, chlorine bleaching, sodium hypochlorite, sodium chlorite and sulphur dioxide gas [1].

### 5.2.9 Pollutants Associated with Dyeing

Many pollutants are associated with the dyes and chemicals used in dyeing processes. These may originate from the dyes themselves (e.g. salt, surfactant, levellers, lubricants and alkalies). Pollutant impacts are also associated with chemicals used during dyeing, equipment maintenance and cleaning. Dyeing contributes most of the metals and essentially all of the salts and colour in effluent from textiles operations and are the priority areas for pollution prevention. There are certain reports stating that dyeing consumes 7 % of the water and contributes 5 % of the BOD in a typical cotton finishing operation. Table 8 details the pollutants associated with various dyes.

### 5.2.10 Pollutants Associated with Textile Printing

Textile printing, similar to dyeing, also generates varying amounts and types of pollutants. Table 9 presents the main pollutants associated with printing and identifies their sources.

Printing produces high BOD and COD loads only if preparation operations (scouring) are done on site. Print application consumes less water and produces less BOD than preparation operations such as desizing, scouring and bleaching. It is reported that, in a typical print plant, printing contributed only 6 % of the BOD to the total pollutant load and accounted for 7 % of water consumption. Print washing, on the other hand, uses more than one quarter of the total water in the mill but produces only 1 % of the total BOD load.

### 5.2.11 Pollutants Associated with Finishing

Finishing operations generate solid and liquid wastes as well as atmospheric pollutants. Pollutant categories include [36]:

- Solid wastes: fabric scraps and trimmings from salvages and seams: fibre dust and fragments from napping, shearing and related operation, paper tubes and empty chemical drums

**Table 8** Pollutants associated with various dyes

| Dye class | Fibre | Type of pollution |
|---|---|---|
| Direct dyes | Cotton | Salt, unfixed dye, copper salt, cationic fixing agents |
| Reactive dyes | Cotton | Salt, alkali, unfixed dye |
| Vat dyes | Cotton | Alkali, oxidising agents, reducing agents |
| Sulphur dyes | Cotton | Alkali, oxidising and reducing agents, unfixed dyes |
| Chrome dyes | Wool | Organic acids, unfixed dyes, metals, sulphide |
| 1:2 Metal complex dyes | Wool | Organic acids, metals |
| Acid dyes | Wool | Organic acids, unfixed dyes |
| Disperse dyes | Polyester | Reducing agents, organic acid carriers |

**Table 9** Pollutants associated with textile printing

| Pollutant | Typical sources |
|---|---|
| Suspended solids | Discarded print paste and clear (pigment printing) |
| Formaldehyde | From binder |
| Urea | Print paste (wet printing) |
| Air emissions | Drying/curing oven emission (solvents, acetic acid) |
| Solvents | Non-aqueous oil/water thickeners, machine cleaning, screen cleaning |
| Aquatic toxicity | Surfactants, solvents |
| Colour | Discarded print paste, colour kitchen operations, implement cleaning |
| Metals | Discarded print paste, photo operations, reducing agents in discharge printing, screen making, engraving operations |
| Water (and heat) | Washing of printed cloth, desizing operation |
| BOD | Back-coating operations, carpet printing |

- Liquid: discarded finishing mixes and rinse water from finishing implements and equipment as well as facility cleanup
- Vapours: exhaust gases from drying and curing.

### 5.2.12 Health Hazards

The textile industries use synthetic organic dyes such as direct, basic, vat, sulphur, naphthol, developed dye and reactive dyes. Table 10 outlines the hazardous chemicals and their impact. The large variety of chemicals used in bleaching and dyeing processes render them very complex. These chemicals are used in an attempt to produce more attractive popular shades of fabrics for a competitive market.

**Table 10** Hazardous chemicals and their impact

| Hazardous chemicals | Hazard |
|---|---|
| Stain remover: carry solvents such as $CCl_4$ | Ozone depletion; capacity ten times more than CFC |
| Oxalic acid: used for rust stain removal | Toxic to aquatic organisms; boosts COD |
| Printing gums: preservative pentachlorophenol | Dermatitis, liver and kidney damage, carcinogenic; banned |
| Fixing agent: formaldehyde and benzidine | Harmful; internationally banned |
| Bleaching: chlorine bleaching | Skin diseases (itching); harmful |
| Dyeing: amino acid liberating groups | Carcinogenic; internationally banned |

### 5.2.13 Hazardous Dyes

Some reactive dyes such as reactive, vat and disperse dyes are recognised as respiratory sensitisers. Breathing in respiratory sensitisers can cause occupational asthma. Once a person is sensitised, re-exposure to even very small amounts of the same dye may result in allergic symptoms such as runny or stuffy nose, watery or prickly eyes, wheezing, chest tightness and breathlessness. Some dyes can also cause similar allergic skin reactions. Other dyes can also relate to health hazards. Dyes based on benzidine are thought possibly to cause cancer.

### 5.2.14 Risk of Explosion

As these dyes are oxidising agents, they may make an existing fire more intense by fuelling it with oxygen. Corrosive chemicals can cause serious burns and may react dangerously with other chemicals. Violent reactions may be caused by substances which are dangerous when wet such as hydros. Hot liquids can also lead to many scalding accidents. Fire hazards can also arise from the use of flammable liquids, which are easily ignitable.

### 5.2.15 Pollution Prevention Guidelines and Various Emission Limits

Pollution prevention and control programs should focus on reduction of water use and on more efficient use of process chemicals. Process changes might include the following:

- Match process variables to type and weight of fabric (reduces wastes by 10–20 %)
- Manage batches to minimise waste at the end of the cycle
- Avoid non-degradable or less degradable surfactants (for washing and scouring) and spinning oils
- Avoid the use, or at least the discharge, of alkylphenol ethoxylates; ozone-depleting substances should not be used; the use of organic solvents should be minimised

- Use transfer printing for synthetics (reduces water consumption from 250 to 2 L/kg of material and also reduces dye consumption); use water-based printing pastes, when feasible
- Use pad batch dyeing (saves up to 80 % of energy requirements and 90 % of water consumption; reduces dye and salt usage) for knitted goods, exhaust dyeing, with a ratio of 10:1, where feasible
- Avoid benzidine based azo dyes and dyes containing cadmium and other heavy metals
- Do not use chlorine-based dyes
- Use less toxic dye carriers and finishing agents; avoid carriers containing chlorine, such as chlorinated aromatics
- Replace dichromate oxidation of vat dyes and sulphur dyes with peroxide oxidation
- Use peroxide-based bleaches instead of sulphur- and chlorine-based bleaches, where feasible
- Control makeup chemicals
- Reuse and recover process chemicals such as caustic (reduces chemicals costs by 30 %) and size (up to 50 % recovery is feasible)
- Replace non-degradable spin finish and size with degradable alternatives
- Use biodegradable textile preservation chemicals; do not use polybrominated diphenylethers, dieldrin, arsenic, mercury or pentachlorophenol in mothproofing, carpet backing, and other finishing processes; where feasible, use permethrin for mothproofing instead
- Control the quality and temperature of water used
- Improve cleaning and housekeeping measures (which may reduce water usage) to less than 150 $m^3$/ton of textile produced
- Recover heat from wash water (reduces steam consumption)

### 5.2.16 Emission Guidelines

Emission levels for the design and operation of projects implemented with World Bank assistance must be established through the Environmental Assessment (EA) process, based on country legislation and the Pollution Prevention and Abatement Handbook as applied to local conditions. The emission levels selected must be justified in the EA and acceptable to the World Bank Group.

The following guidelines present emission levels normally acceptable to the World Bank Group in making decisions regarding provision of World Bank Group assistance; any deviations from these levels must be described in the World Bank Group project documentation. The guidelines are expressed as concentrations to facilitate monitoring. Dilution of air emissions or effluents to achieve these guidelines is unacceptable. All the maximum levels should be achieved for at least 95 % of the time that the plant or unit is operating, to be calculated as a proportion of annual operating hours [20–22].

### 5.2.17 Liquid Effluents

The effluent levels to be achieved are given in Table 11. Effluent requirements are for direct discharge to surface waters. Mercury should not be used in the process. The liquid effluent should not be coloured. The effluent should result in a temperature increase of no more than 3 °C at the edge of the zone where initial mixing and dilution take place. Where the zone is not defined, use 100 m from the point of discharge [15].

### 5.2.18 Sludge

Sludge containing chromium or other toxins should be treated and disposed of in a secure landfill. Incineration of toxic organics should effectively destroy or remove over 99.99 % of them. Frequent sampling may be required during start up. Once a record of consistent performance has been established, sampling for the parameters listed above should be done at least weekly. Only those metals detected or suspected to be present should be monitored. The key production and control practices which lead to compliance with emissions guidelines can be summarised as follows:

- Avoid the use of less degradable surfactants (in washing and scouring operations) and spinning oils
- Consider the use of transfer printing for synthetics; use water-based printing pastes where feasible
- Consider the use of pad batch dyeing
- Use jet dyes instead of winch dyers, where feasible
- Avoid the use of benzidine-based azo dyes and dyes containing cadmium and other heavy metals; chlorine-based dyes should not be used
- Do not use mercury, arsenic and banned pesticides in the process
- Control the makeup of chemicals and match process variables to the type and weight of the fabric
- Recover and reuse process chemicals and dye solution
- Substitute less-toxic dye carriers wherever possible; avoid carriers containing chlorine
- Use peroxide-based bleaches instead of sulphur- and chlorine-based bleaches, where feasible
- Adopt countercurrent rinsing and improved cleaning and housekeeping.

### 5.2.19 Noise

Excessive noise resulting from textile manufacturing industries is threatening the life of workers and the residential areas around them. Although machinery manufacturers made considerable effort to keep noise emission as low as possible while improving the speed of their machines, their measures are inadequate to protect the

**Table 11** World Bank emission limits for liquid effluents

| Parameter | Maximum value |
|---|---|
| pH | 6–9 |
| BOD | 50 mg/L |
| COD | 250 mg/L |
| Total suspended solids | 50 mg/L |
| Oils and greases | 10 mg/L |
| Pesticides (each) | 0.05 mg/L |
| Chromium (total) | 0.5 mg/L |
| Cobalt | 0.5 mg/L |
| Copper | 0.5 mg/L |
| Nickel | 0.5 mg/L |
| Zinc | 2 mg/L |
| Phenol | 0.5 mg/L |
| Sulphide | 1 mg/L |
| Temperature increases | $<3$ °C |
| Coliform | 400 MPN/100 mL |

textile workers from occupational hearing loss. Small units are still continuing with their roaring machines. While the new technological methods involved with machinery and servicing are not being adopted, this situation cannot be tackled.

### 5.2.20 Dust

Dust consists of particles coming directly from substances being handled during processes, such as fibre dust, coal dust, ash, saw dust and grain dust. The first victims of inhalation are the workers. Later this dust mixes with air and increases the suspended solids and pollutes the air. The inhaling of air polluted with cotton dust during blowing, drawing, carding, combing, etc. can cause health hazards such as acute respiratory diseases. Use of extraction equipment has been seen in some of the big textile industries, but the small sector is still lagging behind. There is a need for proper methods to suppress the dust and avoid reaching the air limits.

### 5.2.21 Toxic Waste

Toxic waste can be in any form of effluent, in water, air and dust, and could be phenol, toxic organic compounds, phosphates, chlorinated solvents, non-degradable surfactants etc., originating from various processes such as fibre preparation, dyeing, printing, bleaching, cleaning, etc. Some can even resist the treatment process and produce acute toxicity in effluent. Toxic dangers also exist in the dyeing and finishing sections of the textile industry. In dyeing and printing, workers are frequently exposed to dyes which can contain a variety of acids such as formic, sulphuric and acetic, fluorescent brighteners, organic solvents and fixatives. Workers in the finishing operations are frequently exposed to crease-resistant agents, to flame retardants, and to a number of toxic solvents used for degreasing and spotting. The resulting impacts are skin diseases of the dermatitis type and are common with bleaching, dyeing and finishing, in the preparation of flax and in the use of solvents for making synthetic fibres. Certain dyestuff intermediates can produce bladder cancer. Occupational health effects include byssinosis, chronic bronchitis, dermatitis, and cancer of the bladder among dyers and of the nasal cavity among weavers and others. Because of lack of information about waste management, these hazardous chemicals and solids are disposed of in unsecured landfills, which are extremely harmful for air, soil and groundwater. These areas might later be used for residential purposes [18, 19].

### 5.2.22 Internal Environmental Issues

Above we have described the environmental problems caused by the textile industry to its surrounding environment and cumulatively affecting the residential areas, water resources, plants and animals. The following describes the environmental issues related to the various internal processes from spinning and weaving to the processing (fabric finishing) stages.

### 5.2.23 Process Waste

Process waste is usually generated during fibre preparation and yarn formation. Washing and rinsing are common processes in textile processing during which impurity levels on fabric must be reduced to a predetermined level. Process-waste includes all waste generated during textile production, as shown in Table 12, where the fibres are cleaned, straightened and aligned. Subsequently they are drawn out and twisted into yarn.

These stages produce waste such as:

- Reworkable waste: fibre scrap, yarn scrap, cotton scrap, wastewater, etc.
- Non-reworkable waste: produced during processes such as cleaning, carding, etc.
- Hard waste: produced during stiffening process of yarn

### 5.2.24 Controllable Cause Waste

This kind of waste is usually generated right from raw material to textile production and is mostly generated during the spinning and weaving processes. The waste is usually a result of the following factors:

- Erroneous working methods
- Rejected materials, off specification materials, failed quality control

**Table 12** Textile processes and environmental issues

| Main process | Intermediate process | Environmental issues |
|---|---|---|
| Spinning | Fibre preparatory | Process waste |
| | Yarn manufacturing | Controllable cause waste |
| Weaving | Fabric production | Solid waste |
| | | Chemical additives |
| | | Lint waste |
| Chemical processing | Bleaching | Hazardous chemicals |
| | Dyeing | Health hazards |
| | Printing | Risk of explosion |
| | Other processes | |

- Equipment malfunctions
- Poor housekeeping techniques

This kind of waste is considered controllable because it can be avoided through closer attention to the above factors.

### 5.2.25 Solid Waste

The primary residual wastes generated from the textile industry are non-hazardous. These include scraps of fabric and yarn, off-specification yarn and fabric and packaging waste. There are also wastes associated with the storage and production of yarns and textiles, such as chemical storage drums, cardboard reels for storing fabric and cones used to hold yarns for dyeing and knitting. Cutting room waste generates a high volume of fabric scraps, which can often be reduced by increasing fabric utilisation efficiency in cutting and sewing. Table 13 summarizes solid wastes associated with various textile manufacturing processes.

The majority of this waste originates from other sources during operations such as transportation, bale openings, servicing process, house-keeping, etc. The waste under this category includes:

- Tubes—pallets
- Cones—containers/drums
- Plastic wrap—corrugated cardboard
- Seam waste—paper waste
- Bags—shipping cartons

All the above wastes can find their way to recycling and valuable products can be recovered.

**Table 13** Sources and types of solid wastes from textile manufacturing

| Source | Type of solid waste |
|---|---|
| Mechanical operations of cotton and synthetics: | |
| • Yarn preparation | Fibres and yarns |
| • Knitting | Fibres and yarns |
| • Weaving | Fibres, yarns and cloth scraps |
| Dyeing and finishing of woven fabrics: | |
| • Sizing, desizing, mercerising, beaching, washing and chemical finishing | Cloth scraps |
| • Mechanical finishing | Flock |
| • Dyeing and/or printing | Dye containers |
| • Dyeing and/or printing applied finish) | Chemical containers |
| Dyeing and finishing of knitted fabrics | Cloth scraps, dye and chemical containers |
| Dyeing and finishing carpets: | |
| • Tufting | • Yarns and sweepings |
| • Selvage trim | • Selvage |
| • Fluff and shear | • Flock |
| • • Dyeing, printing and finishing | • Dye and chemical containers |
| Dyeing and finishing of yarn and stock | Yarns, dye and chemical containers |
| Wool fabrication: | |
| • Wool scouring | • Dirt, wool, vegetable matter, waxes |
| • Wool fabric dyeing and finishing | • Flock, seams, fabric, fibres, dye and chemical containers |
| Packaging | Paper, cartons, plastic sheets, rope |
| Workshops | Scrap metal, oily rags |
| Domestic | Paper, sheets, general domestic Wastes |
| Wastewater treatment | Fibre, wasted sludge and retained sludge |

### 5.2.26 Chemical Additives

Desizing and scouring are the main processes adapted to fibre and yarn formation/preparation. A size is a mixture of primary and auxiliary chemicals. These sizes are similar to natural products (starch), fully synthetic products, semi synthetic products (carboxy methyl cellulose, hydroxyl ethyl cellulose, etc.), adhesives and binders. All these go into the waste stream from desizing operations. Scouring is a cleaning process which removes impurities from fibres, yarn or cloth. The impurities include lubricants, dirt and other natural materials, water-soluble sizes, antistatic agents and fugitive tints used for yarn identification. Scouring uses alkali to saponify natural oils and surfactants to emulsify and suspend non-saponifiable impurities in the scouring bath. All the above synthetic compounds, auxiliary chemicals, have very high BOD values and the sizing agents are also responsible for up to 80 % of total COD load in the wastewater.

### 5.2.27 Lint Waste

Lint can originate from many textile production steps, particularly from preparation, dying and washing operations. Removing lint is usually fairly easy by means of primary control measures such as filters, which can be placed in the circulation line of dyeing and other equipment. The filters must be maintained and cleaned out on a regular basis to ensure proper operation. The collected lint can usually be dried and then sent to land fill or incinerated. Higher quality lint can be marketed.

### 5.2.28 Hazardous Chemicals

The processing stages involve intermediary processes such as bleaching, dyeing, printing and other chemical treatments to furnish the cloth. All these processes include use of hazardous chemicals, which make up the pollution. Bleaching is a chemical process which eliminates unwanted coloured matter from fibres, yarns or cloth. Bleaching decolourises coloured impurities which are not removed by scouring and prepares the cloth for further finishing processes such as dyeing or printing [37]. The most common bleaching agents include hydrogen peroxide, sodium hypochlorite, sodium chlorite and sulphur dioxide gas. The dyes and chemicals used in the dyeing process relate to many pollutants, which originate from the dyes themselves (e.g. salt, surfactant, levelers, lubricants and alkalinity). Every chemical is associated with pollutant impact during dyeing, equipment maintenance and cleaning. Dyeing contributes to most of the metals and essentially all the salts and colour in effluent from textiles operations [2].

## 6 Consumers' Responsibility

According to Bratt [4], despite the increased awareness of environmental issues, recycling of solid waste was still not a priority of the public. In addition, research has found that there is no "general" environmental behaviour among consumers; different people tend to focus on different aspects of environmental issues. To safeguard our environment from further pollution, consumers can make environmentally responsible decisions when they make purchase decisions, during product usage and maintenance, and at the time of product disposal. In recent years, textile companies have invested in the development of more environmentally responsible processes, but these processes tend to have the drawback of raising the prices of end products [27].

Although federal and state regulators have issued guidelines for standardizing the use of terms such as recycled and recyclable to reduce consumer confusion, consumers should be aware that many of the environmental benefit claims such as "environmentally friendly" or "ecosafe" can be misleading and should be interpreted carefully. The second place where consumer behavior affects the environment is during the usage and maintenance of the product. To minimize the environmental impacts from using textile products, consumers can avoid items requiring dry cleaning. In addition, consumers can choose environmentally responsible washing detergent containing no chlorine bleach, optical brightener, phosphate, or unnecessary additives. Finally, items that are more durable or long lasting (e.g. stronger and better quality fibres) can save money and are more environmentally responsible because they need to be replaced less frequently and hence can reduce landfill [33]. The last place where consumers help the environment is when the textiles are discarded. Other than throwing them away, the most common form of recycling textile products is for consumers to give the items to nonprofit organizations. It is not easy for consumers to make informed environmental decisions when purchasing textile products. Hence, knowledge of products and their environmental merits is key to helping consumers make the right choice. In general, one way to keep abreast of the environmental knowledge of the products they purchase is for consumers to obtain information on the product or a similar product, request literature from the product manufacturer to help assessing the validity of the claims, and identify important factors in measuring the ecological merit of a product [34].

## 7 Conclusions

With global textile consumption estimated to be more than 30 million tons a year, the issue of environmental consequences of textile production is important. The full environmental impact of any textile product may be broken down into those associated with its production, its maintenance, and its eventual disposal. Production issues include, among other things, the renewability of the raw materials and the toxicity of the chemicals (crop treatments, chemical by-products, solvents) released during production and processing. Issues pertaining to usage are primarily the quality and nature of the chemicals used for laundering or dry cleaning during the products' lifetime. Finally, disposal issues include the products' recyclability and/or biodegradability. Today, there is an ever-growing appreciation of the extent, complexity and subtlety of the environmental impacts associated with these issues. These concerns have prompted manufacturers to reexamine their manufacturing processes using the three Rs as the guidelines. As a result, many manufacturers now claim their products are "environmentally responsible". Because of the multifaceted nature of the impact, terms such as environmentally responsible or green are difficult to apply, and current usage of such terms is sometimes misleading about the real environmental qualities of textile products. Our analysis indicates that, in one way or another, virtually all textile products have a negative impact on the environment. In addition, it seems that the environmental impacts of usage and maintenance of textile products are often neglected by both the textile industry and the consumers. Although textile companies are increasingly responding to the rising environmental concern, partnerships between government, industry and consumers are important in order to create efficient solutions to environmental problems. Although the environmental issues are complex, one thing is certain; they are major issues that affect humankind and must be addressed. A product incorporating environmentally safe and/or recycled materials can be considered a good product but this is only part of the equation. This is why textile manufacturers also have to consider the fibre production, product manufacturing processes, as well as what will happen to the textiles during and after their useful lives when designing their products.

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# Who Influence the Environmental Adaptation Process of Small and Medium Sized Textile and Garment Companies in Vietnam?

**Nga H. Nguyen, Robert J. S. Beeton and Anthony Halog**

**Abstract** The pressure on Small and Medium sized Enterprises (SMEs) in emerging economies to adapt their production and management systems to meet global industrial environmental standards is enormous. Yet an effective way to help SMEs overcome these challenges is not reported. This chapter argues that identifying key stakeholders involved in the adaptation process is a first important step to fill this gap in knowledge. It uses the Stakeholder Theory to analyse interviews with government officials, non-government organizations and enterprises to answer the fundamental question of "who are the key actors influencing the environmental adaptation process at textile and garment SMEs in Vietnam". Customers and company managers are found to be the most important actors, of which customers have more influence over the decision-making and managers have more influence over the implementation. These findings have important implications for the development of environmental adaptation strategies for the textile and garment sector in Vietnam in particular, and in developing countries in general.

**Keywords** Environmental adaptation · Textiles and garments · SMEs · Key actors

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**Table 1** Definition of SMEs in Vietnam per sector

| | Very small enterprises | Small sized enterprises | | Medium sized enterprises | |
|---|---|---|---|---|---|
| | Number of labourers | Total capital | Number of labourers | Total capital | Number of labourers |
| Agriculture, forestry and fishery | 10 persons or fewer | VND 20 billion or less | More than 10 and less than 200 persons | VND more than 20 billion and less than 100 billion | More than 200 and less than 300 persons |
| Industry and construction | 10 persons or fewer | VND 20 billion or less | More than 10 and less than 200 persons | VND more than 20 billion and less than 100 billion | More than 200 and less than 300 persons |
| Trade and service | 10 persons or fewer | VND 10 billion or less | More than 10 and less than 50 persons | VND more than 10 billion and less than 50 billion | More than 50 and less than 100 persons |

*Source* Decree 56/2009/CP-ND

# 1 Introduction

## *1.1 SMEs in Vietnam*

There are different definitions of SMEs. In this study, we use the definition specified in Decree 56/2009/ND-CP[1] of the Government of Vietnam: "Small and medium-sized enterprises are business establishments which have registered their business according to law and are divided into three levels: very small, small and medium according to the sizes of their total capital (equivalent to the total assets identified in an enterprise's accounting balance sheet) or the average annual number of labourers". Table 1 further explores this definition for each sector of the economy.

In Vietnam, any enterprise meeting the requirements of either the criteria for the number of employees or the criteria on the amount of capital is considered an SME. Regardless of the forms of ownership, SMEs can be private enterprises, state-owned enterprises, foreign-owned enterprises and joint stock or joint venture companies.

There is no exact data indicating the number of SMEs in Vietnam. However, UNU-WIDER [36] shows that more than 95 % of total enterprises in Vietnam are SMEs. The distribution of enterprises in terms of size varies significantly across industries.[2] The proportion of SMEs is high in the food processing sector (93 %),

[1] Decree 56/2009/ND-CP dated 30 June 2009 stipulated supporting measures for SMEs (replacing Decree 90/2001/CP-ND).

[2] General Statistic Office, Statistical Yearbook, Hanoi, 2004.

but considerably lower in the leather and footwear sector (50 %) and textile and garment sector (73 %).

SMEs in Vietnam play a vital role in the economy. They employ more than 50 % of the labour force in the country and contribute to 31 % of the GDP.[3] In recent years, the number of non-state enterprises has increased dramatically. The most important organisational form of private enterprise in Vietnam is household firms. The next largest group are industrial cooperatives and quasi-cooperative production groups.

In spite of SMEs being the engine of growth in Vietnam, these enterprises face significant difficulties. Access to finance remains the most serious problem for SMEs in Vietnam [36]. Almost 40 % of SMEs in Vietnam are considered credit-constrained. Finding sufficient funding is difficult and many SMEs have had to turn to investment funds for both money and management assistance [6]. Additionally, unskilled labour, a lack of land for business premises and weak supporting services in the areas of technology and information are significant problems for SMEs in Vietnam [12, 36].

Recognizing such constraints, the government of Vietnam has issued various decrees to promote the development of SMEs (Decree 90/2001/CP-ND and Decree 56/2009/CP-ND) and has called for support from international donors. An agency for SME development (ASMED[4]) within the Ministry of Planning and Investment (MPI) was also established to enforce the implementation of these decrees. Organizations such as the Vietnam Chamber of Commerce and Industry (VCCI), the World Bank, the Asian Development Bank (ADB), the United Nations Industrial Development Organization (UNIDO), the European Union and many foreign governments through their embassies or their development cooperation agencies such as the German (GIZ), Danish (DANIDA), Canadian (CIDA), Japanese (JICA), Swiss (SECO), United States of America (USAID) and Australian (AusAid) have implemented a variety of programs supporting SMEs in Vietnam to help them improve working skills, working conditions and business environment. The SME support institutions in Vietnam are set out in Fig. 1.

## *1.2 Textile and Garment Sector in Vietnam*

The textile and garment industry in Vietnam has developed rapidly in recent years and has become a vital activity within the country's economy. In terms of total production, it is the second biggest industry in Vietnam (after the oil and gas industry), accounting for 31 % of total industrial products. The production

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[3] General Statistic Office, Statistical Yearbook, Hanoi, 2004.

[4] Agency for Small and Medium Enterprises Development (ASMED) is the central government agency that is responsible for coordinating policy formulation and policy implementation for the development of SMEs in Vietnam. ASMED acts as the Permanent Secretariat of the SME Development Promotion Council, chaired by the Minister of Planning and Investment.

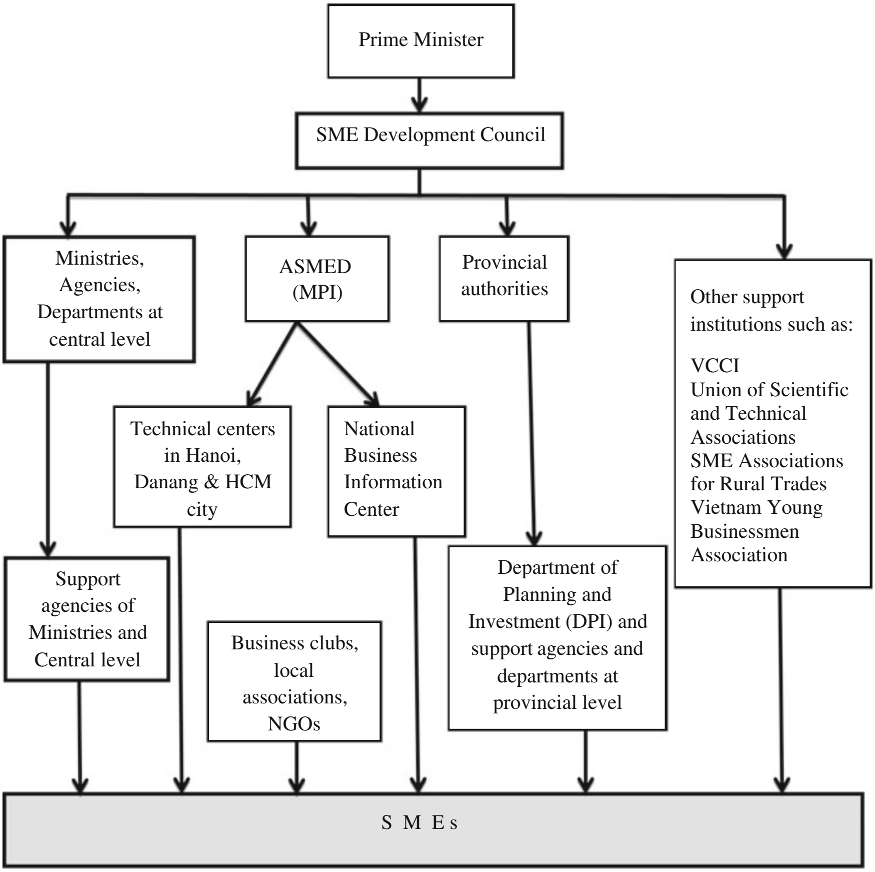


**Fig. 1** SME support institutions in Vietnam

capacity in 2005 increased fivefold compared to the production capacity in 2000 [23]. Exports in 2011 reached US$15.8 billion, an increase of nearly 38 % compared to 2010. In 2012 and 2013, despite many challenges in production and business, exports still earned a record US$17.15 billion and US$20 billion respectively [38, 39].

With a labour force of more than 2 million people working in more than 3,800 companies [35], Vietnam's textile and garment industry has become one of the strongest players in the global market. It ranks fifth worldwide in textile and apparel exports. The industry is considered a very important producer and exporter. However, it is also one of the most serious polluters. At each of the stages typically required to make a garment there are negative environmental impacts. Figure 2 describes this production process and the environmental impacts at each of the stages.

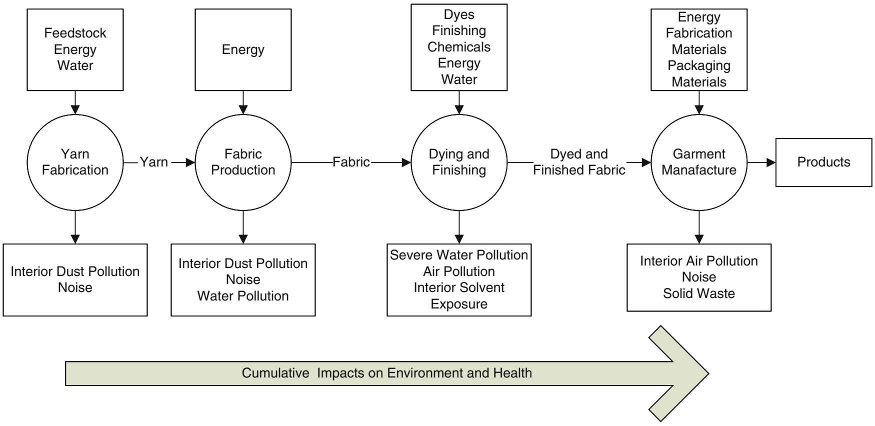


**Fig. 2** The production process and its environmental impacts

In general, there are four main steps in the textile and garment production process: yarn fabrication, fabric production, dyeing and finishing, and sewing. Small and medium sized companies normally operate one or two stages of this process. For example, some only produce yarn or fabric; some can produce fabric and also provide dyeing services. Only few large companies in Vietnam operate all four stages of the production process.

Currently, raw materials are mainly imported from overseas. About 400,000 mt of cotton are consumed annually, of which 35 % was imported from the United States, 32 % was from India and 19 % was from South Africa [35]. Some was imported from other countries such as Pakistan, Brazil, Australia, and Indonesia. Materials imported into Vietnam have to comply with the quarantine regulations in Vietnam, including requirements for environmental protection.

The main environmental problems of yarn fabrication and fabric production are dust and noise. Dust arises from fibre scraps and fabric scraps. Noise comes from the operation of the spinning or weaving machine. In addition, some small companies are still using coal and firewood and the air emission, including some hazardous chemicals such as $SO_2$ and $NO_2$, are polluting the air.

Dyeing and finishing consume a vast amount of water, energy and inorganic chemicals. If waste water is not properly treated before discharging into the environment, it has well known and serious impacts on the environment. Duong [10] reports that more than 90 % of the textile companies in Vietnam are violating environmental requirements.

### 1.3 Environmental Management in the Textile and Garment Industry

In order to control environmental pollution, the Vietnamese government has implemented many policies and measures, mainly following the traditional command-and-control system of environmental regulations, such as end-of-pipe treatment solution, fines and penalties, relocation and even forced closure of polluting enterprises. In addition, Vietnam has started introducing environmentally friendly technologies and business practices directed at achieving cleaner production.

However, current practices of environmental protection and environmental management at textile and garment companies, especially the small and medium sized ones, remain poor. Many do not meet the national standard requirements of environmental management practices. They are equipped with old manufacturing technologies which result in both inefficient use of resources and high emissions. Environmental protection technologies are a luxury to such enterprises. Some tried to install pollution control facilities but, because of lack of adequate monitoring, most of these facilities have not been put into operation for economic reasons [27]. Their only use is to show to environmental inspectors.

Although most textile and garment companies have been relocated to suburban districts or industrial zones, the problem of location remains increasingly problematic because of the fast rate of urbanization. Pham [27] observed that more and more companies are becoming parts of residential neighbourhoods. While these SMEs cannot adopt a proper environmental protection technology, the pollution caused by their production activities is almost certainly having serious impacts on the health and daily life of the people.

### 1.4 Rationale of the Study

A lot of studies have been trying to explain the reasons for the poor state of environmental management of companies by examining the monitoring and enforcement of environmental policies [2, 13] or investigating firms' compliance behaviours [4, 5, 14, 28, 32]. There is well-established international literature on SMEs and the environment [7, 15, 26, 33]. There is also information available on the impact of regulations on SMEs' environmental performance [3, 16, 19]. Much of the research in these areas discusses the difficulties experienced by SMEs when developing and implementing environmental policies and practices [7, 15, 25, 26, 29].

Based on these theoretical developments and empirical studies, many proposals have been made for the improvement of environmental quality. However, considering the facts presented above, the efficiency and effectiveness of those measures are doubtful. So, what is hindering the environmental performance of Vietnam's SMEs? Nguyen et al. [22] argue that it is not enough just to consider compliance behaviours or assess monitoring and enforcement policies. Rather, it is more crucial to investigate the environmental adaptation process and identify the conditions under which SMEs' adaptability can be enhanced. This allows observers to comprehend why the majority of SMEs have not adapted proactively to changes in environmental requirements and have not attempted to enhance their adaptive capacity. It is based on such observations that appropriate interventions should be developed.

Environmental adaptation is to do with people, their attitudes and behaviours. It has also become clear that there is a strong relationship between the stakeholders perspective and the number of practices at company level such as corporate social responsibility and sustainability, which include environmental protection and environmental management [34]. Therefore, in order to identify the conditions under which SMEs' environmental adaptability is highest, it is first necessary to understand who the key actors are and how they influence the environmental adaptation process. Here we report on an investigation of the fundamental question of *who are the key actors influencing the environmental adaptation process at textile and garment SMEs in Vietnam*.

# 2 Stakeholders Theory

## *2.1 Stakeholder Theory*

The issue relating to key actors of corporate environmentalism has been studied by many researchers [18, 30, 31] based on the stakeholder theory, which suggests that organizations are driven to environmental responsibility by pressure from stakeholders.

In the traditional view of firms, the shareholders or stockholders are the owners of the company and the company has a binding duty to put their need for profitability and capital protection first. Stakeholder Theory argues that there are other parties involved in the operation of a firm, including employees, customers, suppliers, financiers, communities, government bodies and trade associations, [11]. Although these individuals and groups have different interests with different intrinsic values [11], they all participate in an enterprise to obtain benefits and there is no priority of one set of interests and benefits over another [9].

Donaldson and Preston [9] consider three aspects of the Stakeholder Theory—descriptive accuracy, instrumental power and normative validity:

*Descriptive accuracy* the theory goes well beyond the descriptive observation that "organizations have stakeholders". It is both general and comprehensive. It is used both to describe and to explain specific corporate characteristics and behaviours.

*Instrumental power* the theory is used to identify the connections, or lack of connections, between stakeholder management and the achievement of traditional corporate objectives. For example, it is used to explain the relationship between stakeholder perspective and the company's performance in its corporate social responsibility strategy [34].

*Normative validity* the theory is used to interpret the function of the corporation, including the identification of moral or philosophical guidelines for the operation and management of corporations.

The inclusiveness of this theory makes it difficult to recognize which stakeholder play the most influential role in a corporate's environmental responsiveness [20]. It is unclear who the stakeholders of the firm are and to whom (or what) the managers should pay more attention. As a remedy to this problem, Mitchell et al. [20] proposed using *a normative theory of stakeholder identification* to explain why managers should consider certain individuals or groups as stakeholders and using *a descriptive theory of stakeholder salience* to explain the conditions under which the managers consider certain individuals or groups as stakeholders.

In the theory of stakeholder identification, Mitchell et al. [20] claim stakeholders as primary or secondary stakeholders, as owners and non-owners of the firms, as owners of the capital or owners of less tangible assets, as actors or those acted upon, as those existing in a voluntary or an involuntary relationship with the firm, as right-holders, contractors, or moral claimants, as resource providers to or dependents of the firm, as risk-takers or influencers, and as legal principals to whom agent-managers bear a fiduciary duty. In any case, a stakeholder is understood to be any group or individual who can affect or is affected by the achievement of the organization's objectives.

In Mitchell et al.'s theory of stakeholder, a salience model is proposed which justifies the argument that managers should pay specific kinds of attention to each kind of stakeholder. They propose classifying stakeholders by their possession or attributed possession of one, two or all three of the following attributes: (1) the stakeholder's power to influence the firm; (2) the legitimacy of the stakeholder's relationship with the firm; and (3) the urgency of the stakeholder's claim on the firm. Power is a relationship between social actors in which one social actor, A, can get another social actor, B, to do something which B would not otherwise have done. Legitimacy is an assumption that the actions of an entity are desirable, proper, or appropriate within some socially constructed system of norms, values and beliefs. Urgency is the degree to which the stakeholder claims call for immediate attention.

## 2.2 A Triad-Networks Model for Stakeholder Analysis

After identifying relevant stakeholders, it is important to understand the relationships between each stakeholder and the enterprise as well as the interrelationships between these stakeholders. A so-called triad-network developed by Mol [21] is adopted to explore these relationships.

The triad-network model includes three networks: (1) economic network: (2) policy network; and (3) societal network. The term "network" is used to describe different kinds of actors/stakeholders who are linked together in a political, social or economic life. Networks may be loosely structured but still capable of spreading information or engaging in collective action.

Mol's triad-networks model has the advantage of combining both the structural properties of institutions and the interactions between the actors making up a network. It has been used by a number of scholars [1, 8, 17, 24, 37] and has shown its usefulness both in the analysis of the relationships between an industry/enterprise and its social, economic and political environment and in the generation of ideas on institutional arrangement and environmental restructure of industries [24].

*Policy network* includes a group of actors or stakeholders, each of them with an interest or "stake" in a given policy sector and the capacity to help determine the success or failure of a policy. Within a policy network, the interactions and institutional arrangements between the state organizations and the industry are primarily governed by political administrative rules and resources.

*Economic network* consists of economic and market actors or stakeholders who interact and are structured by economic relations, rules and resources. Economic network studies look at (1) the vertical interactions from raw material producer up until the final consumer; (2) the horizontal relations between competitors; and (3) relationships with other economic agents.

*Societal network* consists of social groups and civil society organizations. This network could theoretically be important in the process of environmental reform [24].

## 3 Stakeholders Who Influence the Environmental Adaptation Process of Small and Medium Sized Textile and Garment Companies in Vietnam

The theoretical underpinnings of our work are the Stakeholder Theory from Freeman [11] and Mitchell et al. [20], and the triad-networks model from Mol [21]. Following this approach, the research consists of a number of steps: (1) identifying relevant stakeholders; (2) clustering stakeholders using the triad-networks model; (3) mapping and prioritising stakeholders' clusters; and (4) understanding how priority is given to stakeholders and their influence. Data include both secondary source (government reports, project reports, journal articles, internet website) and primary source (interviews and conversations with government officers, non-government officers, and companies).

Interviews were conducted with three groups: (1) officials of government agencies who have the state mandates of monitoring environmental performance at SMEs (MONRE, VEA, provincial EPA, DONREs, DPCs) and who have mandates for supporting SMEs (ASMED, VCCI,[5] VITAS,[6] DPCs); (2) experts from NGOs

[5] VCCI: Vietnam Chamber of Commerce and Industry.

[6] VITAS: Vietnam Textile and Apparel Association.

**Table 2** Stakeholders in the environmental adaptation process at textile and garment SMEs in Vietnam

| | |
|---|---|
| Company owners | Company managers |
| Managers' assistants | Shareholders |
| Employees | Translators (for foreign companies) |
| Partners | Competitors |
| Suppliers | Branch offices |
| Investors | Customers (both international and domestic) |
| Local communities | Consumers and consumer associations |
| The media | Government (both national and local level) |
| Trade union | Business association |
| Non-government organizations | Research institutes |
| Financial institutes | Auditing and certification institutes |

and related projects; and (3) CEOs or managers of textile and garment SMEs in Ho Chi Minh City, Dong Nai and Binh Duong.[7] A total of 21 interviews were conducted, of which 8 were with government officials, 3 were with NGOs and 10 were with SMEs. The number of interviews stopped when saturation was reached.

The interviews employed open-ended questions. The questions are directed to identify key actors and current actions in the environmental adaptation process by SMEs. Each session took about an hour and was audio-recorded in some cases where the interviewees felt comfortable doing so.

Step 1: Identification of relevant stakeholders

Based on the theory of stakeholder from Freeman [11] and Mitchell et al. [20], a stakeholder considered in this study is any person or any group who can be positively or negatively impacted by, or have influence on, the environmental adaptation process at textile and garment SMEs in Vietnam. The interviewees identified 22 relevant stakeholders in the environmental adaptation process at textile and garment SMEs in Vietnam (Table 2).

Step 2: Clustering stakeholders

Mol [21]'s triad-networks model was used to classify the relevant stakeholders of textiles and garment SMEs in Vietnam. Figure 3 describes this triad network model. Stakeholder analysts argue that all persons or groups with legitimate interests participate in an enterprise to obtain benefits and that there is no priority of one set of interests and benefits over another [11]. Hence, the arrows in Fig. 3 between the firm and its stakeholder network constituents run in both directions.

[7] The geographical scope for this study has been based on the following criteria: (1) the impact on the environment of the industry; (2) available data; and (3) available access to both the SMEs and data.

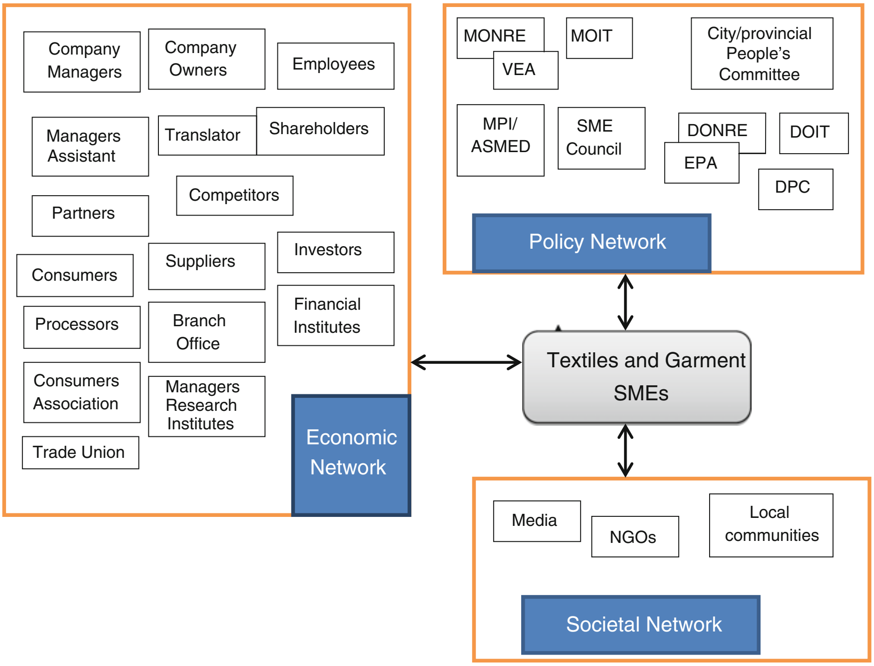


**Fig. 3** A triad-networks model of stakeholders in the textile and garment industry in Vietnam (constructed after Mol [21])

## *3.1 Policy Network*

In Vietnam, the policy network is complex and can play a governing role over other networks [8, 24]. Stakeholders for textile and garment SMEs in the policy network are the government agencies at both national and local levels.

At the national level, two main stakeholders of textile and garment SMEs are the Ministry of Industry and Trade (MOIT) and the Ministry of Natural Resources and Environment (MONRE). MOIT is the line ministry and acts as the management agency for the textile and garment sector. This ministry promulgates legal documents which guide the sector on professional issues, some of which relate to environmental matters. However, although MOIT has an agency (which is equivalent to a department) with a mandate for environmental protection and environmental management, the environmental issues regarding the production within the textile and garment sector are still predominantly in the preview of MONRE. MONRE is the highest national environmental agency. It issues the Law on Environmental Protection and takes responsibility for improving the environmental performance of industries via Environmental Impact Assessment appraisal and the promulgation of environmental decrees, standards and programs. In practice, MONRE authorises the Vietnam Environment Administration (VEA) to execute the implementation of environmental policies throughout the whole country. VEA is a subsidiary body under MONRE to advise and assist the Minister of MONRE in the field of environmental management and to provide public services in compliance with the laws.

Other important stakeholders in the policy network are the Small and Medium Enterprise Development Promotion Council (SME Council) and the Agency for Small and Medium Enterprise Development (ASMED). The SME Council and ASMED were established following the issue of Decree 90/2001-ND-CP[8] on support for the development of SMEs in Vietnam. The SME Council consists of representatives of Ministries, representatives from a selected number of provinces and representatives of business and professional associations. The Minister of the Ministry of Planning and Investment (MPI) provides the chairman of the Council, and the Prime Minister appoints members to the Council. The main mandate of the Council is to give advice to the Prime Minister on policies and mechanisms to encourage SME development. ASMED, which is under MPI, is responsible for coordinating policy formulation and policy implementation for the development of SMEs in Vietnam. In 2008, under the restructure of MPI, the name of ASMED was changed to (Agency for Enterprise Development) AED and its new mandates include SME development promotion, business registration, SOE reform and international cooperation. AED only provides coordination and facilitation and does not get involved in direct service provision, apart from regulatory information. It still acts as the Permanent Secretariat of the SME Council. It has also established three SME Technical Support Centers in the north, centre and south of Vietnam to advise SMEs on practical issues.

At local level, the relevant stakeholders in the environmental adaptation process for Vietnam's textile and garment SMEs are the city/provincial People's Committee (PC), the Department of Natural Resources and Environment (DONRE), the Department of Industry and Trade (DOIT) and district and commune PCs. The City or provincial PC is the highest government body. DOIT is responsible for the sector development and DONRE is in charge of environmental issues in their city or province. Both are under the technical supervision of MOIT and MONRE but they operate under the direct management of the city or provincial PC. Similarly, the office of Natural Resources and Environment within the district and commune PCs are under the technical supervision of DONRE, but are directly managed by their PCs. In practice, environmental issues at companies, including textile and garment SMEs, are mainly monitored and managed by the Provincial Environmental Protection Agency (EPA), which is under DONRE. EPA's main mandates include: (1) give advice to DONRE Director on environmental implementation at the province; (2) give guidance to organizations and individuals in the

[8] Decree 90/2001-ND-CP was dated 23 November 2001. It was later replaced by Decree 56/2009-ND-CP dated 30 June 2009 stipulated supporting measures for SMEs.

province to implement environmental regulations and standards; and (3) cooperate with the inspectors to monitor the environmental performance of the organizations and individuals in the province.

### 3.2 Economic Network

Stakeholders of textile and garment SMEs in the economic network are further classified into three groups:

*Vertical relationships* key actors in this group include raw materials suppliers, company owners, shareholders, company managers, employees, customers and consumers. These actors participate directly in the production process and definitely play an important role in adapting to and complying with environmental requirements.

*Horizontal relationships* the main stakeholders in this group are partners and competitors. These relationships exist because of cooperation or competition for both raw materials and markets. In order to gain a competitive advantage, a company may want to pursue certain international requirements or standards, including environmental ones. By doing so, they can improve their brand name and expand their market share. In some cases, the companies have to cooperate with each other in order to meet the requirements from the customers. Therefore, cooperation and competition do have some influence on the environmental adaptation process at the textile and garment SMEs.

*Relationships with other economic agents* economic agents such as financial institutes, tax agents, auditors, investors, research institutes and branch associations can play a role in the environmental reform of industries [24]. Currently, many customers require an auditing report for both commercial and non-commercial activities, including environmental issues. Only when the companies have good reports from the auditor, investors or research institutes can they establish good relationships with customers, especially overseas customers.

### 3.3 Societal Network

This network consists of interrelationships between textile and garment SMEs and social groups and organizations. The three main stakeholders in this group are local communities, NGOs and the media. The companies are now under pressures for environmental adaptation, not only from the government and the market but also from the local communities. Local people are actively participating in the monitoring of environmental performance of the companies. So is the media. In many cases, the violation of environmental law was discovered by local people

**Table 3** Influence of the stakeholder network on environmental adaptation

| | Power | Legitimacy | Urgency |
|---|---|---|---|
| Economic network | 4.62 | 4.33 | 4.24 |
| Policy network | 3.81 | 3.00 | 2.90 |
| Societal network | 2.14 | 1.81 | 1.57 |

and the media. NGOs have an important role in building capacity and raising awareness for companies to adapt to environmental requirements.

Step 3: Mapping and prioritising stakeholders' clusters

In this step, the three stakeholder's networks would be analysed in order to find the most important network in terms of their influence on the environmental adaptation process at textile and garment SMEs in Vietnam. Interviewees were asked to rate the level of influence of each stakeholder network using the five-point Likert scale for each of the three variables identified in the salience model developed by Mitchell et al. [20]:

- *Power* the capacity or ability to influence the company's decisions in adapting to environmental requirements (1 = no power; 5 = highest power)
- *Legitimacy* the stakeholder's demands for environmental adaptation to be considered as appropriate by the company (1 = no legitimacy; 5 = highest legitimacy)
- *Urgency* the degree to which a stakeholder's claim calls for immediate attention (1 = no urgency; 5 = highest urgency)

Table 3 shows the average scores on each of the variable that the interviewees gave in each of the stakeholder network.

Even though no stakeholder network was given the maximum score or none of them was totally ignored, a number of differences can be detected. The economic network stands out. They have the highest score in all three variables. They have greater power to impose environmental actions, have more legitimacy to do so, and their environmental demands are more urgent and therefore receive more attention from the companies.

The policy network occupies the second place in all variables. The government has some influence over the companies through its legislative system. However, the companies do not consider this a high priority. They normally try to avoid or defer the implementation of the government's requests. This has been happening for several reasons. First, the environmental requirements from the governments are too difficult for the companies, especially the small ones. They don't have enough human and financial resources to respond to these requirements. It was assumed that the government would have played a more important role if they could provide both technical and financial support to the companies. Second, there exist several forms of corruption in the government's system. In many cases, the violation of environmental law happened because of this corruption. On the other hand, the local authorities have to suffer from political pressure. For example, they cannot punish a company if someone from a higher level tells them not to. They also have to suffer from the social economic pressure of the province. In order to gain some economic target, they sometimes have to accept the current state of the environment and allow the companies to do their business.

The societal network, in spite of having some power, is afforded the least priority. Among the three main stakeholders in this network, the media and local communities have greater influence on the companies' decisions than the NGOs and associations. However, the legitimacy and urgency of all three stakeholders are still low. As for the companies, NGOs and associations only play the role of information sharing but they are quite weak. With limited capacity and resources, they cannot gain influence over this group.

Step 4: Identifying the most important stakeholders

The analysis in Step 3 shows that the economic network consists of the most influential stakeholders in the environmental adaptation process for textile and garment SMEs in Vietnam. In this step, each stakeholder in the network would be considered in terms of its influence on decision-making and the implementation of the environmental adaptation strategy and plans at these SMEs. This was done based on the assumption that: (1) not all stakeholders in the priority network have the same level of influence; and (2) a stakeholder may have some influence on the decision-making but does not have influence on the implementation, and vice versa.

The influence of each stakeholder was scored based on the five-point Likert scale for each dimension (1 = no influence and 5 = maximum influence). Table 4 shows the average scores of each of them.

When firms were asked to specify the most important actors having influence on their environmental adaptation attitudes and behaviours, customer (90.5 %) and manager (57.14 %) were the two most cited.

Most interviewees said they would implement environmental practices if there were requirements for purchasing orders from the customers. Only a few small companies said they would not follow any requirements from the customers if they were too strict. In these cases they decide to lose the order because they cannot afford the investment for environmental compliance. In addition, interviewees mentioned that only big and overseas customers have requests on environmental protection and environmental management. Small or domestic customers are only concerned about product design and price. However, currently 80–90 % of textile and garment products are for export. Therefore, customers are still the most important actors influencing the company's environmental behaviours.

According to the interviewees, managers play an important role in making decisions on whether to implement the adaptation activities or not. However, their first priority is to keep their business running and they have to spend their capital on their core business. Investment on environmental issues is not an easy decision for many of them. Their awareness of the importance of implementing adaptation strategies is, therefore, very important. If they understand that complying with environmental requirements is a part of their brand name or the company's

**Table 4** Influence of the stakeholders in an economic network over decisions and implementation

| Stakeholder | Influence over decisions | Influence over implementation |
|---|---|---|
| Company owners | 3.37 | 3.12 |
| Shareholders | 2.50 | 2.50 |
| Company managers | 4.00 | 4.50 |
| Managers' assistants | 3.37 | 2.87 |
| Employee (workers) | 2.62 | 3.65 |
| Interpreters/translators | 2.37 | 2.37 |
| Partners | 2.37 | 2.12 |
| Competitors | 2.25 | 2.37 |
| Suppliers | 2.12 | 2.12 |
| Customers | 4.75 | 4.37 |
| Consumers | 2.00 | 2.00 |
| Investors | 2.12 | 2.75 |
| Financiers | 2.37 | 3.37 |
| Auditors | 2.37 | 3.00 |
| Branch offices | 1.62 | 2.00 |
| Research institutes | 1.25 | 1.25 |
| Trade unions | 1.62 | 1.62 |

reputation and such compliance influences the survival of the company in the future, then attitudes and behaviour are more positive.

Customers and managers are, indeed, the two most important stakeholders in the environmental adaptation process in textile and garment companies. However, customers have more influence over decisions than company managers. In contrast, company managers have more influence over the implementation than customers. When making decision on whether or not to respond to environmental requirements, the company always considers requests from the customers first. They give this priority if it is a request from the customer as a condition for a purchasing order. However, during the implementation stage, the managers plays the most important role. They are persons in charge of the success or failure of the implementation.

The second most important stakeholders are company owners and managers' assistants. In most cases, as the companies are small and medium sized, the company owners are also company managers. In cases where company owners do not manage their company, they still have influence on the decisions and some influence on the implementation. They are the persons who approve requests from company managers. Managers' assistants also play some role in decisions, especially in the cases of state-owned companies. In these cases, managers do not have as much insight on the issues as their assistants and they normally follow the suggestions or proposals from their assistants. However, once the adaptation plans are implemented, the role of the manager's assistant is no longer important.

At the implementation stage, apart from the leading role of the managers, the employees, financiers and auditors are the most important. Financiers provide financial support, without which the adaptation plans cannot be implemented. Employees are actually implementers. If they do not strictly follow all rules and regulations, then the adaptation strategies could not be successful. Auditors provide monitoring and evaluation services which can ensure that the adaptation plans are properly implemented. Many customers trust auditors' reports in making their purchasing decisions.

The role of the interpreter and translator is also very important because he/she is the person who translates all the government's legislative requirements (for foreign companies) and all the foreign customers' requests (for Vietnamese companies). If the translation of requests is wrong, the responses could not be correct.

Other stakeholders such as partners, competitors and suppliers share similar levels of influence over both decision-making and implementation. Their influence exists but is not critical.

The least influential groups includes consumers, branch officers, research institutes and trade unions. Most of the garment companies in Vietnam do outwork (processing) for overseas customers. The consumer's attitudes are not of great concern to them. Their only concern is with the customers. In addition, as they are small and medium sized companies, many of them do not establish any trade union and if a trade union exists within the company, its voice is unimportant. The roles of branch offices and research institutes are very weak. They have little influence over decision-making or implementation of environmental adaptations strategies.

## 4 Conclusion

Environmental adaptation in the textile and garment SMEs in Vietnam involves more than just compliance with government regulations. The economic network is the most important network compared to the policy and societal ones. The economic network include key actors who participate directly in the production process such as raw materials suppliers, company owners, company managers, partners, competitors, employees, customers and consumers and those who participate indirectly in the production process such as financial institutes, investors and auditors.

The significance of the economic network is driven by the importance of customers as key actors influencing environmental decisions, and company managers as primary actors influencing the implementation of these decisions. When deciding whether to respond to environmental requirements or not, the company always considers requests from the customers first. Companies give priority to a request from a customer as a condition for a purchasing order. However, during the implementation stage, the managers play the most important role and strongly influence the success or failure of the implementation.

The important implication from these findings is that both national and local policies on environmental protection and environmental management in SMEs should be formulated based on the interaction of commercial reality and the desire of the government to implement international standards. This is particularly important as government regulations are currently driven by NGOs and external aid. The challenge to the government is how to harmonise competing realities in an emerging economy operating in a globalised and competitive world.

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# The SURF Framework Applied to the Textile Industry

**Marilyn Waite**

**Abstract** One of the major challenges of the twenty-first century textile industry is transformation for sustainability. There are various metrics by which textile players can evaluate sustainability performance, but practitioners often say that at least one key component of the sustainability paradigm is missing or inadequate. The SURF Framework aims to fill the gap between tools, which address specific aspects of the sustainability model and the very broad definitions that surround sustainable development. SURF (supply chain, user, relations, and future) addresses the quadruple bottom line of sustainability: social, environmental, economic, and intergenerational equity results. This chapter provides an overview of the SURF Framework, providing specific case studies in the realm of cotton textiles. Section 1 provides an overview of the SURF Framework; Sect. 2 summarizes the various textile-specific initiatives, standards, methods, and tools that relate to each component of SURF; Sect. 3 provides an example of the SURF Framework applied to cotton textiles in particular; Sects. 4 and 5 describe case studies of how the SURF Framework applies to two different companies selling cotton shoes and jeans, respectively; Sect. 6 is a conclusion for the chapter.

**Keywords** SURF framework · Cotton · Supply chain · Future generations · Users · Stakeholders · Sustainable textiles · Sustainability · Sustainable development

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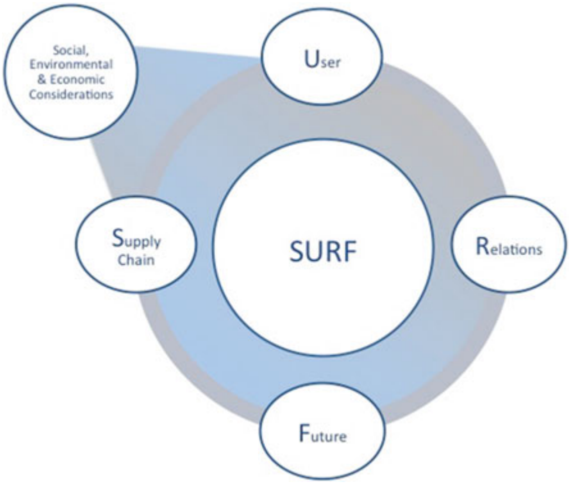


**Fig. 1** Representation of the SURF framework [24]. Each component, supply chain, user, relations, and future, is equally weighted. Social, environmental, and economic considerations underlie each SURF component for products, services, results, processes, organizations, and the entire society

## 1 Overview of the SURF Framework

The SURF Framework represents: (1) supply chain considerations which address sustainability criteria; (2) user considerations which address sustainability criteria; (3) relations with employees, colleagues, the surrounding community, and society at large; and (4) concern for future generations [24]. Social, environmental, and economic concerns underlie each element of SURF, with future planning also receiving adequate attention (Fig. 1).

**S** stands for all of the components making up the supply chain of a company's product or service. The textile industry is so complex and globalized that many "B to C" companies do not fully account for their entire supply chain and the many encompassing "B to B" transactions. It therefore becomes especially important to address the entire supply chain in the textile sector. How do the products in the supply chain measure when it comes to greenhouse gas emissions, water use, energy use, land use, transportation, waste, pollutants, labor, working conditions, and long-term profit? The demand for more sustainable products at every level of the value chain forces the textile system to move toward sustainability.

**U** stands for user. What does the user do with the product or service? Do they throw the product away immediately to pile up in a landfill? Can it be easily re-used or recycled? Is it biodegradable and have the proper systems been put into place to render that biodegradability useful? Even with the best intentions, sustainability efforts can fall short if the user does not use the product or service in a sustainable manner (or if sustainability systems are unavailable to the user) [24]. Location is important. Few and far between are worldwide textile recycling systems as developed as those for paper and plastic. Many textile products which could be biodegraded in a dedicated area are not given the chance because of the lack of infrastructure. In the case of fast fashion, textile end-users are encouraged to use items for a short time and develop a "throw-away" attitude.

**R** stands for relations—both external and internal. This is especially critical for the textile industry since it has a poor track record for social responsibility and stakeholder relations. Is the work environment healthy and safe for workers? Do employees feel that there is a positive work environment? Are company operations and financing transparent? Do stakeholders participate in decisions in which they have an interest and/or which have an impact on them? It is also seen as a risk management tool in the locations where organizations operate, creating and maintaining positive relationships contribute to the sustainability of products and services [24]. The "R" component of the SURF Framework involves stakeholder engagement and community involvement.

**F** stands for future. The notion that we are responsible to future generations is one that keeps us questioning the impact of our operations. Do we have a 10-year plan? Or a 50-year plan? The "triple-bottom-line" (TBL) is often used to convert sustainable development into practical decisions. TBL entails a three-pronged approach of meeting social, environmental, and economic needs. However, an equally important and essential aspect of sustainable development is the idea of intergenerational equity, or the quadruple bottom line (QBL). A four-pronged approach or a four-legged stool is therefore more likely to bring to the forefront the temporal considerations sustainable development engenders [24].

## 2 Specific Textile Initiatives, Standards, Methods, and Tools

There are many different certification schemes and labels addressing sustainability in the textile industry. According to Ecolabel Index, an organization tracking 444 ecolabels in 197 countries and 25 industry sectors, there are 24 eco-labels worldwide covering textiles, clothes, apparel, and garments [13]. The global organic textile standard (GOTS) harmonizes the following country-based organic textile certification schemes [5]:

- North American Fiber Standard—Organic Trade Association (USA)
- Guidelines 'Naturtextil IVN Zertifiziert'—International Association Natural Textile Industry (Germany)
- Standards for Processing and Manufacture of Organic Textiles—Soil Association (UK)
- Certification and Standards for Organic Cotton Products—Japan Organic Cotton Association (Japan)
- EKO Sustainable Textile Standard—Control Union Certifications (formerly Skal International, Netherlands)

- Standards for Organic Textiles—Ecocert (France)
- Organic Textile Standard—ICEA (Italy)
- Standards for Organic Textiles—ETKO (Turkey)
- Organic Fiber Standards—Oregon Tilth (USA)
- Standards for Processing of Organic Textile Products—OIA (Argentina)

## *2.1 SURF and Textile Certifications/Eco-Labels*

Most of the textile ecolabels are focused on organic textiles. Nevertheless, "organic" does not cover all aspects of sustainability. The organic content standard (OCS) verifies that a final product contains the accurate amount of a given organically grown material; it does not address the use of chemicals or any social or environmental aspects of production beyond the integrity of the organic material [17]. The GOTS does go beyond the strict definition of organic to include wider environmental, human toxicity, and minimum social criteria. For that reason, it covers the supply chain and relations components of the SURF Framework.

The Higg Index 2.0 is an indicator-based assessment tool for apparel and footwear products. The Index asks practice-based, qualitative questions to gauge environmental sustainability performance and drive behavior for improvement [15]. As does the GOTS, the Higg Index primarily addresses the supply chain and stakeholder relations' components of the SURF Framework.

There are at least two standards addressing the "user" component of the SURF Framework since they deal with the recycled content of fibers. Recycled content implies that consumers have the logistical infrastructure available to return their textile products for recycling at the end of their use. The recycled claim standard (RCS) by the textile exchange (TE) verifies the presence and amount of recycled material in a final product through input and chain-of-custody verification from a third party. The RCS uses the ISO 14021 definition[1] of recycled content [18]. The TE global recycle standard (GRS) applies to the full supply chain and addresses traceability, environmental principles, social requirements, and labeling for products with recycled content [16].

The Cotton Made in Africa label is a social sustainability initiative addressing the relations component of the SURF Framework; those who wish to use the label pay a license fee to the Foundation and, in return, African smallholder farmers

[1] ISO 14021 defines recycled content as the proportion, by mass, of recycled material in a product or packaging. Only pre-consumer and post-consumer materials shall be considered as recycled content, consistent with the following usage of the terms: (1) pre-consumer material is material diverted from the waste stream during a manufacturing process; (2) post-consumer material is material generated by households or by commercial, industrial and institutional facilities in their role as end-users of the product, which can no longer be used for its intended purpose [6].

learn more efficient growing methods and benefit from social projects such as school improvement [1].

Sustainable textile production (STeP) is part of the OEKO-TEX® certification system for certifying achievements in sustainable production; requirements include management of chemicals, environmental performance, environmental management, social responsibility, quality management, health and safety [10]. STeP addresses some of the supply chain and relations components of the SURF Framework.

Table 1 positions these various textile-specific standards, certifications, and tools in the SURF Framework. What is visibly missing is a future-orientation, the very thing separating sustainability from pure social, environmental, and economic frameworks. The future is implicit when labor and environmental standards are enforced throughout the supply chain. However, innovative products and business models can evolve when explicitly addressing the question of intergenerational equity. What is being done to ensure that future generations working in the textile sector maintain, and improve upon, sustainability criteria? How are future generations considered in the strategic planning of the textile company? It becomes apparent that the current body of sustainability-oriented textile standards is not directly asking intergenerational questions. One solution proposed by Rapanui Clothing is an "A to G" rating for textiles, similar to what is used for the energy efficiency of white goods in many markets worldwide [12]. The label would resemble the following [12]:

- A: organic ethical sustainable
- B: ethical with some work to sustainable
- C: ethical
- D: not bad, not good either
- E: needs improving
- F: some organic, ethical, or sustainable
- G: not organic, ethical, or sustainable

Rapanui has presented the rating method and calculation to the European Union (EU). The Carbon Trust has completed a base case for a T-shirt using the criteria. The proposal includes how the calculation would include multiple variables in three broad categories: people, planet, and product, benchmarking existing standards for each category. The score is converted to an overall percentage; a textile product with an overall score of 90–100 % would achieve an "A" rating (Fig. 2). The EU's response was that there (already) exists a European Ecolabel encompassing textiles [12]. However, the general EU Ecolabel provides no information on granularity and thus can mislead the consumer regarding a product's sustainability attributes.

**Table 1** SURF framework and existing sustainable textile standards (non-exhaustive list of textile-specific standards)

| Supply chain | User | Relations | Future |
|---|---|---|---|
| Global organic textile standard (GOTS) | Recycled claim standard (RCS) | Global organic textile standard (GOTS) | (Nothing explicitly future-oriented) |
| Global recycle standard (GRS) | Global recycle standard (GRS) | Global recycle standard (GRS) | |
| Organic content standard (OCS) | | Cotton made in Africa | |
| Sustainable textile production (STeP) (OEKO-TEX® certification) | | Sustainable textile production (STeP) (OEKO-TEX® certification) | |
| Higg index 2.0 | | Higg index 2.0 | |

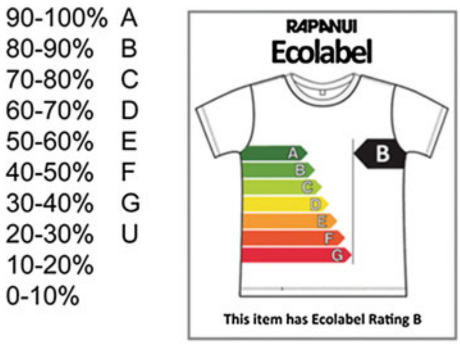


**Fig. 2** Rapanui Ecolabel proposal for textiles [11]

# 3 Example of SURF Framework in Cotton Textiles

This section presents the SURF Framework using a cotton textile end product as an example.

## *3.1 S: Supply Chain in Cotton Textiles*

There are more than 20 million cotton producers in 77 countries worldwide [4]. The large number of producers alone creates a challenge for ensuring that sustainability criteria are met throughout the supply chain. The cotton textile manufacturing process can be summarized as follows: picking bolls, ginning where the cotton lint fibers are separated from the seeds, cleaning, carding, and spinning the fibers into yarn, weaving the yarn into cloth, and finally assembling a final product with the cloth. Cotton textile players should require information based on sustainability criteria, for all suppliers involved: (1) raw material sourcing, (2) manufacturers of the fiber, (3) manufacturers of the yarn (including spinning), (4) manufacturers of the cloth (including weaving and knitting), and (5) textile finishers (including dyeing), designers and manufacturers of the end product (Fig. 3). By doing so, textile companies can benefit from better risk management, recognition by both shareholders and different stakeholders, improved image, and long-term viability [24]. Certification schemes can help in this matter, but in the absence of existing certification or in the presence of prohibitory costs for obtaining certification, the receiver of the supply has a responsibility to ask for sustainability information.

1. Sample Questions for Cotton Boll

   - Is the cotton sustainably harvested (no over-extraction, monoculture, etc.)?
   - Is the cotton grown organically?
   - What is the impact on biodiversity by growing the cotton?
   - Is the cotton certified sustainable by a third-party?

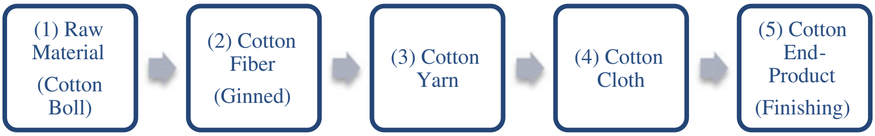


**Fig. 3** Cotton textile value chain

- How much energy is used in obtaining the cotton (including transportation)?
- How much pollutant is used and generated in growing and obtaining the raw cotton (including transportation)?
- How much water is used in growing and obtaining the cotton? Is irrigation used or is the cotton rain-fed?
- How is waste dealt with in the process to obtain the cotton?
- Are sound social and ethical business practices employed (including fair wages and a safe working environment)?
- How is long-term profitability ensured?

2. Sample Questions for Cotton Fiber

- Is the most environmentally sound, healthy, and safe manufacturing process being used to convert raw cotton into clean fiber?
- Is the cotton fiber certified sustainable by a third-party?
- How much energy is used in manufacturing the cotton fiber (cotton gin, transportation, etc.)?
- How much pollutant is generated in separating the cotton fiber (including transportation)?
- How much water is used in manufacturing the cotton fiber (cleaning)? Is water recycled?
- How is waste dealt with in the cotton fiber separation process? Is a closed-loop cycle employed (are cotton seeds and small lint fibers thrown away)?
- Are sound social and ethical business practices employed (including fair wages and a safe working environment)?
- How is long-term profitability ensured?

3. Sample Questions for Cotton Yarn

- Is the most environmentally sound, healthy, and safe manufacturing process being used to convert fiber into yarn?
- Is the cotton yarn certified sustainable by a third-party?
- How much energy is used in manufacturing the cotton yarn (spinning equipment, gassing, transportation, etc.)?
- How much pollutant is generated in manufacturing the cotton yarn (including transportation)?
- How much water is used in manufacturing the cotton yarn?
- How is waste dealt with in the cotton manufacturing process? Is a closed-loop cycle employed (are fiber pieces thrown away)?

- Are sound social and ethical business practices employed (including fair wages and a safe working environment)?
- How is long-term profitability ensured?

4. Sample Questions for Cotton Cloth/Canvas

- Has the most environmentally sound, healthy, and safe manufacturing process been used to convert yarn into cloth?
- Is the cotton cloth certified sustainable by a third-party?
- How much energy is used in manufacturing the cotton cloth (weaving and knitting equipment, transportation, etc.)?
- How much pollutant is generated in manufacturing the cotton cloth (including transportation)?
- How much water is used in manufacturing the cotton cloth?
- How is waste dealt with in the cloth manufacturing process? Is a closed-loop cycle employed (are cut pieces thrown away)?
- Are sound social and ethical business practices employed (including fair wages and a safe working environment)?
- How is long-term profitability ensured?

5. Sample Questions for Cotton Finishing and End-Product Manufacturing

- Has the most environmentally sound, healthy, and safe manufacturing process been used to convert cloth into an end product?
- Is the end product certified sustainable by a third-party?
- How much energy is used in manufacturing the end product (equipment, transportation, etc.)?
- How much pollutant is generated in manufacturing the end product (including from scouring, bleaching, mercerizing, dyeing, transportation, etc.)?
- How much water is used in manufacturing the end product?
- How is waste dealt with in the end product manufacturing process? Is a closed-loop cycle employed (are cut pieces thrown away)?
- Are sound social and ethical business practices employed (including fair wages and a safe working environment)?
- How is long-term profitability ensured?

## *3.2 U: User in Cotton Textiles*

In the case of a cotton end product, one should consider the user's ability to use the product for a long duration, to use it with little water, energy, chemicals and other pollutants, and to either upcycle the end product or biodegrade it (Fig. 4). One hurdle to a sustainable textile industry is the lack of appropriate dedicated textile-biodegrading infrastructure [24]. For example, a cotton pillowcase which may theoretically be biodegradable has a difficult time doing so if it is thrown in with a mixture of materials in a general landfill.

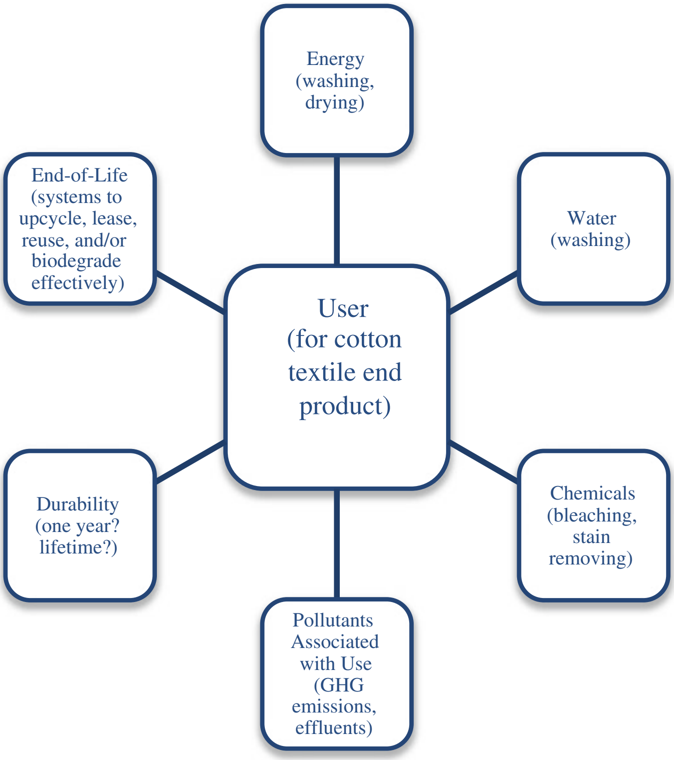


**Fig. 4** User considerations for a cotton end product. Modified from Waite [24]

### 3.3 R: Relations in Cotton Textiles

Figure 5 shows the various relationships to be created and maintained with a cotton end product in mind. The stakeholders in the cotton textile sector include workers at each stage of the supply chain, government (including regulatory officials), civil society, communities surrounding operations, third party certifiers, and internal and external clients.

### 3.4 F: Future in Cotton Textiles

It is long-term thinking setting sustainable development apart from previous social, economic, and environmental considerations. Even if the social, economic, and ecological implications of a product, service, or decision are taken into account, they can still fail to meet sustainable development goals if only the *short-term* social, economic, and ecological implications are considered [24]. For cotton

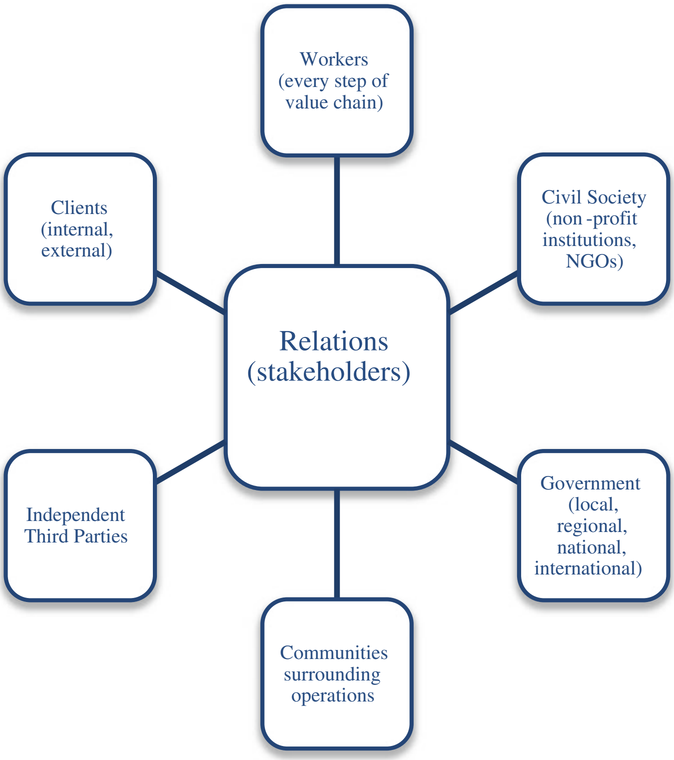


**Fig. 5** The "R" in the SURF framework [24]

textiles in particular, the impact of cotton growing and manufacturing must be assessed for future generations. Is there enough land to grow cotton for future generations? Are sustainable cotton-growing practices being passed on from generation to generation? How does the age pyramid break down for each step of the cotton supply chain?

## 4 Case Study 1: SURF Framework Applied to Veja Cotton Shoes

Veja is a design-oriented footwear company driven by sustainability principles. From the outset, two entrepreneurs planned to do business differently—and differently meant ensuring social, environmental, and economic viability at each step in the supply chain. Veja's portfolio includes shoes and accessories made from organic cotton, rubber, and vegetable-tanned leather. Veja purchases cotton from over 300 small family-run farms whose primary livelihood stems from cotton production. The organic cotton is grown in the Northeast Region of Brazil, in collaboration with cooperatives using agro-ecological principles (including rotation farming, contour planting, no pesticides, no fertilizers, and no genetic modification). The shoe-making factories are located in South Brazil near Porto Alegre. Veja produces about 100,000 pairs of tennis shoes annually and is experiencing organic growth. With a policy of no marketing and no advertising, Veja follows the guiding principle of going beyond words, or "doing rather than talking" [7].

So how does Veja's business model and operations fit within the SURF Framework?

The *supply chain* for organic cotton is both third-party organic (IBD certified per EU regulation Nr. 2092/91) and fair trade certified (FLO-cert for FAIRTRADE mark) [20–23]. This illustrates that the cotton is grown without pesticides and fertilizers, protecting the health of the farmers and the environment. Fair trade ensures that the producers are receiving a non-exploitative, livable wage. The supply chain is also kept simple, and local sustainability accountability is administered through Veja's partnership with five cooperatives. One such cooperative is ADEC, a Brazilian non-governmental organization allowing the group of farmers to use the same warehouse in order to optimize resources. Veja and ADEC mutually agree on a price per weight for certified organic cotton (2.45€ per kilogram in 2013) and for cotton currently undergoing organic transformation (2.04€ per kilogram in 2013). An additional premium of 0.5€ per kilogram is paid to cotton producers; a fair trade certification premium is paid to ADEC at the end of the cotton harvesting season [19–23]. The cotton lint is sent to independent factories where it is turned into yarn and woven into cloth. These factories are monitored and certified for adhering to sustainability practices.

All shoes are shipped by boat from Porto Alegre in Brazil to Le Havre in France. The packaging is made of recycled and recyclable cardboard. Veja is able to ensure the financial viability of its final product, priced competitively with footwear brands paying up to four times less on manufacturing, by (1) not paying for advertising (zero advertising) and (2) only producing orders placed 6 months in advance (zero stock).

The *user* of Veja's organic cotton shoes is located mainly in Europe, with growing customers in North America and Asia. One area for sustainability improvement would thus involve local Brazilian consumption of the end products, limiting transportation costs and the associated pollution. Serving the local population "Made in Brazil" may also add cultural and social importance to products emanating from an emerging economy. Veja does not produce a biodegradable or compostable shoe; however, they are actively searching for ways to recycle the different parts of their footwear line. Veja produces resistant high-quality sneakers, but the user may be short of options after the useful life of the footwear. While there are many things Veja can improve to create a cradle-to-cradle system, governments and local authorities can also help by offering textile collection and recycling facilities (as they may for plastic bottles). It is thus at the user stage where Veja's biggest room for sustainability improvement lies.

The *relations* between Veja and its stakeholders are based on transparency and fairness. Veja's operations in the Northeast of Brazil in particular help to address the steep wealth inequalities and provide stable employment for cotton producers. Long-term contracts are signed for 3 years; this means producers can be guaranteed a price for at least that length of time, underpinning financial stability and confidence for small farmers.

Veja operations are audited as a part of the Fairtrade certification process. The International Labor Organization standards are a minimum; Veja goes beyond these social standards to ensure that workers are free to assemble and stand up for their rights, live in proximity to their work, maintain a wage enabling a good standard of living and purchasing power parity, and enjoy social benefits. Factory workers in Brazil are entitled to 4 weeks of paid vacation and do not work on official holidays; overtime is paid, and the factory provides pre-arranged bus services for its employees [19–23].

Veja are partners with a French non-profit organization called Atelier Sans Frontières (ASF), whose mission is to help socially excluded people find sustainable employment [19–23]. When Veja products arrive in France at the Le Havre port, they are shipped by barge to ASF's location in the Paris region. ASF employees are in charge of the logistics. The workers are empowered through their efforts and are responsible for preparing, packing, and dispatching the eco-goods to stores in-country and online.

Veja has considered *future generations* in its strategic outlook by ensuring the future generation's ability to consume (by sustainably harvesting cotton, minimizing waste, and improving the foundation of a healthy economy by paying fair wages). Veja has a rather young workforce, with the average age roughly around 30 years. Veja is working on incorporating age diversity more and more in its operations. Veja also helps to guarantee a sustainable source of energy for future generations by using ENERCOOP, a renewable electricity cooperative. The company also helps to ensure a future supply of raw materials for shoes through their eco-sourcing.

Veja has committed to transparency and continuous improvement. They openly indicate unsustainable areas of their current operations (examples: shoe laces are not made with organic cotton; moss used to maintain the shoe ankle is a petrol-based synthetic material; North American and Asian orders are delivered by carbon-intensive airplane transportation; synthetic rubber is used for the insole). There are various technical and scale obstacles currently impeding progress in rendering a 100 % sustainable product. The pigments used for dyeing the cotton are not made from natural sources, though Veja uses conventional dyes that conform to eco-labeling criteria set by the European Union. To help remedy this setback, Veja is investing in research and development for non-polluting and vegetable-based color pigments [19–23]. The organic supply chain, just as any other, faces vulnerabilities; for example, in 2006, one cotton production area faced a caterpillar attack and was subsequently sprayed with pesticides. In 2009, ADEC producers lost half their harvest because of heavy rains [19–23]. Despite these challenges, Veja continues to strive for sustainability excellence and is far along the path to sustainable development through its quadruple-bottom-line business.

Veja seeks to be known for attractive, desirable shoes and accessories, and its management and employees understand that ecological and social impacts are an important element in attractiveness.

## 5 Case Study 2: SURF Framework Applied to Mud Jeans

Mud Jeans International B.V., is an apparel company running its own fashion label, Mud Jeans®, as well as supplies to other labels. Mud Jeans offers an innovative textile business model epitomizing sustainability principles. Their offering? Organic and fair-trade jeans, fleeces, and other apparel—for lease. Instead of the traditional and often wasteful flow of "denim jean purchase" and "denim jean throw-away," customers can rent a pair of jeans for a low monthly fee. Leasing increases access to high-quality sustainable jeans to those of a modest income and also provides the eco-conscious with an alternative to fast fashion. During the lease, customers benefit from a free repair service. After 12 months of leasing, they can decide to trade in their jeans for a new pair, keep their jeans at a discount lease, or return their jeans to the Mud Jeans® factory. Customers can return products during the first 14 days after purchase; at the end of the usable life of the jeans, customers ship the jeans and are reimbursed for the shipping cost. Figure 6 illustrates the jeans-leasing concept from Mud Jeans®.

Mud Jeans ensures the sustainability of each step of their *supply chain* through numerous certifications, including the FAIRTRADE mark, GOTS, business social compliance initiative (BSCI), MVO Nederland (Dutch national CSR knowledge center and network organization), and SA8000 Standard by Social Accountability International [8]. The materials used for apparel are organic cotton, organic Tencel®, recycled cotton, and recycled PET. The tags are all from recycled "waste cotton," and the tag printing is made with ecological, water-based ink. Mud Jeans is working with Wageningen University to research natural indigo dye.

The carbon emissions associated with the production and transportation of goods are offset by Soil and More. The $CO_2$ Neutral label by Soil and More indicates that the calculated emissions associated with a product or service have been neutralized through high quality carbon credits [14]. The organic fabric originates from factories in Turkey and the jeans are made in Italy. Mud Jeans does not contract directly from cotton producers, but relies on certification from the fabric manufacturers. The returned jeans are sent to Italy for recycling. Since Mud Jeans is based in the Netherlands, its European-centered supply chain cycle helps to reduce greenhouse gas emissions.

For the *user* aspect of the SURF Framework, Mud Jeans is completely aligned with the functional and circular economy. As one of the founding members of the Dutch Circular Economy Foundation, Mud Jeans® abides by the principles of the circular economy whereby a nonlinear functional service model dominates. The

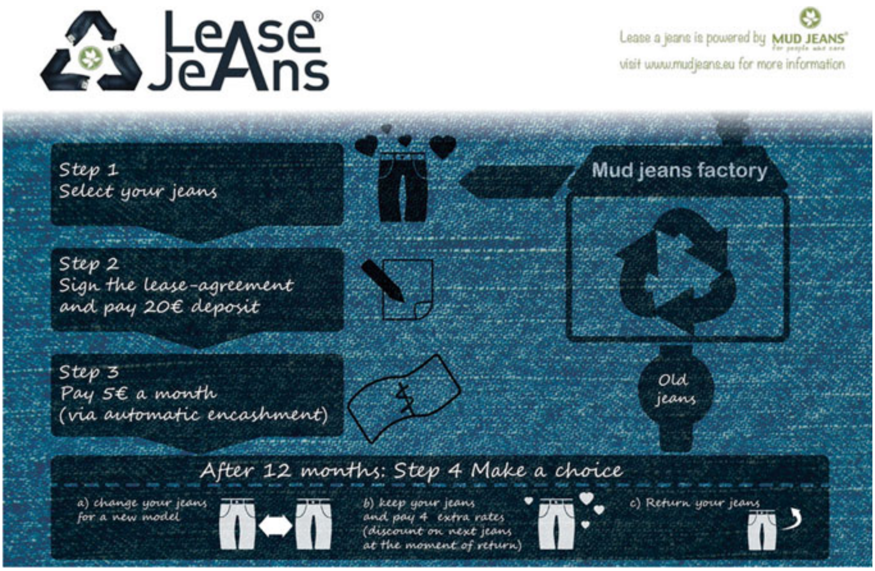


**Fig. 6** Mud Jeans® leasing [9]

user is given ample options for dealing with the jeans at the end of their useful life for the customer—keeping it longer, trading it in for a new one, and returning it to be recycled by Mud Jeans®. The option to return the product to the manufacturer is rare in today's textile industry. There are certain materials, such as buttons and zippers, which are not yet recyclable. Mud Jeans is currently exploring options for up-cycling these materials into products such as jewelry.

With respect to stakeholder *relations*, Mud Jeans has partnered with BSCI to ensure sustainable labor conditions throughout the Mud Jeans® production chain. Launched in 2003, BSCI is a Foreign Trade Association initiative to support companies in improving working conditions in the global supply chain.[2] By engaging BSCI, Mud Jeans is actively seeking to build and maintain positive relations with its direct and indirect workers and their surrounding communities.

*Future* generations are considered by Mud Jeans through its ecologic and social orientation. By selling organic and recycled products, cutting carbon dioxide emissions, and paying employees a fair wage, Mud Jeans is helping to ensure a brighter future for the next generation. The future supply of cotton fibers is promoted by both organic production, and even more by recycling cotton fibers from denim jeans. Although it is not yet possible to have 100 % recycled cotton jeans

[2] The BSCI Code of Conduct: freedom of association and the right to collective bargaining, no discrimination, prohibition of child labor, wages that are of the legal minimum and/or industry standard, working hours consistent with national laws and not to exceed 48 h regular time +12 h overtime, no forced labor or disciplinary measures, healthy and safe workplace, respect for the environment, social accountability policy, anti-bribery policy, and anti-corruption policy (BSCI [3].

**Table 2** SURF framework: Veja cotton shoes and mud jeans® cotton jeans

| | Plus or minus | VEJA | Plus or minus | MUD JEANS |
|---|---|---|---|---|
| Supply chain | – | Increased air transportation with geographical growth in customer base | – | Little visibility of pre-fabric supply chain (rely on certifications) |
| | – | Shoe components not organic or natural (laces, ankle, insole, dyes) | – | Jean components not recyclable (buttons, zippers) |
| | + | Certifications (organic and fair trade) | + | Certifications (organic, fair trade, social accountability) |
| | + | Cooperation with local non-governmental organization | + | Jean components (tags) are made from sustainable materials |
| | | | + | Carbon offsets |
| User | – | Lack of recycling for shoes | + | User has choice of returning product to manufacturer for recycling |
| | – | Shoes not biodegradable | + | User can keep jeans longer |
| | + | Resistant shoes | + | User can trade in old jeans for new ones |
| Relations | + | Long term contracts with suppliers with fair price | + | Partnership with sustainable labor non-profit |
| | + | Cooperation with local non-profit | | |
| | + | Employee benefits | | |
| Future | – | Age diversity | – | Leasing scheme not available for pre-adult generations |
| | + | Use of renewable energy through ENERCOOP | | |
| | + | Products available for younger generations | + | Age diversity |

because of the short fibers emanating from the recycling process, Mud Jeans® currently has a 30/70 split between recycled cotton and virgin organic cotton. Their future plan is to produce a 50/50 split between recycled and virgin organic cotton.

Although Mud Jeans staff includes multiple generations, Mud Jeans faces challenges when it comes to providing its leasing scheme to younger generations. A Dutch television show called RamBam helped to bring awareness of sustainable fashion to the younger generations of the Netherlands. Textile industry disasters, such as the factory collapse and reported sweatshop conditions in Rana Plaza in Bangladesh, have also helped to awaken the public. However, the adolescent age group "*is very fond of fast fashion, has little money to spend, and expects less expensive products*" a Mud Jeans representative explained [2]. The margins for selling jeans to a pre-adult age group are smaller than adult margins, since the customer expects a much lower price; the cost of producing organic cotton jeans remains higher than producing chemically-grown cotton jeans, independent of jean size. Nevertheless, the business case for leasing jeans to pre-adults is still present. Kids grow fast and there is thus an added benefit to leasing textile products for shorter use. It takes greater awareness and demand from consumers to improve the intergenerational aspects of this business model.

## 6 Conclusion

This chapter illustrates the use of the SURF Framework for textile operations, using cotton textiles and two companies selling cotton products as examples. The current textile standards for sustainability have not clearly articulated the "F," or future component of SURF. Intergenerational thinking (as a key component of a sustainability paradigm) was also a challenge for the textile companies interviewed. An in-depth consideration for the supply chain, user, stakeholder relations, and future generations is often missing among textile players. While some organizations may fare well in one element of the SURF Framework, they may lack in another element. The chapter includes key questions to be asked along the cotton supply chain constituting sustainability criteria. The goal of the SURF Framework is to help organizations understand its sustainability strengths and work towards improving the less sustainable elements of its operations. Table 2 provides a general strengths and weaknesses summary of the two textile companies examined in this chapter. Other organizations can perform a similar analysis to help create a roadmap for future improvements.

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# Sustainable Business Development Through Designing Approaches for Fashion Value Chains

**Rudrajeet Pal**

**Abstract** Global fashion value chains are expanding rapidly, driven by forces of globalization. Large-scale outsourcing has led to long lead times and forecast-driven apparel value chains, resulting in increased forecasting errors and over-production-related difficulties. Typically, in the developed countries in Europe, United States, and Japan, we see the emergence of strong fashion brands as core manufacturing has faded from the scene, leading to several other challenges related to sharing responsibility in the value chain, unsustainable consumption, etc. This has a lasting impact on the key financial performance of the fashion brands along with the detrimental environmental and social impacts, thus challenging the right balance of the strategic vectors for sustainable business development (SBD) in fashion value chains. Various stakeholders have realized that the future of fashion value chains increasingly depend not only on economic sustainability but also on safeguarding the environment, safety, and welfare of those associated with it. In this context, the work addresses these strategic issues motivating the sustainable design of closed-loop fashion value chain to propose a holistic model towards developing a design for sustainable business development (DfSBD).

**Keywords** Business development · Design for sustainability · Fashion and apparel · Sustainability

## 1 Introduction

Sustainable business development (SBD) is a compelling requirement in global fashion value chains, given the market turbulences in the form of current fierce competition and globalization trends, intensive pressure on resources, higher

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consumer expectations and awareness, etc. [16, 36]. In the case of fashion value chains, large-scale outsourcing of manufacturing from the developed countries in Europe, United States, and Japan to low-cost bases has led to long lead times and forecast-driven apparel value chains, resulting in increased forecasting errors, mark downs, and lost sales [11, 50]. Chasing a lower cost of production has resulted in an excess of inventory, more discounted merchandise, greater consumer dissatisfaction because of lost sales, and ultimately reduced profits [39, 47]. Estimates are that the amount of merchandise sold at mark-down has grown to over 33 %, while only about one in three customers are able to find their first SKU[1] preference [29, 50]. This has certainly challenged the economic viability of fashion businesses.

In contrast to this, the current industrial system of fashion business is based on extremely fast cycles along with technological advancements, delocalization of manufacturing to lower-cost countries, and consumers' unsustainable desire, resulting in today's value chains predominantly becoming buyer-driven in nature [61]. Such value chains operate by enforcing operational strategies similar to agile manufacturing, lean production, and business process reengineering [36]. Quick response (QR) has been a strategy implemented since the 1980s by major fashion retailers along their apparel pipeline to operate more efficiently and continually meet changing requirements of a competitive marketplace which promotes responsiveness to consumer demand; encouraging business relationships and reliability towards building of resilient value chain [11, 13] by making effective use of resources and shortening the business cycle throughout the supply chain pipeline [63]. For 'seasonal' fashion (fast fashion products), QR management has become essential for fashion companies with multi-season assortments, especially during the re-ordering process by using various QR tools such as bar codes, point-of-sale (POS) data, electronic data interchange (EDI), etc. (cf. QR Practicability Tool-kit in Pal [63]). Even though appropriate implementation and execution of QR strategies has been quite able to solve the problems related to the declining retail performance measures of fashion businesses, other consequences have eventually emerged, related to conformation of the current 'fast' fashion industrial system. Over the last decade, consumers have been conditioned to low-cost changing styles with the fast cycles of fashion trends, continuous new customer needs, shortened product life cycles (a study by Procter and Gamble shows that the life cycles of consumer products have dropped by 50 % between 1992 and 2002 [81]), and increasing pace of planned obsolescence. This has taken its toll in terms of lower product quality and short-term durability, hence increasing textile wastes in various forms and thus causing phenomenal environmental burden [61]. Consumption level has also increased substantially; in a recent survey conducted by Deloitte, it was found that global fiber consumption has reached nearly 12 kg per capita while the average for the Nordic region is 16 kg per capita. On average, 16 kg of clothes is equivalent to 16 pairs of jeans or 64 T-shirts; typically 16 pairs

[1] Stock Keeping Unit.

of jeans requires 58,000 L of water, 48 kg of chemicals, 6,400 MJ of energy, and 208 $m^2$ area of harvested land[2] [18]. Global Footprint Network 2013[3] measures show that the ecological footprint of production and consumption in terms of the Earth's capacity to regenerate natural resources has increased from less than 0.5 in 1960 to 1.5 Earths currently, and by 2050 we will need 2.3 Earths. Overall, continuing business as usual (BAU) would result in severe resource scarcity, high volatility in resource prices as shown in Fig. 1, and hence threaten the profits and success of fashion industry's business models.

Thus, today the fashion apparel industry is locked in competition for higher profitability amidst downturns in the global economy, facing sustainability challenges and consumer uncertainty. Eventually, the notion of SBD has broadened from just the economic perspective to include the social and environmental dynamics as well. Established international fashion brands such as PUMA, H&M, Marimekko, etc., have all adopted "green" practices in their supply chain. H&M, for example, has joined the sustainable apparel coalition (SAC)[4] in an attempt to reduce the environmental and social impacts of its apparel and footwear products around the world. PUMA, on the other hand, has published an Environmental Profit and Loss statement (in 2012) for calculating the environmental impact for greenhouse gas emissions, water use, land use, air pollution and wastes up to tier four suppliers for PUMA—expected to be circulated to all PPR group members, including brands such as Gucci, Alexander McQueen, and YSL, by 2015 [18].

Despite the acknowledged relevance of designing sustainability along the pillars of "triple bottom line" approach [20] implementation and tackling of these sustainability issues have not been at the forefront; however this is increasing steadily. Even though the green international brands (GIB) have shown different ways to manage sustainability in the supply chain [in terms of managing supplier's code of conduct (CoC), supplier assessment, and corporate social responsibility (CSR) contract amendments] they are still quite poor in engaging with the local networks [18]. Caniato et al. [5] have defined these GIBs as well-established international corporations which have directed themselves towards environmental sustainability through incremental changes in their traditional business models and supply chain structure, such as that of Patagonia—an American outdoor clothing company (also presented by Chouinard and Brown [9], Napapjiri—an Italian

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2 Water consumption during production depends on the need for irrigation: 576–4,377 L/kg with an average of 1,818 L/kg and for finishing 105–145 L/kg (cf. Chapagrain et al. 2005; Blackburn and Burkinshaw 2002) quoted in DEFRA 2010. For chemicals cf. 'Mapping Chemicals in Textiles', Danish Environment Protection Agency, Publication no. 113, 2011. Water and energy consumption during production, manufacturing and for care cf. Levi's LCA for Levi's 501 Jeans Levi's 2010:(http://www.levistrauss.com/sites/default/files/librarydocument/2010/4/Product_Lifecyle_Assessment.pdf) Land use based on Global Cotton Yield 2011/2012 of 752 kg/hectare, cf. Agricultural Outlook Forum 2012, February 2012.

3 http://www.footprintnetwork.org/en/index.php/GFN/ (February 2014).

4 http://www.apparelcoalition.org/

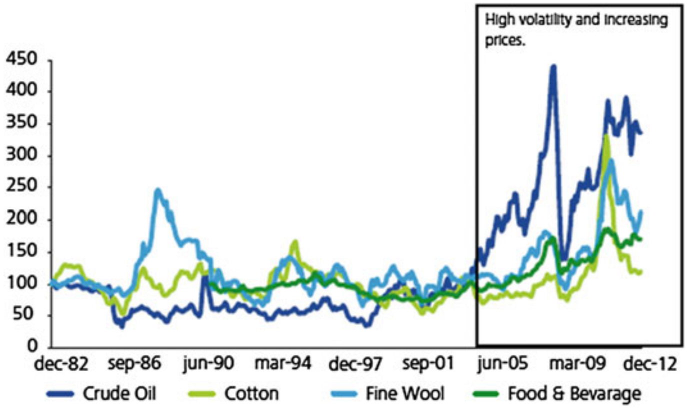


**Fig. 1** Price development for crude oil, cotton, fine wool, and food and beverage (1982 index = 100). *Source* indexMundi 2013. http://www.indexmundi.com/ (February 2014)

sportswear company, Nike, etc. These companies have made incremental changes in their organizations persuading suppliers to respond better to the environmental criteria; however, they have not completely revised their inbound supply chain. GIBs are mostly concerned with a wide set of key performance indicators (KPIs) (for measuring water pollution, energy consumption, etc.) by setting up green performance management systems and certifications.

On the other hand, new alternative approaches are provided by small and medium enterprises, known as small alternative firms (SAFs) [5]. These firms aim at finding new ways of competition in the marketplace by redirecting their vision from being small manufacturing firms driven by cost effectiveness towards being branded manufacturers integrating forward in the value chain to reach directly to the final consumers. SAFs are in direct control of their production processes and, hence, are able to influence the product and process design activities to impact the environmental performance strongly through investments in greener processes. As well as redesigning the external value chain architecture, these firms are also able to foster sustainability internally in their respective value chains. It is mainly the active wear brand manufacturers, for example, Astorflex—an Italian shoe company, Ali Organic Wear—an Italian underwear company, etc., which are able to reconfigure their traditional fashion business models by changing the value proposition and arrangement of the value constellation.

In this context, the next section first reviews the main challenges which hinder SBD in fashion supply chains. An impact of these typical fashion business challenges is investigated along the three sustainability pillars: economic growth, social equity, and respect for the environment. First, the chapter highlights and categorizes key issues challenging the sustainability of fashion businesses, in terms of supply and demand problems along with the potential mismatch between them. Then the impacts of these challenges are specified in terms of the three sustainability pillars.

The following section starts with a brief discussion on SBD, proposing the building blocks for designing SBD along the three-dimensional concurrent engineering (3-DCE) approach, viz. product-, process-, and supply chain-designing practices. The next section deals with a thorough discussion on SBD along various fashion value chain activities. The design for sustainable business development (DfSBD) framework as proposed in this work comprises design for sustainability (DfS) approaches along the processes of "Design and Product Development," "Sourcing and Production," "Distribution and Logistics," "Retail and Marketing," and "In Closed Loop." Finally, a concrete model for DfSBD along the 3-DCE pathways is hypothesized to operationalize the construct.

The research conducted has been purely deductive, proposing the SBD model and how to operationalize it along the 3-DCE pathways. Following the development of the framework, desk research is conducted to find relevant fashion business cases available on secondary data sources such as journals, trade and business magazines, blogs and reports, web pages, etc., to ascertain the proposition. A number of cases are used to highlight various proponents of DfSBD. Even though research on SBD has been active for around 10 years, the present viewpoint or lens of 3-DCE provided to design sustainable business development is fairly new and less explored. In this regard, the research aims to set up the platform for advancement in more established and detailed academic future research on this topic.

## *1.1 Challenges of Fashion Value Chains*

The problems in fashion business practices can be summarized in four inclusive challenges, viz. (1) fashion logistics challenges, (2) challenges of overproduction, (3) challenges of irresponsible consumption, and (4) challenges of fulfilling social responsibility. These are explained briefly below.

### 1.1.1 Fashion Logistics Challenges

Long lead time from order placement by the fashion retailers till its delivery is the biggest challenge to efficient fashion logistics in a globalized setting, also referred as "the lead time gap" by Christopher et al. [10]. Typically, the lead time in case of traditional fashion value chains, with up-front buying based on seasonal forecasting and planning, can sometimes be as high as 8–9 months. In an investigation of the key performance measures of major European fashion retailers, it was found that traditional fashion companies (marked by traditional product designs and slow response) [4], such as Mango—a Spanish branded retailer, Lindex—a Swedish branded retailer, John Smedley—a UK-based retailer, had production lead times up to as long as 26 weeks.[5] However, the majority of this time is non-value adding, contributed to by activities such as storage or transportation. In the 1980s the American consulting firm Kurt Salmon Associates conducted a supply chain analysis of the textile and apparel industry in the United States which revealed the average lead time from raw material to consumer was 66 weeks [47]. However, only 11 weeks were associated with manufacturing processes (value adding), while nearly 40 weeks were non-value adding waiting time in warehouses or in transit. The remaining 15 weeks were comprised of the shelf time in the store before the garments were purchased. In a similar study, Christopher and Peck [12] identified the processing time (value-added) and inventory time (non-value-added) for a knitwear garment. Out of the total lead time of 167 days, processing time was 57 days, while the waiting time or inventory time was calculated as 110 days.

Geographical spatiality (hence long lead times) in the fashion value chain necessitates long-range forecasts ahead of sales seasons [11]. This has severe negative impact on the financial performance of the companies caused by lack of forecasting accuracy leading to loss of revenue and profits, excess of inventory, and hence a large number of products which must eventually be sold at discounted prices, and risks customers not finding what they want in the shop [50]. Today, a 12-months lead time is quite common and it is estimated that it causes a sales forecast error of approximately 40 %; shortening the lead time to 9 months reduces this error to 23 %. Three months additional reduction of lead time from here reduces the error by only 4 % for each period of 3 months. Eventually, this means that even at the beginning of the sales period the forecast error is still 10 %. The economic impact of long lead times is discussed in Sect. 1.2 (cf. *The economic impact*). In addition, long lead times caused by the dramatic relocation of production sites towards the Far East have resulted in higher transportation costs, loss of employment in the manufacturing sector, and higher carbon footprints (even though transportation has a minor share of total energy consumption of 3–6 % of primary energy) [1]. Regarding transportation costs, the contribution is only a small part of the overall costs with shares between 4 % for European German producers and 7 % for the Chinese. However, the most critical impact is in terms of the decline in 'employability' in the manufacturing sector, with the textile and clothing industries having lost one-third of its jobs within 10 years, since 1996 [48].

### 1.1.2 Challenges of Overproduction Caused by Forecasting Error

Forecasting error has severe implications on sustainability along the three pillars. On average, fashion retailers only sell two-thirds of their seasonal fashion products

[5] KELANO (2010–2012) was a joint research project between Tampere University of Technology, Finland and The Swedish School of Textiles, University of Borås, Sweden aimed at finding an ecologically efficient, quick-response sourcing-production-distribution chain for fashion products.

at full price, while the rest has to be discounted [50]. Improving the retail performance measures by reducing lead times explains the method of improving response time in the fashion pipeline through development of QR—a business strategy to optimize the flow of information and merchandise between value chains members to maximize consumer satisfaction [43]. QR implementation by realizing various technologies, such as sharing POS information, EDI, electronic transmission of orders and invoices, computer-aided design (CAD), the use of computer technology and manufacturing, and electronic point of sale (EPoS), i.e., collecting sales information at the cash register from barcodes, etc., efficiently reduces safety stocks, avoids overproduction, and minimizes unsold merchandise [63]. Avoiding overproduction has substantial environmental impact, considering the fact that textile and apparel raw materials production are dominated by energy-intensive processes such as washing, drying, etc. Other major environmental impacts are also related to controlled use of toxic chemicals, release of chemicals in waste water, and generation of solid wastes [1] (further discussed in Sect. 1.3 (cf. *The environmental impact*). At the operational level it is crucial to take timely decisions on what to buy, what to move, and what to make, vital supply chain planning to counter demand uncertainty.

### 1.1.3 Challenges of Irresponsible Consumption

The high volatility and uncertainty in the demand pattern of fashion products resulting in increasing unsustainability cannot be totally blamed on the production system; consumers are equally irresponsible considering the fact that, on average, Europeans consume 15–16 kg of clothes every year, utilizing nearly 58,000 L of water, 48 kg of chemicals, 6,400 MJ of energy, and 208 $m^2$ of harvested land. This leaves substantial footprints on the Earth [18]. In a study by MISTRA,[6] the impacts of modern consumerism are along three phases: purchase, use and maintenance, and discarding. During the purchase phase the average Swede spends about 687 SEK per month, showing a significant gap between environmental and social awareness and actual purchase behavior. However, Guardian reports that nearly £1.6 bn of unused clothes are hanging in women's wardrobes annually.[7] In the use and maintenance phase, the use of washing machines, etc., is regular, while, despite the high awareness of environmental and social issues in the purchasing process, this awareness does not seem to translate into the discarding phase [38].

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[6] http://www.mistrafuturefashion.com/en/Sidor/default.aspx

[7] http://www.theguardian.com/sustainable-business/fashion-rental-startup-rentez-vous (March 2014).

#### 1.1.4 Challenges of Fulfilling Social Responsibility

The social issues of responsibility along the fashion value chains translate into the role of the fashion retailers in determining their CSR. This can be broken down into the three main areas of wages, working hours, and working conditions [66]. Fashion retailers have been accused of chasing cheap labor and, even though there are traditional monitoring methods such as codes of conduct and inspections in place, they have failed to pay their workers a living wage, have used child labor, have abused human rights, enforced minimum labor standards in the workplace, etc. [49]. Several ethical scandals have been reported in the supply chains of several global fashion retailers, including Zara, Gap, Nike and Marks & Spencer, in recent years. Awaysheh and Klassen [2], in this regard, have identified four broad categories of mechanisms aiming to encourage supplier to assume socially responsible practices: international standards, extended frameworks, supplier codes of conduct, and supplier social audits. However, the effectiveness of the buyer's responsibility to ensure compliance beyond first tier suppliers in an outsourced business model is questionable at present.

### *1.2 The Economic Impact*

The challenges of 'lead time gap' and overproduction reflect on the financial performance of fashion companies in terms of their profitability, activity ratios, and retail measures. Lead times are traditionally long and buying decisions are often made 7–8 months prior to the start of the selling season. This leads to high forecast errors, resulting in sell-through just around 65 % and average mark-down of 35 %, as compared to replenishment sourcing error of just around 8 % [50]. In turn, this leads to low inventory turnover over the year, resulting in higher risk of obsolescence, higher mark-downs, and items being liquidated at clearance. Also, considering that the products are not sold at full price, the cost benefit is minimized as the cost incurred in terms of the factors of production is potentially huge (e.g., for just the UK clothing and textile industry the essential inputs in 2004 were: primary energy consumption—989,000 tons of oil equivalent, water consumption—90 million tons, etc.) [1]. This typically lowers the retail performance measures such as gross margin and gross margin return on inventory (GMROI).

### *1.3 The Environmental Impact*

The textile and fashion industry is one of the biggest sources of greenhouse gas (GHG) emission, because of the huge size and scope of the industry as well as the many processes and products which go into the making of fashion products [24] (also cf. Vivek Dev, "Carbon Footprint of Textiles"[8]). Based on the estimated annual global textile production of 60 billion kg of fabric, the estimated energy and water needed is at a mind boggling level of 1,074 billion KWh of electricity (or 132 million metric tons of coal) and 6–9 trillion L of water. Moreover, in terms of water consumption, it takes nearly 30,000 L to create 1 kg of cotton (1 cotton shirt uses approximately 2,700 L of water).[9] Along with this enormous stake in the natural capital (water, chemicals, energy, raw materials), outputs from the industry are rising all the time. In the UK alone, the clothing and textile waste is estimated to be the fastest growing waste stream between 2005 and 2010, amounting to 1.5–2 million tons annually [17]. $CO_2$ emission, waste water, and solid wastes were 31 million tons, 70 million tons, and 1.5 million tons (in UK—2008) [1]. In landfills this waste causes methane emissions to air and pollution to groundwater through toxic chemicals [30]. The increase in textile waste is a consequence of the increase in textile and clothing consumption, which saw a growth rate of 30 % in 1995–2005 in Britain [17], while in Finland Nurmela [62] estimated that the consumption of clothing and footwear will increase by 23 % from 2006 to 2010.

### 1.4 The Social Impact

The social impacts of fashion value chains are equally derogatory. For instance, there have been several "sweatshop" incidents revealed in the value chain of international fashion brands, such as Nike, Zara, H&M, and many others, while unfair wages have every now and then been a burning issue. Fashion businesses, over the decades, have strengthened their CSR but mostly using self-audits and own internal compliance teams to evaluate factories based on their company values and ranking system. Among other issues, this can threaten labor safety. Outsourcing injustices in apparel has caused fire and similar disasters.

### 1.5 Scope

In this context, the future of fashion businesses as far as long-term success is concerned depends on developing a holistic SBD model incorporating social and environmental profit formulas along with economic profits, as discussed and argued in the next section.

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8 http://www.domain-b.com/environment/20090403_carbon_footprint.html (March 2014).

9 http://www.ethical.org.au/get-informed/issues/fashion-footprint/ (March 2014).

## 2 Sustainable Business Development

SBD is essential to achieve enhanced financial performance of organizations along with social and environmental objectives, thus balancing profit and planet. For fashion value chains—one of the most complex, 'dirty,' and demanding of all, in terms of fast clockspeed and product life cycle, process modularization, geographical dispersion, footprints, and stake in natural capital, consumer expectations, etc.—SBD has become a global theme for success or survival in recent times, amidst intensified competition, frequent natural, political and financial disruptions and turbulence, changes in government policies, increased society's expectations, and awareness of sustainability [36]. Various stakeholders have realized that the future of fashion value chains increasingly depends not only on economic sustainability but also on safeguarding the environment, safety and welfare of those associated with it. Notably, there have been several pieces of research and a number of articles have been published on identifying the building blocks of SBD, aiming for the creation of a framework. Gunasekaran and Spalanzani [36] enlist the literature (written between 2000 and 2010) on SBD based upon the major building blocks, and most certainly they include advancements in various business processes, such as product/process design and development, supply operations, production, distribution chain operations, and in remanufacturing, recycling, and reverse logistics, along the three sustainability pillars of economic, environmental, and social aspects. However, most studies have investigated these sustainability pillars, in terms of challenges and solutions, along a few supply chain pathways, e.g. Schoenherr [75] highlighted the influence of SBD in manufacturing plant operations. On the other hand, some research provided a more holistic picture of the entire value chain but along just one or two of the sustainability pillars, e.g., Caniato et al. [5] provided an analysis of fashion brands' value chain but only with regard to their environmental performances.

In this context, DfSBD demands a holistic overview of all the aspects which could possibly be 'designed' or configured along the entire value chain to attain sustainability in terms of the 'triple bottom line' approach. For this, it is necessary for researchers and, in practice, for all businesses to identify the building blocks of value chain, viz. products, processes, and supply chain. DfSBD should cover all aspects of product design, process design, and supply chain design along all the value chain operations, both independently and concurrently. This calls for looking into SBD through the lens of 3-DCE as discussed briefly in the next section (cf. *A holistic designing approach for SBD in fashion value chains*).

From the global value chains (GVCs) perspective, companies follow various business models depending on how their value proposition (in terms of a product/service and an associated customer), value constellation (through the company's internal and external value chain networks), and revenue architecture (profit equation based on sales revenue, cost structure, and capital employed) are organized to capture value for the customers [7, 83]. However, rising problems related to climate change, water shortage, industrial pollution, high-priced energy, etc., has compelled businesses to expand their classical business models and include a comprehensive ecosystem view, resulting in a fourth component or dimension defining business models, i.e., social and environmental profit equation [83]. Thus designing a sustainable business model should encompass a holistic approach as highlighted in Fig. 2.

## 3 A Holistic Designing Approach for SBD in Fashion Value Chains

Strategic adoption of independent or concurrent designing of products, processes, and supply chains is essential to develop sustainable competitive advantage in businesses [27]. These practices establish the designing aspects classified by 3DCE, by matching the supply chain design attributes to the product and process design requirements with an overall integration (early supplier involvement—ESI, concurrent engineering—CE, quality management, and customer involvement) to design improved financial performance [28, 67]. 3DCE essentially provides a holistic view towards understanding the intrinsic problems related to non-sustainable performance along all strategic vectors. However, the diagnosis of the functioning of an organization to determine the distinctive competencies through careful understanding and mapping along 3DCE has mostly been performed in measuring economic viability/sustainability [73]. However, the simultaneous design of product, process and supply chain have been proposed as a way to improve traditional new product development (NPD) outcomes, such as reduced time to market, lower costs, and improved customer acceptance [22]. Competitive priorities, such as improved quality, reduced lead time and time-to-market (TTM), delivery performance (speed), cost minimization, reduced relationship risk, improved product innovation, etc., are also considered as measurement characteristics to determine organizational performance together with all three sustainability pillars [76].

### *3.1 Product Designing*

Product designing encompasses all the decisions related to the product’s features, such as the choice of materials, development of the product’s components, and the design of the packaging [22]. As for any other product, such as textiles and fashion apparel, designing is determined by new product technology, better functionality new material and model—which ultimately lead to enhanced brand value; this leads to better development of the critical success factors (CSFs) and economic profit. In a study of Swedish clothing firms, it was observed that firms with higher level of product innovation in terms of product designs, product models, new

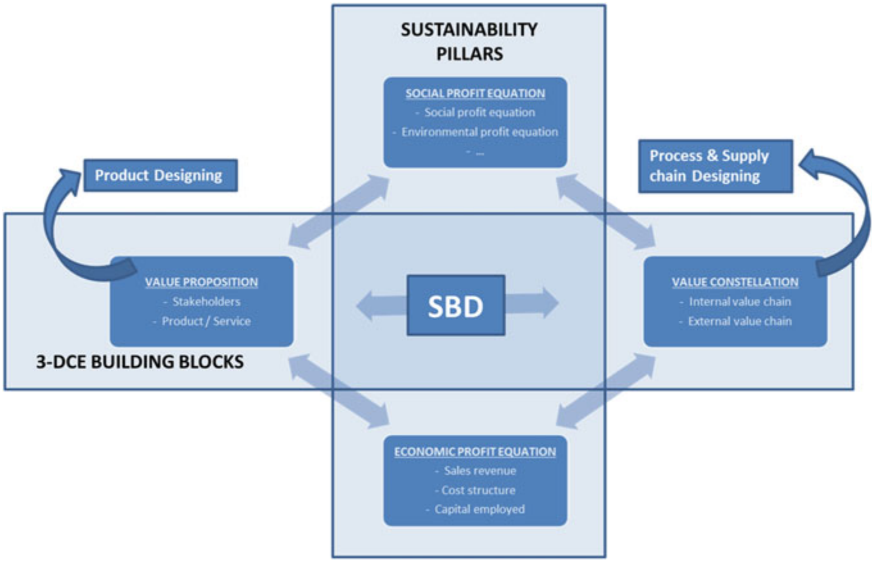


**Fig. 2** SBD model

technology, functionality or brand value had higher profits than firms with lower product innovation [64]. Designing aspects related to product variety–volume relationship and portfolio are also crucial to create product development (PD) capabilities such as modularized products [27], better product performance and quality, cost minimization, and higher productivity (through economies of scale), higher product–volume flexibility, and higher service level (through product customization), contributing towards better financial success drivers [64].

In the case of fashion companies, product designing and development generally start with inspiration for the coming season's collection through close monitoring of fashion shows and trends, inspirations from other industries, etc. Following the initiation stage, team meetings and range plans are organized by design managers, designers, representatives from the marketing department, purchase and sales departments to discuss the core brand values, collection details (themes, size and materials, type), philosophy, etc. At this stage, the design team takes a key role in choosing the key materials and shapes for the collection. Corporate values and inspiration from top management, complemented by a radical mindset among the designers, play a critical role in determining the choice of raw materials, product recyclability, hazardous chemical content, etc., with implications on social and environmental profit formulas of the business. Product design strategies during the design and PD stages should focus on extending the product life span, customer satisfaction, and product intimacy, and finally involve the customer in co-designing in an open innovation platform [61]. Such product design practices are also critical in the manufacturing and packaging operations in terms of choice of new eco-friendly or recyclable material, or sustainable packaging, etc. [5] and have a significant role to play in moderating SBD in fashion value chains along the attributes highlighted in Table 1.

### 3.2 Process Designing

Process design includes the design of production processes from raw materials to the finished product. Designing processes is also key for the foundation of 3-DCE, focusing on management, methods, facilities and equipment, technology and operations used for supply source-make-store and distribute-sell processes [27, 71]. Attributes of process designing include process innovation, identifying and improving process capabilities (through value addition, quality improvement, higher responsiveness, cost efficiency, higher productivity, etc.), higher process engagement, and faster rate of process development [64]. In a study of Swedish textile and clothing firms in Pal and Torstensson [64], companies with increased process engagement showed higher profit, suggesting that higher degrees of process control are significantly important in improving operational, and hence financial, viability. Process innovation is another crucial criterion for process designing to match innovative products and supply chains. Caniato et al. [5] highlighted the requirement of designing clean production processes, low energy consumption operations and facilities, etc., to ensure sustainability along all strategic vectors as well (cf. Table 1).

### 3.3 Supply Chain Designing

Supply chain design considers the aspects of sourcing decisions, contracting decisions (type of relationship an organization has with other members), make–buy decisions (insourcing or outsourcing), coordination decisions (logistical channels, suppliers, and customers) [8, 64, 65].

Supply chain design innovations through delivering 'new' ways for make/buy decisions, enhanced sourcing, and coordination decisions significantly enhance customer–supplier information exchange for ensuring systemic integration [21, 44]. Findings of the study by Pal and Torstensson [64] showed that higher supply chain innovations in terms of sourcing decisions result in higher flexibility in the value chain while higher coordination and trust are developed through enhanced decision making and increased coordination decisions. Sourcing and contracting decisions were also instrumental in controlling the success factors, viz. product quality, lead time, cost minimization, service level, and information sharing among partners. A properly integrated supply chain is essential to optimize the inventory level and hence cost tied up with stock keeping and maintenance, improve demand visibility and hence forecasting accuracy, supplier/customer

**Table 1** Product, process, and supply chain designing practices. Based on Caniato et al. [5] and Pal and Torstensson [64]

| Contributing directly to economic profit | Contributing directly to social and environmental profit |
|---|---|
| *Product designing practices* | |
| • Variety-volume portfolio (local production vs. customization) | • Natural raw materials (through local suppliers), e.g., organic cotton through fair trade suppliers |
| • Product life cycle and quality enhancement | • Sustainable packaging |
| • Product innovations and new product development (NPD)—degrees and rate | • Recyclable products (multiple life cycles)<br>• Product life cycle enhancement (multiple life cycles, modularity, slow fashion) |
| • Brand value, technology and functionality (slow fashion, co-creation, etc.) | • Low chemical/hazardous substances |
| *Process designing practices* | |
| • Process development and innovations—eco-friendly cleaner process, flexible/agile manufacturing | • Low energy and raw material consumption facilities and processes |
| • Process system capabilities (value addition, quality, responsiveness, cost efficiency, innovation) (fast fashion, QR, etc.) | • Cleaner production and transportation<br>• Collection and recycling of disposable products |
| *Supply chain designing practices* | |
| • Focus on collaboration, cost minimization, QR, quality functions, flexibility and coordination, social and environmental concerns | • Control over supplier through environmental certifications; code of conduct; development programs; green projects with suppliers |
| • Coordination decision/logistics; supply chain partnership and integration<br>• Differentiated supply chain strategies | • Logistics integration through transports optimization; short supply chain and local production network; reverse logistics; fair trade for raw materials |

relationship and coordination, increased responsiveness and agility, hence economic sustainability [64].

Along the other strategic vectors of sustainability, supply chain designing through efficient involvement of supplier and subcontractor (using code of conducts, certified suppliers, etc.), optimized transportation and logistics, green supply chain management (GSCM) practices, etc., have considerable impact [5] (cf. Table 1).

## 4 Sustainable Business Development Along Various Value Chain Activities

Fashion value chains are increasingly plagued by lower performance measures in a world of higher demand uncertainty. For development of sustainable businesses it is necessary to achieve an optimum balance between environmental protection, economic prosperity, and social equity [36]. Clark [14] has emphasized that about 30–80 % of the environmental impact of a product and/or service originates at the design stage. Hence the potential for maximum intervention lies at the design stage to develop an effective approach towards SBD. Maxwell and van der Vorst [51]'s model of sustainable product and service development (SPSD) provides an essential way to products/services more sustainable throughout their life cycle considering the traditional product parameters such as quality, market, technical and cost issues. Furthermore, collaborative planning, forecasting and replenishment (CPFR) can be uses as a tool to improve subsequently the supply chain effectiveness for demand planning, synchronized production scheduling, logistics planning, and new product design. Such supply chain designing approaches essentially lead to SBD by redesigning various business processes such as product development, manufacturing, distribution, retailing, and consumer use. A detailed discussion on how DfS is and can be integrated further into fashion value chains along all the business processes is discussed in the following sections.

## *4.1 Design for Sustainability in Design and Product Development*

Sustainable product design initiatives, such as ecologically intelligent design, product re-manufacture and reuse strategies, recycling and material transformation strategies, green product design, etc., are essential to reduce the stake on the natural capital (water, chemicals, energy, raw materials) [32]. At the same time, they increase the economic benefits of the organizations as well. Simon [78] classifies DfS around two distinct clusters, as "techno-centric design" (weak in sustainability) and "eco-centric design" (strong in sustainability) [31].

For leveraging the key strategic role of sustainable product design (also called environmental design, environmentally sustainable design, environmentally-conscious design, green design, etc.) there is a need for the fashion industry to:

- Comply with the principles of economic, social and ecological sustainability
- Eliminate negative environmental impact completely through skillful, sensitive design
- Reduce use and impact of non-renewable resources on the environment
- Use more recycled and reusable materials
- Relate people with the natural environment.

One way the fashion industry strives to do this is by using life cycle assessment (LCA), which quantifies the impact of everything which happens to make and use clothing, including raw materials extraction and production, manufacturing, product packaging and transport, use, maintenance, and disposal or recycling. For example, a high-impact item that can be worn often and kept for a long time may represent a lesser environmental investment than a low-impact item worn once or twice for a short fashion cycle. Brands and manufacturers can use the results of LCA to identify areas of environmental impact or risk, optimize product design and processes, and communicate their business and product impacts. Global international brands such as Levi's and Nike have both developed their own eco-matrices for key product areas in order to be more transparent [31].

In this context, another "eco-centric" product designing approach which has gained prominence has been related to the development and implementation of a new sustainable apparel design and production model, called cradle to cradle apparel design (C2CAD) method. The C2CAD model has been developed by integrating the cradle-to-cradle thinking/approach introduced in McDonough and Braungart [53]. Following the C2CAD model, a project funded by the US Environmental Protection Agency under a STAR Research Assistance Agreement was organized to develop a "four-season sustainability" children's knitwear prototype [33]. The C2C design approach has been successfully applied by some textile product manufacturers such as Nike, Designtex, and Shaw Industries [53].

Designtex,[10] for instance, has followed this design principle [McDonough Braungart Design Chemistry (MBDC)] of "waste = food" to develop more environmentally friendly fabrics for compostable upholstery. This ensures the effects of sound product designing for environmental sustainability. Apparently, in a study by Niinimäki and Hassi [61], nearly 80 % of the consumers when interviewed were interested in the concept of slow fashion (marked by long-lifetime, repairability and having multiple life cycles). Such product design strategies were able to increase the uniqueness and personalization of the product. Design-led strategies, for example, developing technologies and systems for slow fashion movement such as multi-functional garments or 'design for empathy' [37, 61], can be highly durable as well. Antithesis[11] is a company advocating this philosophy of 'new' consumerism based on local sourcing and manufacturing, increased transparency and versatility of its products to ensure enhanced connection or relationship between wearer and the garment rather than just its exchange value. A deeper connection is also established when the garment is co-designed by the wearer.

Yet another cause of non-sustainability in fashion value chains is demand uncertainty, which leads to mismatch between production systems and consumption patterns. Overproduction in fashion value chains is a characteristic problem which affects supply chain performance to a great extent, and thereby business sustainability. Typically, in forecast-driven value chains, fashion products/collections are developed upfront several months before the season starts. The PD lead time can be up to 6–9 months sometimes. One of the inherent sustainability-related problems originates at the prototyping phase when prototypes of the styles in the collection are demanded by the retailer/marketer from all their potential manufacturers. Only about 40 % of the actual concepts or ideas developed or

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10 http://www.designtex.com/

11 http://antithesis.co/about/our-brand/

sketched finally end up in the salesmen's sample collection while the rest are lost in the iterative design process. Further, only about three-quarters of the approved samples are confirmed for production (during the preproduction stage) while the rest are canceled depending on the responses obtained by the salesmen on the expected sales volume. On average, about five sales samples (viz. pre-production sample, production sample, shipping sample, reference sample, etc.) are produced per style. The entire decision-making process from idea to production via the reiterative prototyping process, is not only time-consuming but also leads to enormous wastage of raw materials (fabrics) for prototyping and sampling purposes with no role in value creation, and on the top of that creates a huge environmental footprint in terms of resource consumption. Combating sustainable product design strategies can be done in various ways [60, 61] as discussed below.

#### 4.1.1 Innovative Pattern Making and Garment Design for Zero Waste

Around 30–80 % of the environmental impact of a fashion product is decided at its design stage, generating nearly 90 % of the toxic emitted chemicals. Innovative pattern-making and toiling phases of PD are critical in reducing material and resources usage by identifying all types of wastes in the pipeline. Creative approaches to pattern-cutting such as identifying and developing multi-functional garments is a way to reduce the stake on resource consumption. Zero-waste patterns are also developed to improve the efficiency of pattern making and minimize fabric waste. Typically, in conventional cut-order-planning (COP) there is fabric wastage of the order 5–8 %; this can go up to even 15 % [69]. This can be reduced through the design stage, either by working with special geometric shapes, 'new' construction methods, or by approaching techniques not requiring a direct cutting process [37]. The North Face Zero-waste project was, in this regard, a collaboration between North Face and Textile Environment Design (TED) to create a zero waste version of down jackets leading to an increased efficiency of 23.2 % compared to the current pattern. Rapid prototyping techniques are also available and those can be beneficial to open up a number of creative opportunities for designers to support personalization, digital manufacturing processes, etc. This is not only a way to lead to environmental sustainability by reducing wastes but also improves cost effectiveness.

#### 4.1.2 Through Customization, Halfway Products, and Modular Structures

Mass customization (MC) has found an increasing significance for creating a deeper emotional connection with the customers. Using fast, flexible, digital manufacturing technologies and computer-aided designs, companies have had a positive effect on the economic sustainability of fashion value chains, by reducing markdowns, reducing returns (>1 % return rate), and increasing customer satisfaction [45]. In the fashion business, global brands such as Levi's, JC Penney, Nike, Brooks Brothers, and Ralph Lauren have customized solutions for consumers [82]. Other smaller- and medium-sized brand retailers have also entered into customized product selling, such as Tailor Store[12]—an online retailer in Sweden allowing the customer to configure a shirt's color, sleeve length, and other options, the customer receiving the product in 10–15 days; the Finnish Left Shoe Company[13] (formerly known as The Leftfoot Company), where both feet of a customer are scanned by sales personnel to manufacture perfectly fitting shoes which are delivered to the customer within 3 weeks [77]. Adidas, on the other hand, embraced MC and, instead of producing 230,000 sample models every season, it has now become possible for them to replace the physical shoes by virtual shoes displayed on screens in stores. Adidas expects to save several million dollars per season through this [72]. Various digital technologies and creative tools, such as 3D fashion software and avatars (Lectra's Modaris, 3D Fit, etc.), 2D to 3D converters (TPC Limited base in Hong Kong has developed an automatic pattern generation system to allow designers create the 3D model first and then produce 2D patterns semi-automatically), connecting virtual tools, etc., have been developed to make MC widespread and profitable [34]. This personalized PD scheme also requires significant process designing skills to use the digital technologies effectively. For instance, Caterpillar's production system cuts out shoe parts according to customers' measurements with an automated, computer guided cutter. This necessitates manufacturing process designing to facilitate the customized value chain.

In one way, MC demands investment in the necessary technology and flexible production and distribution, thus increasing the cost of production. U.S. based footwear retailer, K-Swiss allows its customers to choose colors and also to have their name inscribed at the back of the shoe. The price of these customized shoes has a price level approximately 6 % higher than mass produced ones. However, this leads to an increased value for customers, hopefully thereby reinforcing the company's brand [15]. Larsson (2012) discovered that customers who bought the custom-made garments were willing to both wait longer and pay more than in an ordinary clothing chain. Another study by Pal and Torstensson [64] identifies that customized products (with higher brand value and fashion content) strongly influence supply chain design attributes characterized by QR, cost minimization, higher flexibility and coordination, along with sustainability concerns. Such SC designing features are also essential to drive faster cash flow, asset turnover, and hence profitability, implying economic sustainability. Modular manufacturing is also a 'new' designing process aimed at reducing environmental impact and enhancing product longevity. Development of a range of detachable product features can facilitate easy cleaning of parts of garment and easy replacement or repair, thus creating novel and creative attachment systems [37, 61]. From the

12 http://www.tailorstore.se/

13 http://www.leftshoecompany.com/home

environmental point of view, both customized production and modular products help in reducing the impact on energy and natural resources and deliver cost effectiveness.

## 4.2 Design for Sustainability in Sourcing and Production

LCA suggests, in terms of energy consumption, that nearly 25 % of the total energy required (109 MJ) to produce a 100 % cotton T-shirt is used in material and production stages (while it is as high as 80 % of the total energy consumption (51 MJ) for a 100 % viscose blouse). In another environmental report, by the Italian leather industries association UNIC, 1 $m^2$ of leather requires 113 L of water; total environmental cost amounted to 2.2 % of turnover, around 68 % are caused by water treatment, 24 % by waste management, and 8 % by air emissions and other costs [80]. Delphi studies conducted by Allwood et al. [1] from the University of Cambridge suggest that innovative production technologies with local recycling would be favorable globally in reducing the emission of 'Climate Change Impact' (measured in terms of a thousand tons of $CO_2$ emission), waste disposal, and 'Environmental Impact'[14] [46].

Efforts in sustainable sourcing, procurement, and manufacturing are growing. Different production processes can affect the environment within the supply chain in many different ways. Some of these include the use of certain raw materials, the ability to integrate reusable or remanufactured components in the fashion industrial system, and how the processes are shaped to prevent waste. A C2C apparel design and production model [33], in this context, considers environmental sustainability in production by ensuring safety of material inputs and sustainable material flows in terms of energy usage, air emissions, water, and solid waste.

Several certifications, labels, and standards exist, aiming at facilitating, supporting, or monitoring sustainable practices in sourcing and production. The Bluesign® system[15] is such a standard solution, aiming at sustainable textile production. It eliminates harmful substances from the start of the manufacturing process and sets and controls standards for environmentally friendly and safe production. This ensures the final textile product meets very stringent consumer safety requirements worldwide, but also provides confidence to the consumer that he has acquired a sustainable product. Table 2 lists all the textile-only certifications.

[14] Representing the combined effect of ozone depletion, acidification (acid rain), nutrient enrichment (algae growth that can cause fish death), and photochemical ozone formation (smog). The aggregated environmental index is measured in 'person equivalent targeted' (PET) units, i.e., the impacts are normalized to one person's share and weighted according to political reduction targets.

[15] http://www.bluesign.com/

**Table 2** Certification in the textile industry. *Source* ecolabel index (February 2014)

| | |
|---|---|
| BioForum biogarantie and ecogarantie—a Belgian organic label | Made by—umbrella label used by fashion brands and retailers to show consumers that their clothes are produced in a sustainable manner |
| Bluesign standard—analyzes all input streams from raw materials to chemical components, to resources with a sophisticated "input stream management" process | 'Made in green'—certifies that the product, throughout its traceability chain has been manufactured in factories which respect the environment |
| BMP Certified Cotton—Australian cotton industry's guide for growing cotton in harmony with natural environment | Migros ECO—label for textiles guaranteeing no substance likely to cause allergies or irritation, or to be harmful to the environment. It also attests to environmental preservation and workforce health and safety |
| China environmental labelling—provides environmental standards for construction materials, textiles, vehicles, cosmetics, electronics, packaging | Naturland—association for organic agriculture is a private certification body and an organic farmers association |
| Coop naturaline: Switzerland—standard for textiles and natural cosmetics made from cotton by controlled biological cultivation according to the guidelines of BIO Suisse or the European Union | Naturtextil BEST—a holistic standard valuing environmental and social criteria along the whole textile production chain |
| eco-INSTITUT—supplies clients with a reliable and significant label for building products and textiles without any health hazards | NSF/ANSI 336: sustainability assessment for commercial furnishings fabric—ecolabel addressing the environmental, economic and social aspects of furnishing fabric products |
| Ecoproof—label for textiles, especially textiles made from cotton | Oeko-Tex (100, 100 plus, 1,000)—are globally uniform testing and certification systems for textile raw materials, intermediate and end products at all stages of production |
| Global organic textile standard—comprehensive rules for ecological and socially responsible textile production | Sustainable materials rating technology or SMaRT—consensus sustainable products standard and label for building products, fabrics, apparel, textiles, and flooring |
| Global recycled standard—standard for companies manufacturing products with recycled content. The standard applies to the full supply chain and addresses traceability, environmental principles, social requirements, and labeling | Soil association organic standard—organic certification for farmers, growers, food processors and packers, retailers, caterers, textile producers, health and beauty manufacturers and importers, in the UK and internationally |
| Green shape—a VAUDE's label for products featuring special ecological manufacturing | Tunisian ecolabel—type 1 national ecolabel to facilitate the access of Tunisian products and services to the European and International markets |
| Institute for market ecology (IMO)—international agency for inspection, certification and quality assurance of eco-friendly products | |

http://www.ecolabelindex.com/

Environmental issues addressed by these eco-label standards mostly consider categories including organic production, energy usage, pollution, and biodiversity conservation, thus concentrating on all aspects of 3-DCE. DfS, in the sourcing and production stages, for producing eco-textiles and clothing mainly concerns the need for less pesticides, allergens, and biologically active compounds. The toxicity profile of a cotton T-shirt suggest that 93 % of the total toxicity is produced in the cotton production phase (in terms of five major chemical groups—insecticides, herbicides, fungicides, growth regulators, and defoliants) [1]. Use of sustainable raw materials, products, technology, and energy such as crops employing no pesticides or have a reduced need for water, use of materials made from renewable resources with ‘alternative-green’ substituted chemicals,[16] and the use of renewable energy are the best practices at this stage. This can lead to economic sustainability, as it was found that use of organic over conventional cotton reduces the number of pest management days needed per year by around 40 %, hence the costs of fertilizers and pest management falls significantly [25].

Additionally, process designing during sourcing and production stages guarantee low energy consumption, less waste production, etc. The University of Cambridge study suggests that the combined waste from clothing and textiles in the UK is about 2.35 million tons,[17] 13 % going to material recovery (about 300 thousand tons), 13 % to incineration, and 74 % (1.8 million tons) to landfill. Several other indicators suggest about 0.6 kg of oil equivalent primary energy is used in the industry per 1 kg of output, about 2 kg of $CO_2$ equivalent emitted to air per 1 kg output, approximately 60 kg of water used, and about 45 kg of wastewater discharged per 1 kg of output [1]. High water consumption being a major concern in cotton production (ranging from 7,000 to 29,000 L for producing 1 kg of cotton fibers), price of organic cotton is expected to rise in the near future due to increased resource utilization.

Collaborations with other industries, such as companies producing renewable energy or using solid waste from apparel production as their biological nutrients or raw materials, are additional means to reduce or eliminate harmful impacts during production. In C2CAD, collaboration and co-development of fabric with vendors is a component (cf. May-Plumlee and Little’s NICPPD model) [52] and so it is in the “cradle to cradle” model—as McDonough and Braungart [54] proposed *intelligent materials pooling* which emphasizes collaborative approaches, such as sharing knowledge and resources between apparel designers and manufacturers with other companies in the supply chain, as important strategies in sustainable development. Other options include enhanced information exchange through EDI [74]. Closer collaboration among the producer, supplier, and final consumer through various

[16] Greenpeace, ‘Moda sin tóxicos, for a future free of harmful Chemicals’, June 2006. Information about the chemicals used in the textile and clothing industry, their effects on human health and claims they can be replaced by other kinds of chemicals; www.greenpeace.org/espana/reports/moda-sin-t-xicos.

[17] ONS, May 2006. Environmental Accounts—spring 2006, Office for National Statistics, pages 23, 35 and 39, www.statistics.gov.uk.

environmentally conscious purchasing practices, by ISO 14000 standards, etc., guarantees integrated chain management (ICM) for higher environmental management, information sharing, and transparency [56]. From a holistic approach, these issues of environmental certification and codes of conduct incorporate green supply chain design management aspects.

The social issues across this category include labor practices, worker health and safety, consumer health and safety, economic development, and animal treatment. Clean Clothes[18] is an example of a pan-European campaign, which has institutionalized a voluntary CoC based on the International Labor Organization (ILO) standards. Other organizations, such as the World Fair Trade Organization (WFTO),[19] The Ethical Trading Initiative (ETI),[20] etc., are concerned with the issues guiding social sustainability, by adhering to the principles concerned with reaching the economically disadvantaged, transparency and accountability, capacity building, promoting Fair Trade and implementing corporate codes of practice, and improving the situation of women, child labor, supply chain working conditions and meeting international labor standards, the environment, and the payment of a fair price. Deloitte's fashion survey investigates how large companies and small companies manage supply chain sustainability. The approach to GSCM has been of two types, viz. (1) conventional approaches including supplier CoC, contract amendments, supplier self-assessment, and audits, and (2) stakeholder-based approaches including supplier worker and stakeholder surveys, supplier-based partnerships, engagement with local networks, etc. Results showed that large companies have a higher degree of focus on both conventional (79 %) and stakeholder-based approaches (44 %) [18]. For example, Nike through Fair Labor Organization (FLA), an NGO, openly shares the results of the audits of its suppliers for maintaining high degrees of transparency. Yet, sometimes these codes of conduct are not really checked in practice, and the code may be paradoxical in nature, given strategic decisions towards low cost, which will likely dominate daily practices on the shop floor [23, 79]. Large companies, as highlighted in the Deloitte study, put a great deal of effort into using supplier CoC but do not significantly engage with local networks for sustainability. There have also been many initiatives from different organizations to gather the industry around a common way of measuring environmental and social impact of fashion and apparel supply chains. Whether these initiatives have failed because of lack of interest or because the tools were too complicated remains unclear. However, major fashion and apparel brands have now gathered around one tool which measures the environmental and social impact of fashion supply chain, the SAC index accepted by a wide range of industry partners such as H&M, Patagonia, Adidas, Asics, Coca Cola Company, New Balance, Nike, and Puma. The SAC-index is a common, industry-wide tool for measuring social and environmental performance of apparel

[18] http://www.cleanclothes.org/

[19] http://www.wfto.com

[20] www.ethicaltrade.org

products and the supply chains producing them. Since several of the major fashion companies have agreed to use this index it is possible that this index will serve as a benchmark in the future.

From the point of redesigning the supply chain, a major change in organizational and value chain structure was catalyzed by the global financial crisis, the ensuing recession, and an uneven global recovery becoming key driving factors for new supply chain business models. “Re-shoring” or “next-shoring” are terms used to describe the return of manufacturing to developed markets with increased wages in developing nations and increased environmental issues [35]. Next-shoring strategies encompass elements such as a diverse and agile set of production locations, a rich network of innovation-oriented partnerships, and a strong focus on technical skills. There have been some attempts already to revive production in the developed nations based on these concepts. For instance, France has created competitive clusters (‘Les pôles de Compétitivité’[21]) on technical textiles as a national strategy for manufacturing competitiveness. European brands which have sought to retain parts of domestic production have focused mainly on technological change, particularly increasing the use of just-in-time and QR (such as Zara) [26] with increased digitization and applications of computer techniques in design, cutting, and finishing along with automation of manufacturing. A very recent step taken in the United States, through the partnership of Royal Park USA (RPUSA) and Industries of the Blind (IOB), is establishing a project (RPUSA-IOB) to re-emerge domestic sewn products and the supporting United States manufacturing companies ‘back to US’ by creating a comprehensive Full Package Center (FPC).[22] The FPC is expected to offer expanded design, product development, and end-model manufacturing based in the United States and also to serve as a centralized resource center connecting brands, manufacturers, entrepreneurs, suppliers, and retailers in the apparel industry. This is also a collaborative attempt to re-shore production, fabric and trim providers, contract manufacturers, equipment companies, and service providers, etc., back to US. From the DfS aspect, this would lead to social–cultural innovation through job creation in the manufacturing sector, extending existing best practices, and development of a constraint-based lean manufacturing model. In essence, a “one stop shop” is being created to enable companies currently using off-shore production to move the business quickly to the United States at very competitive costs.

One challenge is to attract and keep retraining highly-skilled labor. Companies rely on their personnel’s adaptability and their innovation capacity. This implies investment in training, retraining, and good careers advice, aimed at developing transverse and managerial skills to manage organizational adjustments. So, even in a context of production flexibility (as it is the case for the fashion industry), skill development plans for employees, managerial skills, and transverse competencies development can contribute to consolidation. Investing in the skills of employees

[21] http://competitivite.gouv.fr/

[22] http://www.industriesoftheblind.com/royal-park-usa/

is part of a sustainable and responsible human resource management. This is not only beneficial in the long run to the company, but is also one of the numerous facets of the social pillar of sustainability (together with fair labor conditions, discrimination, gender issues, and so on). Better-trained employees can more easily reposition themselves in the labor market if they lose their jobs. Considering the pillar of economic sustainability, nearby production has the added advantage of shorter logistics lead times. Thus companies can keep a major part of their product open for seasonal buying (represented by open-to-buy—OTB) rather than buying upfront based on forecasting before the seasons [50]. This accurate QR approach can enable fashion businesses to achieve a higher inventory stockturn, thus resulting in higher cash flow and GMROI. According to a survey in the United States, forecasting accuracy achieved by firms using QR can be as high as 95 %, sell-through 95 %, and distribution center lead-time can be reduced [41]. A much more recent study in Mustonen et al. [58] indicates that the net profit margin and a rapid turnover of inventory were significantly higher for brand retailers, resulting in higher profitability than for traditional multi-brand retailers.

## *4.3 Design for Sustainability in Distribution and Logistics*

In the global fashion value chains, sustainable initiatives also concern the logistics and transportation functions within each company and also along the entire supply chain, thus demanding reduction in global pollution and increasing awareness among businesses and consumers to contribute towards a greener lifestyle [24]. This is aimed at optimizing the physical flow of goods (through flow management optimization), increasing adoption of resource-sharing solutions, and also, by availing cleaner transportation modes, countering the increased footprints of fashion logistics with increased transportation distances [16]. In the road transport sector, the increase in energy consumption is at a faster pace than that consumed by cars and buses, and is expected to surpass it in the next 10 years [24, 55]. Moreover, the average grams of $CO_2$ emitted per tonne-kilometer for a deep sea container ship, freight train, heavy truck, and long haul airfreight are around 14, 30, 80, and 570, respectively [55]. In this context, attaining sustainability along all three SD pillars, in the logistics and distribution functions, calls for a holistic 3-DCE approach.

First, logistics integration through optimized flow management and consolidation plays a critical role in economic sustainability along the value chain by exercising better control (mainly by downstream fashion retailers). Increased coordination by leveraging effective relationship management is beneficial in favoring reduction in transportation-related costs by ensuring better responsiveness, reliability and shorter throughput times [16]. For instance, H&M has built its distribution centers in their international locations in order to cut down lead times and potential logistical costs. Setting up specific production planning along with centralized warehousing and regional distribution centers, as used by Mango, is also critical for consolidating the flow of fashion goods—supported by clean transportation modes.

Sustainable logistics are also optimized through increased use of different tools, including CPFR, aimed at sharing resource use in transportation and warehousing, joint routing, scheduled deliveries, etc. This subsequently reduces the logistics costs and time, along with the negative impacts on the environment [16]. Such intermodal transportation solution (based on resource sharing), along with the use of clean transport modes, are beneficial in implementing both economic and environmental sustainability—through process and supply chain design approaches. In this context, Clean Shipping[23] is a project aimed at minimizing the environmental impact of shipping. The Clean Shipping Index is a benchmarking tool which calculates and tanks ships on the basis of their environmental performance, based on nitrogen oxide, carbon dioxide, and sulfur dioxide emissions, and control of fuel. Fashion companies, such as H&M, Lindex, etc., have joined the clean shipping project. On the other hand, Carrefour initiated a pilot project in 2002 aimed at testing barge transportation. This project allowed a modal shift from road to river of 30 % of textile flow, through a container line. Barge transport took about 3,000 trucks off the roads, representing a reduction of $CO_2$ emissions of about 130 tons and a cost reduction of 6 %; in 2011, this resulted in 9,000 fewer lorries on the roads and 1,330 fewer tons of $CO_2$ emitted[24] [16]. Changing freight from air or road to rail and water-borne transport can also significantly reduce the retailer's footprint. Continental Clothing, for example, does not use air freight; items from Turkey are delivered by truck and those from China and India by sea, resulting in a transportation cost of about 2–5 % of the product price ($\sim$5 pence per T-shirt). Its dynamic vendor management inventory (VMI) principle helps it to do well in the marketplace.

Apart from structuring the geographical logistics system and streamlining the routes, cleaner transportation can be encouraged through process innovation, such as increase in vessel size (in maritime transportation), high speed shipping lines, achieving better delivery trip optimization, and higher fill rates of the vehicles—thereby the frequency and cost of deliveries and fuel consumption are decreased [16, 36]. A shift from conventional diesel to alternative fuels or battery powered cars can significantly reduce $CO_2$ emissions and other harmful pollutants.

At the product design level, innovative packaging has a positive impact on the environment and in most cases this is a very important part of the supply chain. The shape and material have a significant impact on transportation and cargo. Better packaging using recyclable material together with arranged loading patterns can reduce material use, optimize space taken in warehouses and in containers, and reduce the amount of handling required [74].

Further, regarding social issues, stakeholders consider the concern for consumer health and security as important prerequisites for sustainable logistics practices,

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[23] http://www.cleanshippingindex.com/

[24] http://carrefour-site.ti.smile.fr/sites/default/files/REDD_49_61_EN.pdf

and these can be achieved through various track and tracing technologies [16]. Mostly this is connected to the traceability of the fashion product along the value chain to ensure that it has no contact with any health hazard. The Clothing Traceability[25] is such a project which "connects the businesses and consumers to a deeper understanding of the impact of the clothing life cycle through documentation and visualization of the supply chain, from fibre through manufacturing and production, the project builds on established tools for supply chain transparency to develop a leading approach to sustainable fashion."

Thereafter, the 3-DCE approach plays a strategic role in effectively coordinating sustainable logistics and transportation solutions in the fashion value chain.

## *4.4 Design for Sustainability in Retail and Marketing*

Rethinking the value creation mechanism is vital at the stages of marketing and retailing when the retailers have the highest potential to create an enjoyable product experience in the mind of the customers [61]. Various mechanisms could be enforced to help consumers evaluate connections between the price, quality, and utility of the product, such as explaining to the customers the environmental benefits of the product, the ethical product values and esthetical longevity, the durability and content of the sustainable materials, etc.

### 4.4.1 Guaranteeing Long Life and Product Satisfaction

A short life span of fashion apparel is one of the major problems in current industrial systems, resulting in quick, planned obsolescence. Slow fashion in this context is a movement aiming at enhancing the longevity of fashion life span by focusing on a products' use value instead of its exchange value. By ensuring higher quality and ethical values, slow fashion products are expected to deepen and prolong product–customer interaction.

For instance, UK-based brand manufacturer John Smedley is a SAF engaging in producing high quality and classic design knitwear.[26] Together with Better Thinking Inc., John Smedley has developed a sustainable luxury shirt called "Luxury Redefined." FairTrade organic cotton used for the shirt is sourced from Peru because of the lower water footprint and renewable energy; the shirt is in a natural color and no bleach or dyes are used,[27] thus relating customers to the natural environment. For Patagonia,[28] the key elements in its PD are quality,

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[25] http://www.clothingtraceability.com

[26] http://www.johnsmedley.com/

[27] http://www.coolhunting.com/style/john-smedley-x.php (February 2014).

[28] http://www.patagonia.com/eu/enSE/home

environmental criteria, and innovation. Quality aspects mainly focus on the multi-functionality of the product adding an environmental benefit, as it allows the customers to consume less [68].

### 4.4.2 Co-Creation, Open Innovation and Crowdsourcing

Co-designing approaches encourage customers to have enhanced personalized experience with the products, offering deeper consumer satisfaction. Several studies (e.g., [57]) have highlighted that these aspects symbolize a deepened product attachment, and emotional bonding which may postpone product replacement—which is sustainable in many cases—to decrease the environmental impacts, thus benefiting from sustainable development [61]. Many sectors have undergone or are undergoing structural changes by systematically looking for strategic innovation outside their organization and inviting more players, big and small, to take their place in innovation processes. Crowdsourcing is such a practice, obtaining the required services, ideas, or content by soliciting contributions from a large group of people, and especially from an online community, rather than from traditional employees or suppliers.[29] Open source fashion is a recent phenomenon and in many ways can lead to SBD.

ModCloth,[30] an online retailer based in San Francisco specializing in vintage and vintage-inspired clothing, uses customer feedback to gauge fashion trends and to determine which ideas to implement. Using controlled design tools, a similar online design company—Threadless[31]—supplies its designers with PD ideas (based on scores from outside selectors/customers, score distribution, and their own sense of fashion aesthetics and style trends) [42]. Increased product satisfaction by changing passive customers into active ones can help fashion businesses accelerate their innovation, cut operating costs (being more demand-driven), and increase return on investment (ROI), thus honing economic viability. Zara, the Spanish retailer, has embraced the customer-based idea selection process over a long period of time by manufacturing small batches of numerous designs and also letting the customers determine the latest trends [42]. Not only does this allow Zara to identify popular items; it also enables the company to cut its losses (less mark-down, less inventory level) quickly when a product flops.

Even though the willingness of fashion businesses to collaborate on sustainability issues with outside organizations and individuals is not new, the most striking thing is the changed strategic role and opportunity which these companies perceive in the online open forums in order to develop viable sustainability solutions. In this context, EDUfashion, was an EU financed project for the development of a collaborative platform for fashion creation and continuous

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[29] Crowdsourcing—Definition and More Merriam-Webster.com (February 2014).

[30] http://www.modcloth.com/

[31] https://www.threadless.com/

education emphasizing and oriented toward "ethical" fashion items, meaning no sweatshops, ecologically sustainable, locally produced, and fairly traded apparel, by exploring the forces behind these consumer trends [59]. Initiatives from large international companies such as Unilever's Sustainable Living Lab[32] program, GE's Ecomagination[33] Challenge, etc., have been permanent platforms dedicated to open innovation and to extend and deepen the interactions with external collaborators. In the case of fashion businesses, Nike's Green XChange program similarly capitalizes on public problem solving by sharing intellectual property [19]. This has been economically profitable for Nike during the recent 2008/2009 credit crunch. By adopting the open-innovation platform, through collaboration Nike was able to transform its customers into designers, its sneakers (shoes) into personal fitness consultants, and its intellectual property into free R&D for solving the world's problems. This transition helped Nike to earn a revenue of 19.2 billion USD, with a triumph during the recent crisis [70].

### 4.4.3 Enhancing Product–Service System

Enhancing the engagement between product and service drives fashion companies to concentrate on satisfying customer needs and, at the same time, have minimalistic impact on the environment. A paramount goal of product–service systems, as highlighted by Mont [56], should be to minimize the environmental impact of consumption by closing material cycles, or reducing consumption through alternative scenarios of product use, or increasing overall resource productivity and dematerialization of PSSs, or providing integrated system solutions with improving resource and functional efficiency of each element. The value-added benefits of such innovative systems would provide an enriched personalized experience to the customers and this can be achieved in several ways, such as by selling the use value of fashion products instead on the basis of the exchange value, changing to a 'leasing society,' by substituting goods by means of service machines, by moving away from a throw-away society to a repair society. and basically changing consumer attitudes from sales to service orientation [6, 56]. For instance, even though the idea of leasing clothing rather than purchasing may seem to be unattractive to many consumers, some clothing and textile products already have leasing as a common practice. For example, leasing formal and evening wear, maternity clothes, school uniforms, sports clothing, linen for restaurants or hotels, uniforms for hotels, protective clothing in industry, wedding clothes, etc. [61]. Leasing is an effective way to use products for more of their potential life and this way of sharing and extending the life cycle of clothing by even just 3 months can

[32] http://www.unilever.com/sustainable-living/?dm_t=0,0,0,0,0 (February 2014).

[33] http://www.ge.com/about-us/ecomagination

reduce the carbon footprint by 8 %, water consumption by 10 %, and waste by 9 %,[34] a concept for 'design for longevity'. This concept of collaborative consumption can make an impact on increasing sustainable buying behavior among consumers, thus enhancing their role in social responsibility. 'Design for longevity' also needs to focus on caring for the garment. Fashion businesses must be clear in instructing consumers in the appropriate way to handle garments. Oxfam's vintage guide produced an information guide to support the care of vintage clothing, by providing tips and advice on general care of garments (this includes, specific instructions for washing, drying, and ironing, storing, etc. [38]. This also includes altering care procedures for garments to achieve lower imprints on the ecology, such as reducing laundering, etc.

## *4.5 Design for Sustainability in a Closed Loop*

Re-manufacturing, recycling, reverse logistics, and redesigning are important aspects of SBD, essential in completing or closing the loop in supply chain operations.

After consumer use, the life of fashion apparel is not yet over. Some clothes and textiles are taken to recycling clothes banks operated, for example, by the Salvation Army (which also has door-to-door collection), Traid, Oxfam, or many other members of the Textile Recycling Association.[35] Of all the collected textiles in the world, about 50 % is reused and 50 % recycled. Using recycled textile material in the manufacturing process can considerably reduce carbon emission in comparison with the fiber production which would otherwise have used virgin materials. A study done by the University of Copenhagen in 2008 revealed several benefits of reuse of textile materials in the production of new textiles. Just 1 kg of recycled clothing can reduce carbon emissions by 3.6 kg, water consumption by 6,000 L, use of fertilizers by 0.3 kg, and pesticide use by 0.2 kg.[36]

An example of this is the Stena Metall Group's[37] research and development projects on recycling of apparel with metal parts, such as jeans with zippers and rivets or a bra with metal bracket. Through pyrolysis, textiles break down into gas which cools and forms oil which can be recovered, while the metal parts are collected as they remain intact. The problem with this process is that it is expensive; moreover, numerous material types and extensive use of fiber blends can produce a significant bottleneck [1]. Even though recycling is a considerable challenge,

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[34] http://www.wrap.org.uk/sites/files/wrap/Design%20for%20Longevity%20Report_0.pdf

[35] http://www.textile-recycling.org.uk/

[36] http://www.bir.org/

[37] http://stenarecycling.pl/en/Innovative-recycling/Research-and-Development/

several companies have nevertheless voluntarily chosen to give customers the opportunity to return the garment for reuse and recycling, such as H&M's Garment collecting[38] and Klättermusen's deposit system.[39] H&M's initiative of Garment collecting involves customers gathering leftover clothing from different brands in the 53 markets wherein H&M operates. Any revenue raised from the project will be invested in technology for recycling processes in the textile and social projects. Patagonia, on the other hand, offers a product line of fleece which can be recycled from used PET bottles. Another project in 2009 on recycling favored by EU was textile for textile (T4T),[40] an initiative to guarantee better sorting techniques for upgrading textile recycling. With these process innovations and design aspects, the environmental threat posed by the clothing industry's short life cycle is hoped to become reduce. Recycling also demands technology innovations which may provide a means to extract longer fibers from used textiles (a mode of product design). Similar to this was the 1990 Recycling of Carpet Materials (RECAM) project which has developed a closed loop system for recycling carpet materials and has been a huge technological success; however, it failed to be profitable and hence economically sustainable. However, recycling reduces energy used in production and hence is economically viable. In recycling, the amount of waste from incineration of cotton is significantly lower than the waste generated from the production of electricity to run the recycling operations [1].

Reuse is another way to close the loop. Clothes worth nearly 1 billion USD end up as second-hand clothing every year which is mostly baled and resold in the third world. The second-hand clothes trade in developing countries creates a type of employment, leading to social sustainability [3], incorporating notions of supply chain redesign. There has been a growth in online sales or exchange of garments through retailers such as eBay and Gumtree, which has helped to increase the flow and accessibility of second-hand clothing. A popular event was organized by Marks and Spencer (M&S) in association with Oxfam called 'Shwopping'[41] in 2012, encouraging consumers to donate clothes for reuse or remodeling.

Reverse logistics from a green perspective also manages the flow of products intended for remanufacturing, recycling, or disposal, and utilizes resources more effectively [36]. More and more companies are starting to become involved in the issue of reverse logistics, as it not only provides a positive environmental impact, but also economic benefits [74]. This calls for process and supply chain designing perspectives to devise the remanufacturing processes of reusable parts in reverse logistics [40]. This incorporates the ideas of vehicle routing for re-cycling of end-of-life (EOL) goods to ensure extended product responsibility (EPR).

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[38] http://about.hm.com/en/About/Sustainability/Commitments/Reduce-Reuse-Recycle/Garment-Collecting.html

[39] http://www.klattermusen.se/companysoul.php?id=5&lang=EN

[40] http://textiles4textiles.eu/

[41] http://www.marksandspencer.com/s/plan-a-shwopping

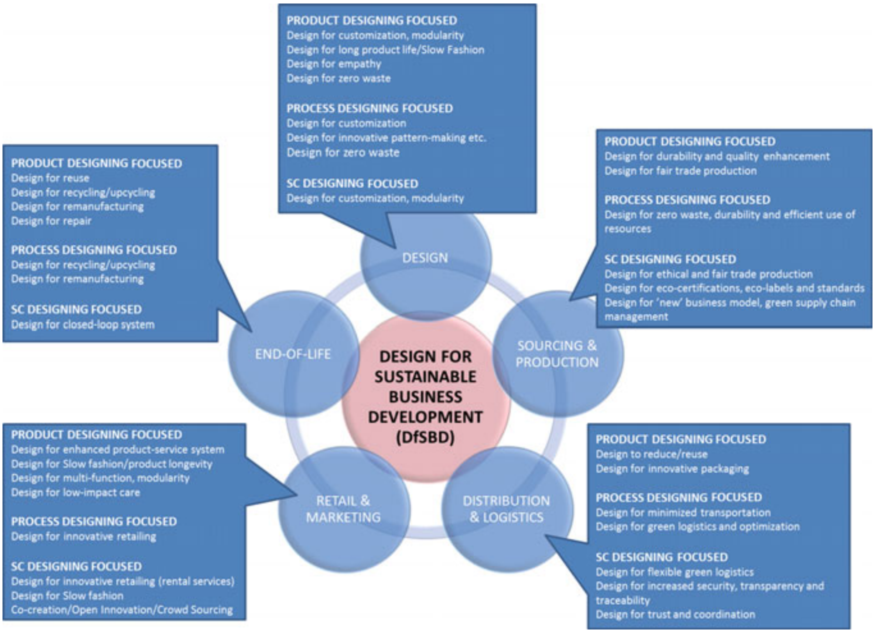


**Fig. 3** Model for design for sustainable business development (DfSBD)

The new strategy of upcycling has also seen prospective growth and business opportunities in the case of smaller fashion labels. Co-designing of garments by consulting the wearers can open up the design innovation process to lead to a greater input in remanufacturing, as was done by London-based fashion designer label Queenie and Ted.[42] This approach provides strong economic and environmental viability as upcycling means upgrading and adding value to a product which may otherwise have been discarded. This calls for 'new' product designing perspectives. Till now, upcycling in the fashion apparel industry has been mainly specific to couture garment designers, as this specializes in small runs of products.

Overall, there are several ways to construct a closed loop value chain and align the fashion industry towards a more sustainable one. These approaches can be by simple repairing worn garments to reuse them, by advanced recycling of wastes and discarded apparel, or by altering the clothing to upgrade it. From a designing aspect, this not only includes product design perspectives but also covers designing simple processes for reconsidering 'how to upgrade garments' which might otherwise be discarded.

[42] http://www.queenieandted.co.uk/Queenie_and_Ted/Home.html

## 5 Concluding Remarks

Some of the conclusions derived from this work are summarized below:

- SBD in the case of fashion businesses requires a holistic design approach, based on designing products, processes, and supply chains both independently and concurrently
- Such designing calls for applying a 3-DCE approach along all the value chain activities of forward loop: design and product development, sourcing and production, distribution and logistics, retail and marketing, and backward loop: recycling, remanufacturing, reverse logistics, and reusing
- An SBD model is supposed to lead to 'triple bottom line' sustainability within economic, environmental, and social perspectives
- An SBD loop does not have a beginning or an end. It contributes towards development of a circular business economy
- DfS along all the value chain activities contribute towards a DfSBD model (cf. Fig. 3).

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# Eco-friendly Coloration and Functionalization of Textile Using Plant Extracts

**Kartick K. Samanta, S. Basak and S. K. Chattopadhyay**

**Abstract** Chemical processing of textiles starting from preparatory processing to dyeing and finishing is important for its value addition in terms of fashion and function. However, these processes are water, energy, and chemical intensive and cause serious environment pollution. Recently, because of the increased global awareness of environmental pollution, demand for natural fiber-based textiles dyed with natural dye and finished with various bio-molecules is gaining academic, research and industrial importance. As a result, dyeing of textile has been carried out using various plant extracts because of to the presence of the inherent coloring compound. Some of these dyed textiles have also exhibited excellent UV protective functionality. Antimicrobial, mosquito repellent, well-being, and aroma functionalities have been incorporated into textiles using a number of plant extracts, such as neem, aloe vera, turmeric, arjuna, sandalwood, tulasi, jasmine, and eucalyptus oil. Cellulosic and ligno-cellulosic textile being highly flammable in nature, flame retardancy of such textiles has been improved using banana pseudostem sap (BPS) and spinach extract. The limiting oxygen index (LOI) of such treated fabrics is reported to increase to $\geq$30 as compared to the LOI value of <21 in untreated jute and cotton textiles, signifying the superior flame resistance property.

**Keywords** Coloration · Finishing · Natural fibers · Plant extracts · Textiles

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# 1 Introduction

Chemical processing of textiles is important as it adds value to them. In wet-chemical processing of textiles, industry consumes significant quantities of water, various chemicals, and auxiliaries. It also produces large amounts of effluent which is finally discharged into the water stream as pollutants contaminated with unused dyes and chemicals. Many of the chemicals used in textile preparatory processing, dyeing, and finishing are not environmentally friendly, and hence cause water, air, and soil pollution, resulting in adverse effects on flora and the fertility of agricultural land. Because of increased awareness of human health and hygiene in recent years, the demand for natural fiber-based apparel and home textiles dyed and finished with natural products, such as natural dyes for coloration, enzyme for bio-polishing, neem and aloe vera for antimicrobial finishing, and other plant bio-molecules for UV protective and flame retardant finishing, is gaining academic and commercial interest. Also, because of simultaneous concern on environmental pollution, climate change, and increased carbon footprint, efforts have been made to replace gradually part of the non-environmentally friendly synthetic chemicals and auxiliaries with eco-friendly plant extracts and bio-molecules. This helps to develop not only green textile products for the traditional market but also new products for the up-coming markets, while preserving the natural resources.

The present chapter reviews the eco-friendly textile coloration and functionalization of cellulosic, ligno-cellulosic, and protein textiles using plant extracts (molecules). It briefly discusses the extraction and characterization of plant molecules suitable for textile coloration. Many of the plant molecules extracted from seed, flower, fruit, and leaf have distinct colors, and hence can be used as a natural dye. Health and hygienic textiles meeting customer demand for fashionable textiles with a functional value are the key challenge needing to be addressed for sustaining the changing textile market. In this regard, antimicrobial textiles are important to protect the wearer from bacteria as well as to prevent the development of unwanted odor caused by microbial growth. The importance of antimicrobial, wellbeing, and aroma textiles using plant extract, such as neem, aloe vera, turmeric, arjuna, sandalwood, tulasi, and jasmine is also discussed in the present chapter. The chemistry of such active molecules present in the extract showing antimicrobial activity and producing wellbeing and aroma textiles have also been probed by evaluating their efficacy, qualitatively, and quantitatively. Many of the plant molecules showed antimicrobial activity of more than 90 % against both Gram positive and Gram negative bacteria. Brief descriptions of essential oils of lavender, thyme, sage, peppermint, and eucalyptus have been reported for their application in cosmetic textiles, skin nourishing and vitamin E finishing of textiles varying the application of various plant extracts in textiles as shown in Fig. 1.

The UV protective finishing of textiles is also very important in our daily life to cope with the substantial UV radiation reaching the Earth along with solar emission causing sunburn, sun-tanning, photocarcinogenesis, and even, skin cancer. Extraction and application of various plant molecules as UV blockers have been identified

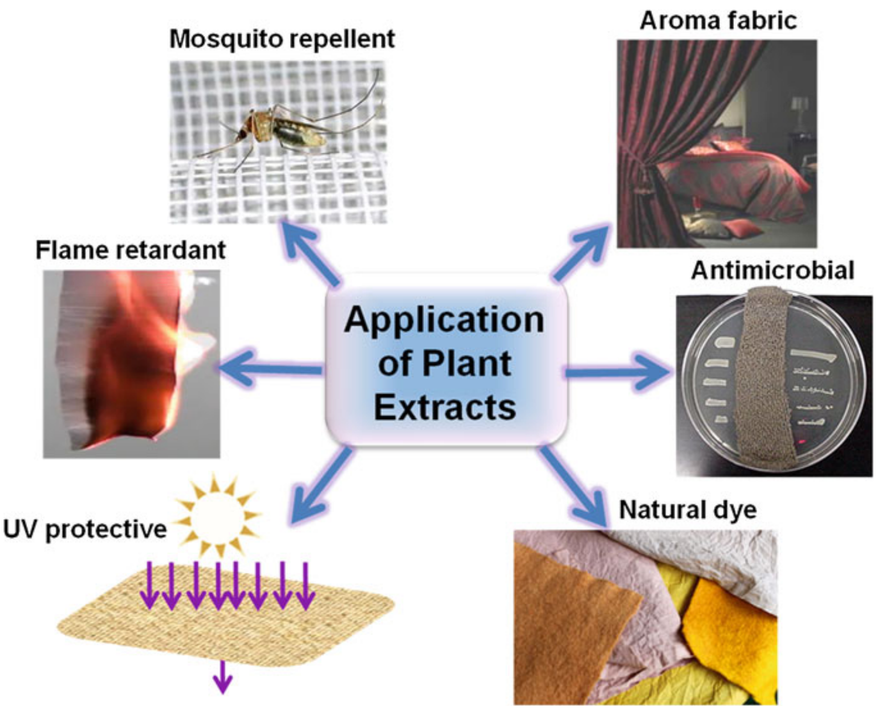


**Fig. 1** Applications of plant extracts in textiles

and applied on jute and cotton textiles. Plant extracts such as manjistha, annatto, marigold, spinach, and banana pseudostem sap (BPS) are used to impart a high degree of UV protection in textiles with UPF ratings of ≥50. Flame retardant finishing of textiles is important for application in home furnishing, hospitals, railways, and aircraft. It is also very important for the workers, who are directly engaged in the oil, gas, and petroleum industries. In many such applications, cotton textiles are used because of their comfort properties associated with high moisture retention and good moisture management properties. However, being a cellulosic fiber, cotton catches fire readily, which is difficult to extinguish. Flame retardant finishing of cellulosic (cotton) and ligno-cellulosic (jute) textiles using agricultural waste, such as BPS, has been achieved and reported. Similarly, flame retardancy functionality was also observed when cotton textiles were treated with spinach extract.

## 2 Eco-friendly Textile Processing and Finishing Using Plant Extracts

Because of the stringent pollution norms and government legislation which has come into force during the past three to four decades, various technologies have been developed and implemented to address water pollution. They are (1) low material to liquid processing, (2) spray and foam finishing, (3) use of enzymes, (4) digital printing, etc. More recently, in the last two decades, a few more technologies have been identified and explored to reduce the pollution and/or make the textile processes more energy and cost-efficient, such as use of (1) infrared and radio frequencies for drying/heating, (2) ultrasound energy in dyeing, (3) super critical carbon di-oxide for dyeing, (4) plasma technology for waterless processing, (5) UV and laser treatment for functional finishing, and (6) natural dyes for textile coloration. In spite of such developments, textile chemical processes remain energy and water intensive, in addition to associated pollution with the use of various non-environmentally friendly chemicals. The chemicals and auxiliaries used in processing and dyeing are caustic soda, acid, hypochlorite, size, stain removers (carbon tetrachloride), and unfixed dyes. Many of the textile chemicals and auxiliaries contain suspended solids and produce large quantities of effluent with low BOD and COD values. Some synthetic dyes, such as azo, are harmful to human skin and have a carcinogenic effect. Similarly, in polyester dyeing, toxic chlorinated compounds are used as carriers, and formaldehyde-based chemicals are used in crease-recovery finishing. In antimicrobial, rot resistance, and moth-proofing finishing, chlorinated compounds, such as pentachlorobenzene, hexamethylene biguanide, and quaternary ammonium compounds are used. Recently, various metal nanoparticles, such as silver (Ag), ZnO, $TiO_2$, and CuO have also been tried for similar applications; however, their interaction with humans, animals, and plants is still not clearly understood. In UV protective finishing, phenyl salicylate-, benzophenone-, and benzotriazole-based chemicals are used. The phosphorus- and nitrogen-based chemicals, such as diammonium phosphate, Pyrovatex, urea, and melamine formaldehyde are used in flame retardant finishing of textiles. Many of the present day chemicals and auxiliaries used in textile processing have an adverse effect on the environment. In the past, however, efforts have also been made to develop environmentally friendly synthetic dyes, chemicals, and auxiliaries, such as BTCA and DMeDHEU for crease recover finishing, halogen free flame retardant agents, enzyme-based desizing and bio-polishing, $H_2O_2$ bleaching, and silicate and ammonium sulfamate-based flame retardant agents, etc.

Because of increased global awareness of environmental pollution, climate change, carbon footprint, health, and hygiene over the last decade, demand for organic/green/eco-friendly textile products is growing exponentially. A number of research groups are working on the development of sustainable green textile processing chemicals, suitable application method, and the design of green textile products. In this context, application of various plant-based extracts (molecules) for textile coloration and functionalization, such as UV protection, antimicrobial, flame retardant, and mosquito repellent, are becoming popular and are discussed below in detail. Textile chemical processing using plant extracts helps to develop eco-friendly textile products, simultaneously adding value to agro-waste or residue.

## 3 Textile Coloration Using Plant Molecules (Natural Dye)

India has been the world leader in textile dyeing and manufacte since the times of the Indus Valley civilization of 3000 B.C. Dyeing of textiles with natural dyes was an ancient craft of India and these textiles were exported till the end of the nineteenth century. However, natural dyes received a setback from the growing research in Europe, which resulted in the availability of synthetic alizarin and indigo. Later on, because of the development of various synthetic dyes, such as reactive, direct, disperse, acid, basic, vat, sulfur, naphthol, and metal complex, and their better performance in terms of shade depth, number of shades, color consistency, economy, and wash durability on both the natural and man-made fibers, synthetic dyes became very popular and started replacing natural dyes. At present mostly synthetic dyes are used for textile coloration. However, for health, hygiene, and eco-concern reasons, in recent times natural fiber-based textiles dyed with natural dyes are once again in demand. In the last two decades, a number of natural dyes have been explored to enhance performance related to wash durability, light fastness, shade, etc., and applied to various textiles meant for apparel and home furnishing. A country such as India has the highest potential for extraction and application of natural dyes, as the country is blessed with a number of plant varieties which can be used as sources for natural dyes.

Chemically, natural dyes have different groups, such as polymethine, ketone, imine, quinines, anthraquinones, naphthaquinones, flavones, indigoids, and chlorophyll. Based on their application, natural dyes are classified into two groups: (1) substantive dyes and (2) mordant dyes. Dyes such as indigo and turmeric are termed substantive dyes, as they can be applied to cellulosic textile directly, i.e., without usage of mordant. On the other hand, dyes such as manjistha, annatto, and babool are termed mordant dyes, as they can only be applied by usage of an appropriate mordant. Dyeing of textiles with natural dyes is a multistep process involving the extraction of dyes, followed by mordanting and dyeing. Natural dyes can be extracted in an aqueous medium in acidic or alkaline condition, depending on the stability of the dye at different pH. Mordants are metallic salts which can be fixed to the fiber and can be combined with the dyestuff. Generally, metal salts and tannin are used as mordants in textile coloration with natural dye. The most commonly used mordant for cotton is alum (aluminum sulfate) and the others are ferrous sulfate, chrome, stannous chloride, and copper compounds. As few of the mordants contain heavy metals, the bio-mordant has also been developed. Chattopadhyay et al. [5] reported the natural dyeing of jute using pomegranate rind, myrabolan, and sumach as bio-mordant, as these molecules are rich in tannin. Further, natural Lodhra (Symplocos racemosa), Kenduka (Diospyroseebenum) and fruit extracts of Haritaki (Terminaliachebula) can also be used as bio-mordants. Mordanted fabrics were dyed at boiling point for 40 min with a suitable mixture of natural dyes. Some of the natural dyes obtained from different parts of the vegetable/plant are given in Table 1. Currently, around 500 vegetable dyes exist and the majority of them have been reported suitable for natural coloration. Natural

**Table 1** Common natural dyes and their sources

| Part of plants | Dyestuffs |
|---|---|
| Root | Madder, turmeric, onions, beetroot |
| Bark of trees | Sappan, khair, sandalwood |
| Leaf | Indigo, henna, coral jasmine, lemon grass |
| Flowers | Marigold, dahlia, tesu, kusum |
| Fruits | Myrobalan, pomegranate rind, latkan |

dyes with different colors obtained from various plants along with their application procedure are described below.

## *3.1 Yellow Color Natural Dyes*

As far as yellow color natural dye is concerned, turmeric obtained from the rhizomes of the plant Curcuma longa is the most popular for textile coloration. Here, the dye molecule is diaroylmethane which can be used directly (without mordant) on cellulosic, silk, and wool fabrics. Fruit pulp of annatto contains two major carotenoid (colorants), bixin and norbixin, which also produce an orange-yellow color on textiles. However, the fastness properties of such dyes are not up to the mark. In this regard, Chattopadhyay et al. [5] studied the natural color properties of annatto with the help of various bio and synthetic mordants on jute fabric. Coral jasmine flowers also contain the carotenoid pigment nictanthin which can be utilized for yellow, orange, and brownish yellow shades. Dolu roots and rhizome extracts can be used to dye wool and silk fabrics yellow without use of mordant. In this regards, copper and iron mordant delivered brown and olive green shades, respectively, along with good fastness properties. The orange flower of Tesu (Butea monosperma), onion (Allium cepa) skins, and marigold (Tagetus patula) have also been explored to produce a yellow color on cellulosic textiles. However, in all these cases mordanting was essential. In dyeing of cotton with marigold flower and pomegranate (Punica granatum) peel on the pre-mordanted fabric, the dyed fabric showed adequate antimicrobial properties besides the yellow color [14, 17, 29]. Samanta and Konar [35] and Samantha et al. [36] has studied the effect of single and double mordanting of bleached jute fabric using harda (myrobalan) and metallic salts as mordants, followed by natural dyeing with tesu (extract of palash flower petals). It was found that 20 % myrobalan followed by 20 % aluminum sulfate had most potential as a double pre-mordanting system, when the important textile properties and color strength of the dyed fabric were being established. The effect of dyeing temperature, time, and pH on the color strength has also been reported. It was found that dyeing at a pH of 11 showed good color strength as well as rubbing and washing fastness. Further, the optimized condition for dye extraction was 60 min with 1:20 MLR and a pH of 11. A dyeing temperature of 90 °C under alkaline condition (pH 11) was the best dyeing condition. Pan et al. [26] studied the dyeing of bleached jute fabric with jackfruit leaf extract (Artocarpus intergrifolia) in the presence of hydrated salt of ferrous sulfate as a mordant. The mordanted fabric after dyeing showed an attractive light brown to light mustard oil shade along with a satisfactory level of fastness. Indeed, ferrous sulfate was optimized at 1 % for mordanting to obtain a brighter color with high fastness properties. Gupta and Laha [9] reported that tannic acid and tartaremetic mordanted cotton fabric can be dyed with Berberin from Berberis aristata roots, bark, and stem extract. Here, the coloring matter is alkaloid berberine which acts as a basic dye. Not just for the cellulosic textile, this particular dye can also be used in silk and wool dyeing.

### *3.2 Red Color Natural Dyes*

Natural red color on cellulosic textiles has been obtained without any mordanting of the fabric. In this regard, Carthamin from safflower (Carthamus tinctorious) petals and bark extracts produced a strong red color with good fastness. Root extract of ratanjot (Onosma echioides) also produced a similar color caused by the presence of Carthamin. Chattopadhyay et al. [5] studied the dyeing of bleached jute fabric with the natural red color of manjistha and ratanjot in the presence of four different mordants. It was observed that the double pre-mordanting with bio and chemical mordants produced uniform color on jute fabric. Coloring matter from the roots of Indian madder (Rubia cordifolia) and European madder (Rubia tinctorium) also provided a red color. However, for these dyes, use of mordants (metal salts) was essential. Active coloring molecule of Indian madder is mainly anthraquinone-based, whereas for European madder, it is mainly alizarin-based. Further, in both of these madders, color could be changed by changing the mordants. For example, the Indian madder produces red and pink colors with alum, a violet color with iron, and a purple color with a mixture of alum and iron. All these dyed fabrics showed adequate light and wash fastness. Chay root (Oldenlandia umbellate) can be used to produce a deep red color on cotton fabric caused by its alizarin-based colorants. Lac dye, which is obtained from the resin secreted by the Laccifer lacca, was used in earlier days for dyeing of wool and silk fabrics. This natural dye has recently been applied to chitosan-pretreated cotton fabric to produce a violet color.

### *3.3 Blue Color Natural Dyes*

Indigo, the most common and best known example of natural dye which provides a blue color, is obtained from the plant belong to the genus Indigofera. Indigo has all-round good fastness properties, and is mostly used for the production of denims. It provides a blue color with a reddish tone caused by the presence of trace amount of red coloring indirubin matter. Samanta et al. [36] used Woad (Isatis tinctoria), a variety of indigo mainly found in Europe to produce a blue color in cellulosic fabric with good fastness properties.

## *3.4 Black and Brownish Natural Dyes*

Plant extracts containing high amounts of tannin generally produce brown to black shades. Catechu (Acaica catechu) produces a dark brown color in cotton fabric. Naik and Maheswari [24] reported that, apart from tannic acid, it also contains catechin and quercetin. These molecules are also responsible for color production besides being used as an astringent and antioxidant. Logwood, harda, and custard apple also belong to these categories. Samanta et al. [36] reported that tannin-rich brown to black color dyes are suitable for coloration of both cellulosic and protein fibers.

## *3.5 Dyeing of Textile with Natural Dyes*

Wool and silk, being protein fibers, contain amine and carboxylic acid groups. Unlike silk, in the aqueous solution of wool there is no net charge because of the presence of an equal number of positive and negative charge molecules. On the other hand, silk in aqueous solution contains more positive amino groups and showed an iso-electric point of 5. Therefore, selection of mordants, dyeing time, temperature, and pH during coloration plays critical roles in natural dyeing. Tannin-rich materials such as harda and gall-nut, and metal salts such as alum, aluminum sulfate, and ferrous sulfate are suitable for mordanting of protein fibers. After mordanting at 80–90 °C with 5 % mordant for 30 min, the fabric can be dyed at acidic pH at 60 °C for 30 min with the MLR 1:25.

Application of natural dyes to ligno-cellulosic textiles was found to be better, particularly on jute fabric, by the double pre-mordanting method. Approximately 10–20 % harda treatment followed by 10–20 % alum treatment was found to be effective, followed by dyeing at 90 °C for 90 min at an alkaline pH of 11–12. After dyeing, the samples were washed and dried at 60 °C for 15 min to study the fastness properties. To improve wash and light fastness, 2 % cationic dye fixing agent, such as tartaremetic, was also attempted.

Synthetic fibers, such as nylon and polyester, can be dyed with babool bark extract by the cold pad batch method. As discussed earlier, a wider range of shades is possible to produce on the textile by altering the mordants. Lokhande and Borugade [20] studied the application of natural dye on nylon fabrics in an open bath, and with the high temperature high pressure (HTHP) process. It was found that, while babool dye extract could be suitably applied in a cold pad batch method, other dyes such as catcheu, pomegranate rind, and turmeric could be applied by the HTHP process.

## 4 Health and Hygienic Textile Using Plant Molecules

A healthy and hygienic textile with due customer satisfaction is the key challenge to be addressed to meet the customers' needs. Presently, a large number of antimicrobial agents are available on the market to make the textile antimicrobial, antibacterial, and antifungal; however they are mostly synthetic chemicals. In the last two decades, because of the rapid growth of nanoscience and technology, various metal nanoparticles have been synthesized and applied to natural as well as synthetic textiles to impart non-durable to durable antimicrobial functionality. Some of the well-explored nanoparticles for textile use are silver (Ag), ZnO, $TiO_2$, and CuO. Though they are very effective as an antimicrobial agent, their interaction with the human body, and their impact on plants and animal bodies are still not clearly understood. As many of the aromatic and medicinal plants have active antimicrobial molecules, they have been explored for antimicrobial finishing of textiles in an eco-friendly manner. The advantages of using such plant-based antimicrobial agents are eco-friendliness, bio-degradability, and economy, as they are produced from renewable and diversified sources of plants and herbs. Plants containing phenols and oxygen-based derivatives are considered as secondary metabolites, which also act as antimicrobial and insecticidal agent. It has been reported that tannins, which is naturally occurring as polyphenols, are also responsible for the antibacterial properties of natural dye. Herbal and plant products such as chitosan, aloe vera, neem, tea oil, eucalyptus oil, and tulsi leaf extracts showed excellent antimicrobial activity on various textile substrates. Chitosan is an effective natural antimicrobial agent derived from chitin. It contains reactive amine groups which can easily react with the negatively charged bacterial cell wall and destroy it. Chitosan citrate has also been utilized for durable press and antimicrobial finishing of cotton textile. Neem-chitosan nano-composite was used for cotton textiles to make them antimicrobial Rajendran et al. [30]. Thilagavathi and Kannaian [47] found that neem, pomegranate, and prickly chaff flower contain the active antimicrobial ingredient which can control the growth of microbes. Neem leaves contain limonoid-based azadirachtin, sallannin, and nimbin, which are responsible for good antimicrobial and insecticidal textile products. A recent patent on microencapsulation of neem oil and application on cellulosic and cellulosic blended textiles showed good antimicrobial efficacy. Joshi et al. [12] reported the antimicrobial property of polyester/cotton blended textile with the neem seed extract. The neem seed extracted molecules were applied onto cotton with glyoxal, aluminum sulfate, and tartaric acid by a two-dip two-nip method in a padding machine, and the treated fabric showed excellent antimicrobial activity against both Gram positive and Gram negative bacteria. The treatment was found to be durable to five washes. Hena and juglone obtained from the walnut contain naphthaquinone which acts as an antibacterial and antifungal agent. Curcumin has been used as a natural dye as well as an antibacterial agent for woollen textiles. Recently, aloe vera gel has been applied to cotton textiles to improve the antibacterial activity against Staphylococcus aureus bacteria [11, 13]. The specimens treated with 5 g/L aloe gel showed excellent antimicrobial activity in terms of high reduction in the number of colonies and a clear zone of bacteria inhibition. The imparted antimicrobial finish was durable to 50 washing cycles (slightly decreased to 98 %). The findings in this study can be used to develop hygienic eco-friendly cotton textiles. Tulsi is very popular as a medicinal plant in India from ancient times, and has good potential to cure or resist many infections/diseases. Tulasi leaf (Ocimum sanctum) extract contains caryophyllene, phytol, and germacrene antimicrobial compounds and its efficacy was studied on cotton textiles after methanol extraction. Tulasi herb dyed bed sheet (fabric) showed good antimicrobial properties and has been used to cure patients suffering from chest cold, cough, itchiness, and mucus problems. Bhatt et al. [39] applied tulasi leaves and pomegranate extract to cotton textiles by different methods, viz. direct application, cross-linking, and microencapsulation. It was found that methanol extract and pomegranate molecules showed a 99.9 % reduction in bacterial growth on cotton fabric when applied by direct pad dry methods. However, as expected, the microencapsulation and cross-linking methods of application showed better results in terms of wash durability (15 wash durable) with a little decrease in Gram negative bacterial growth to 94 and 87 %, respectively for tulasi and pomegranate extracted molecules. Turmeric, cumin, clove oil, karanga, cashew shell oil, and onion skin treated cotton textiles showed good antibacterial properties. These kinds of fabrics can also be used as medial textile, well-being, and casual apparel. Recently, Ahamed et al. [1] has developed a new method of preparing antimicrobial textiles, i.e., by herbal coating in nano form (neem extract nanoparticles). Nano herbal extract treated textile was found to show excellent antimicrobial activity against both Gram positive and Gram negative bacteria. It was interesting to note that the finish was durable to 20 washing cycles, whereas only neem extract treated fabric was durable to 10 washing cycles. Gupta [7] has investigated the antimicrobial activity of cotton fabric treated with a tannin-rich extract of the Quercus infectoria (QI) plant in combination with different mordants, such as alum, copper, and ferrous sulfate. Only QI extracts (12 %) showed antimicrobial activity (40–60 %) against both Gram positive and Gram negative bacteria. After the application of the same plant extract to cotton textiles with 5 % alum and 1 % copper sulfate, the antimicrobial activity was found to increase significantly to 70–90 %. However, the treated cotton fabric lost antimicrobial activity completely when the extract was applied with ferrous sulfate mordant. It might be because of the fact that tannin, i.e., an *O*-phenolic compounds present in the extract, had disrupted the bacterial cell integrity. Iron can easily bind with tannin groups and damage its antimicrobial activity. It was found that the samples treated with only QI completely loses antimicrobial activity after five washing cycles, whereas the samples treated with mordant could retain antimicrobial activity for up to five washing cycles. Figure 2 shows that the QI treated fabric (12 %) has no bacteria growth, whereas in the untreated sample a significant amount of bacterial growth is visible.

Ramya and Maheswari [32] studied the antimicrobial activity of bamboo/cotton blended fabric treated with clove extract by a direct and a microencapsulation method. Both procedures showed good antimicrobial activity and wash durability.

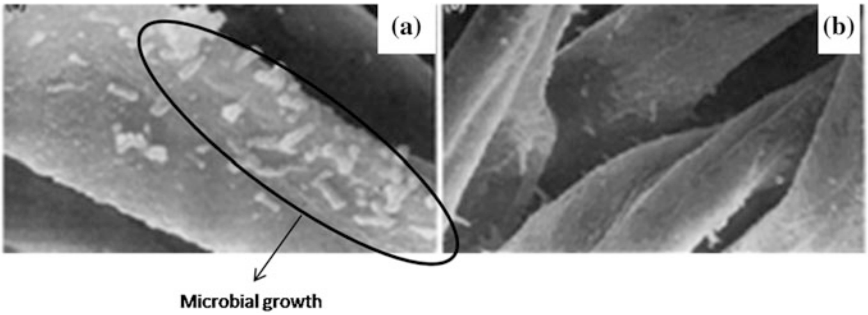


**Fig. 2** Bacterial growth in **a** untreated and **b** antimicrobial finished cotton fabrics [7]

However, microencapsulation treated fabric showed better anti-fungal property and was also durable to 30 washing cycles compared to 10 washing cycles for the direct extract treated sample.

## 5 Mosquito Repellent Textile Using Plant Molecules

Health, hygiene, and safe lifestyle textiles are important for human beings to work with maximum efficiency. Mosquitoes are attracted to people because they emit carbon di-oxide, lactic acid, odor, and heat. Mosquito repellent chemicals help human beings to prevent serious diseases such as dengue and malaria. Mainly synthetic chemicals are available on the market to make the textile mosquito repellent and, in this respect, *N,N*-diethyl-3-benzamide (DEET) is the most popular. Besides DEET, pyrethrene- and permythrene-based chemicals can also be used for similar applications, although they are toxic in nature. Therefore, in the last decade, research has been carried out to develop eco-friendly chemical formulations for mosquito repellent textiles. Medicinal plants, such as tulasi, neem, notchi, lemon grass, citronella, keelanalli, cinnamon oil, eucalyptus oil, turmeric, pine oil, garlic, and peppermint oil can be used as environmentally friendly mosquito repellent chemicals. In this context, Banupriya and Maheswari [3] has used rosemary leaf extract for preparing mosquito repellent cotton fabric with 40–60 g/L at pH 5–6. The fabric was dried at 130 °C followed by curing at 160 °C for 15 min and the sample showed good mosquito repellent efficacy. As expected, just as other finishes using plant molecules, this finish also suffers from the wash durability for their direct application. On the other hand, when the active molecules were microencapsulated for controlled release, durability was found to improve. Similarly, Anitha et al. [2] applied lemon grass extract oil to the polyester fabric by the microencapsulation technique with ionic gelation. Microcapsules prepared with aqueous lemon grass oil extract showed better efficiency as a mosquito repellent (92 %) compared to the methanol extracted lemon grass oil microcapsules (80 %). Specos et al. [42] studied the mosquito repellency of microencapsulated citronella oil on cotton fabric and the treated fabric showed 90 % mosquito repellency even after 3 weeks of treatment. Ramaswamy et al. [31] reported the development of mosquito repellent textiles using Vitex Negundo-loaded nanoparticles. In this study they applied a mixture of nanoparticle of V. Negundo, 5 mL calcium chloride, 95 mL sodium alginate, and 25 mL chitosan to the bleached cotton fabric. Two excito repellency test chambers were performed for measuring the mosquito repellency. Data were taken at 1-min intervals for 30 min and it was found that the direct Vitex Negundo treated cotton fabric showed 68 and 18 % mosquito repellency after 5 and 20 washing cycles, respectively. In contrast, the microencapsulated fabric showed better mosquito repellent efficiencies of 76 and 64 %.

## 6 Well-Being Textiles

Textiles used for making medicinal fabric should be 100 % organic, and completely free from synthetic chemicals and toxic irritants, either in the process of making it or in coloration and/or value addition. This type of fabric should also be biodegradable. As these materials would be free from synthetic chemicals, they are dyed with natural dyes and specific value addition is carried out using medicinal plants and herb extracts, so that it can deliver specific health/wellness benefits. Different types of diseases which can be partially or fully cured by the well-being textiles are arthritis, osteoarthritis, rheumatism, dermatitis atopica, dermatitis from contact, allergies, hypertension, tunnel carpal diseases, rheumatics, diabesis, and psoriasis. Diseases such as asthma, blood pressure problems, and even some forms of cancer can also be cured by wearing these kinds of textiles which have some medicinal ingredient molecules [51]. Different types of wellness which can be accomplished out of this clothing are immune boosting, weight loss, energy giver, blood purifier, skin shining, and reduction in inflammation and respiratory disorders. Chronic medical diseases, such as elevated blood pressure in the arteries, can be reduced by the bark of the Arjuna tree, which contains zinc, calcium, and magnesium minerals, flavones, and co-enzyme Q-10 Terminalia Arjuna [45]. These compositions help to promote effective cardiac performance by regulating blood pressure and cholesterol levels. It also protects the heart from stress, nervousness, and weakness. Sandalwood oil extract helps in fighting stress, irritation, and high blood pressure with its mild fragrance and soothing effect. Diabetes, in which a person has high blood sugar as the body does not produce enough insulin, can be treated with crude extract of shoe flower leaves [22]. Touch me not (Mimosa pudica) leaf and root extracts and champa flower bud extract also help in controlling the blood sugar level in a person by slowing the rate of starch to glucose breakdown Gupta [8]. On the other hand, rheumatoid arthritis, a painful disease of guts and joints, can be eased by treatment of oleation, sweating, and heating. Steam bath relief to the arthritis patient showed the importance of herbal extracts being in contact with the skin. Nirgundi leaf extract is also very effective in controlling joint pain and inflammation. Different molecules extracted from all the parts of the drumstick tree were found to be effective in maintaining body weight reducing the arthritic index score and oxidative stress [50]. Therefore, a suitable combination of these herbs can be used in preparing medicated textiles required for arthritic patients. Ayurvedic experts and physicians advise us to use medicated plant molecules treated cloth during sleeping or meditation. This is because during rest and peaceful activities, medicated textiles help to restore the balance in the body and strengthen the immune system. Because of these advantages, medicated textiles are often used in making bed coverings, undergarments, towels, meditation clothes, sleepwear, and other clothing which stays close to the human skin to enable these active ingredients of herbs to be easily absorbed through the skin.

### *6.1 Aroma Textiles*

Home textiles, such as bed linen, pillow covers, and bed sheets do not remain fresh because of their repeated everyday use. Apparel, intimate garments, sportswear, T-shirts, socks, and shoes are constantly exposed to sweat, providing favorable conditions for microbial growth resulting, in a foul smell. Because of the continuous exposure of textiles in hot and humid acidic to alkaline wet environments, the life of products also decreases in addition to the health and hygiene issue. Therefore, if plant extracts (molecules) with fragrance/aroma can be incorporated into the textile product, it gives a pleasant, fresh, and energetic feel to its users. Aroma is mostly composed of oil materials extracted from fruits, flowers, herbs, and plants. During use these molecules get absorbed into the bloodstream and improve blood circulation, inhalation, throat, and lung. They also have a positive effect on the immune, nervous, and psychological systems of human beings.

The herbs generally used in aroma textiles are sandalwood, jasmine, lavender, champa, etc. These herb oil treated fabrics have good aroma/fragrance properties, and also provides an eco-friendly, healthier, fresh feel. For example, sandalwood contains various oils such as santalols, fusanol, santene, and teresantol which help to deliver a soft, warm, and balsamic aroma smell to the treated fabric [39]. In addition, it nourishes the skin and smoothes facial lines and wrinkles. Jasmine contains special types of aromatic chemical, such as benzyl acetate, linalool, benzyl benzoate, and geraniol, which give off aromas. The jasmine smell present in the fabric is non-toxic, anti-depressant, and antiseptic to the wearer. Lavender contains essential oils, such as linalool, linalyl acetate, limonene, and cineole, and the treated fabrics not only give off a fresh aromatic smell but also help to nourish human skin. Some other benefits are cell regeneration and prevention of scarring and wrinkling of the skin. However, the main limitation of these kinds of aroma finished textiles which hinders their successful commercial use is the lack of repeated wash durability. This is because most of the fragrances are oil molecules which do not form a chemical bond with cellulosic or other textiles. Because of upcoming potential markets, in the last decade considerable research has been carried out on how to improve the wash durability of aroma textiles. Vasanth Kumar et al. [49] studied the fragrance finishing of textiles using lavender and aloe vera aroma in the presence of non-ionic binder. It has been reported that aloe vera finished fabric showed better durability to laundering in terms of stability of fragrance. In a similar study, the fragrance was encapsulated in a polymer capsule and applied onto cotton fabric with a UV resin binder [18]. It was observed that, during the UV initiator curing of resin, the loss of aroma molecules was much less compared to that with thermal curing. The aroma-containing capsules were applied by a padding method with a mixture of 0.72 % initiator and 5 % capsule, and wet pick of 86 % followed by drying and UV curing. It was observed that when the capsules were not cured, it could withstand only five washing cycles. On the other hand, the aroma finished textile could retain the fragrance for up to 50 washing cycles compared to only 25 washing cycles, when initiator was not used. Thilagavati and Kannaian [47] has reported the application of methanolic extract of germanium leaves (10 %) onto cotton fabric by microencapsulation method using natural gum acacia as a shell material. Two methods were explored: (1) first germanium extract was encapsulated by a coacervation technique followed by spray drying into powder, and (2) core and wall materials were spray dried to get the microcapsules. The performance in terms of their wash durability is given in Table 2.

## 6.2 Cosmeto-Textiles and Vitamin E Finishing

Special types of cosmeto-textiles have been developed by merging knowledge of cosmetics and textiles. These fabrics have been used to produce slimming, moisturizing, perfuming, and energizing effects, in addition to healthiness and comfort to the skin [38, 46]. Generally, synthetic organic and inorganic products are used for the preparation of cosmetic textiles. However, for the last two decades, researchers have been trying to use animal and plant extracts in the making of cosmetic textiles. Animal derivatives such as chitosan, and polysaccharides from the exoskeletons of shellfish and crabs, are being used to provide moisturizing and revitalizing effects to the skin. Cosmetic textile ingredients have also been derived from plant-based essential oils, extracts, fruits, and flowers. The herbs used in medication for skin ailment patients, are turmeric, neem, eucalyptus oil, indigo, and sandalwood. These cosmeto-textiles show antimicrobial properties in addition to producing healthier skin. Further, indigo has antiseptic properties for healing burns and wounds of the skin and is also known as a good blood purifying agent. Sandalwood nourishes the skin, smoothing facial lines and wrinkles. Aloe vera herb dyed fabrics are very pleasant to wear, energy inspiring, and also have antibacterial, antiviral, wound-healing and anti-inflammatory properties [43]. Various extracted plant molecules, oils of citrus fruits, rose, pineapple, banana, cherry, and flowers like Jasmine have been utilized for aroma, refreshment, and relaxation effects to the skin. Aroma-based cosmeto-textiles for health and well-being are prepared from natural dyeing

**Table 2** Aroma retention capacity of cotton fabric by different methods

| Application process | Aroma retention after repeated washing (%) | | |
|---|---|---|---|
| | Without wash | 5 washes | 15 washes |
| Pure germanium extract | 100 | 32 | 0 |
| Microencapsulated germanium by coacervation spray drying | 75 | 80 | 15 |
| Microencapsulated germanium by spray drying | 82 | 85 | 25 |

by extracts of sandalwood, jasmine, lavender, champa, etc. These fabrics provide a pleasant aroma feel and fresh effect to human beings. Essential oils of lavender, thyme, sage, peppermint, and eucalyptus can be used in Ayurvedic dyeing of cellulosic and synthetic fabrics by microencapsulation techniques because of their aroma, moisturizing, and refreshing effects [48]. Some flowers, such as innone, citronella, and cidar, can be used in cotton fabric to develop cosmetic effects.

Vitamin E, normally known as "Tocopherol," belongs to the group of fat soluble vitamins. It is available in nature in various fruit and vegetable oils. This oil has good antioxidant and moisture binding properties. Human skin generates free radicals from sun and UV exposure which can damage the skin. These antioxidants act as radical scavengers because of their excellent antioxidant property. Therefore, these oils are very useful for preventing skin ailments and also help to protect the skin cells from oxidative stress [6].

## 7 Flame Retardant Textiles Using Plant Extracts

Cellulosic textiles catch fire readily, representing a serious health hazard in addition to the risk of damage to the textile products. Significant efforts have been made in the past to improve flame retardant properties of cotton textiles using various synthetic chemicals. The most popular and commonly used non-durable flame retardant chemicals available on the market are inorganic salts, borax and boric acid mixtures, di-ammonium phosphate, and urea (Patil and Desmukh [28]; Parikh et al. [27]). Phosphorus-based flame retardants along with nitrogen compounds are the most effective treatments reported so far because of their synergistic effects. In the last few decades, flame retardant formulations based on the phosphoros-nitrogen and halogen-containing compounds such as tetrakis phosphonium salts and N-alkyl phosphopropionamide derivatives have been developed and widely used for commercial applications [10]. However, when such formulations are applied onto cotton textiles, mechanical properties such as tear and tensile strengths are reduced and the fabric becomes stiffer. A few of these chemicals and their application procedures are hazardous, expensive, time-consuming, and energy demanding because of the high temperature curing process (Kei [16]). Efforts have therefore been made to develop cost-effective, environmentally friendly, and sustainable flame retardant chemicals using plant extracts. To date, plant extracts (molecules) have been utilized only for natural dyeing, antimicrobial finishing, well-being textiles, and aroma finishing. As some of the plants contain phosphorus and other minerals, in a recent study plant extracts have been utilized for flame retardant finishing of cellulosic and ligno-cellulosic textiles [4]. In this study, cotton and jute fabrics were treated with BPS, an agricultural waste, and spinach juice (SJ), a vegetable extract. These plant extracts are rich in phosphorus, nitrogen, and other metallic constituents. Further, BPS and spinach juice (SJ) are abundantly available in India, are produced from renewable sources, and are cost-effective compared to any other synthetic flame retardant chemical. The BPS was applied to pre-mordanted (5 % tannic acid + 10 % alum) cellulosic and ligno-cellulosic textiles by the pad dry method in alkaline condition, whereas SJ was applied directly to cotton textile without pre-mordanting. Any textile material having an LOI value of 21 or below is easily ignitable and burns rapidly in an open atmosphere. Samples with an LOI value of $\geq$21 are ignitable but burn slowly. When the LOI value reaches $\geq$27, the material is generally considered to be a flame retardant textile. It can be seen from Table 3 that untreated cotton and jute have LOI values of 18 and 21, respectively. On the other hand, both the BPS and SJ treated samples have LOI values of >27, and hence can be considered as flame retardant textiles. In Fig. 3 it can be seen that BPS and SJ treated fabrics have better flame retardant properties compared to the control cotton fabrics. The BPS treated cotton fabric burns with a flame for only 4 s followed by burning with afterglow (after the flame has stopped) for 900 s. Hence, the total burning time of a 250 × 20 mm sample is 904 s, whereas the untreated sample of the same size burned completely within 60 s with a flame. On the other hand, the SJ treated cotton fabric did not burn with a flame even when the sample was in contact with a flame for 10 s during ignition. However, the sample burns slowly with an afterglow. Because of the slow burning rate, the sample burned completely in 400 s. In all the treated samples, the available time either to escape from the flame zone or to extinguish the flame were much greater (904 s for BPS and 400 s for SJ) compared to only 60 s with the untreated sample. The total heat of combustion measured in term of gross calorific value (GCV) in the oxygen bomb calorimeter was found to reduce from 16.4 to 13.1 MJ/kg in the untreated to the BPS treated cotton fabrics, respectively. As far as the ligno-cellulosic jute fabric is concerned, the BPS treated sample showed an LOI value of 33 and the flame was observed only for 5 s. Similar to cotton samples, the burning rate was quite slow compared to untreated samples. Durability to soap washing of the flame retardant finishes imparted by BPS and SJ compounds in cotton textiles was also investigated. It was observed that the LOI value of the washed fabric decreased from 30 to 24 and 30 to 22 in the BPS and SJ treated cotton fabrics, respectively. This implies that the treated fabrics could retain some flame retardant functionality even after washing.

Figures 4 and 5 show the thermogravimetric (TG) curves of SJ and BPS treated cotton fabrics, respectively at a heating rate of 10 °C/min. The TG curves of the

**Table 3** Different flame retardant parameters of jute and cotton fabrics

| Flammability parameters | Control cotton | Control jute | Plant extract treated textile | | |
|---|---|---|---|---|---|
| | | | BPS[a] on cotton | BPS[a] on jute | SJ[a] on cotton |
| Add on (%) | – | – | 4.5 | 3 | 8 |
| LOI | 18 | 21 | 30 | 33 | 30 |
| *Horizontal flammability* | | | | | |
| Warp way burn rate (mm/min) | 75 | 62 | 7.5 | 15 | 10 |
| *Vertical flammability* | | | | | |
| Burning with flame time (s) | 60 | 60 | 4 | 5 | Nil |
| Burning with afterglow time (s) after flame stop | 0 (as completely burnt with flame) | 0 (as completely burnt with flame) | 900 | 600 | 400 |
| [b]Total burning time (s) | 60 + 0 | 60 + 0 | 4 + 900 | 5 + 600 | 0 + 400 |
| Observed burning rate (mm/min) | 250 | 250 | 16.6 | 24.8 | 37.5 |

[a] *BPS* Banana pseudostem sap, *SJ* Spinach juice
[b] Total burning time of fabric = burning with flame time + burning with afterglow time (after the flame stopped)

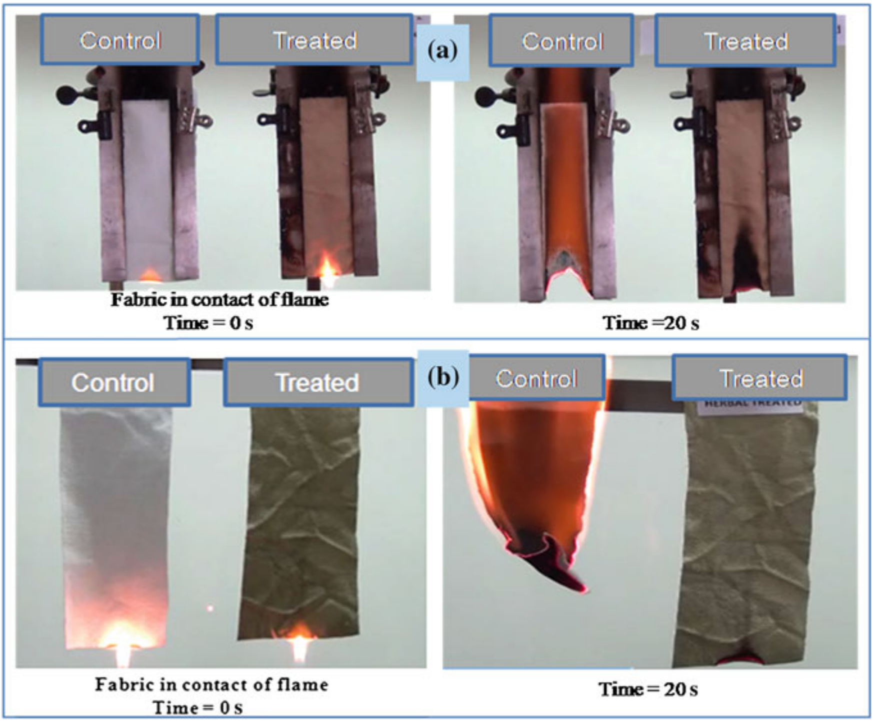


**Fig. 3** Status of **a** control and BPS treated, and **b** control and SJ treated cotton fabrics in contact with a flame [4]

control cotton fabric indicated three stages; in the initial stage, at temperature below 200 °C, the mass loss occurred mainly because of the removal of absorbed moisture from the fabric Mostashari and Mostashari [23]. However, the main pyrolysis occurred over the temperature range of 280–380 °C. Above 380 °C, dehydration and char formation occurred. In contrast, the TG curve of the control sample showed rapid decomposition at 300 °C and it lost around 98 % of its mass at 500 °C. The SJ and BPS treated samples started to lose mass, i.e., pyrolysis occurred from 215 to 225 °C, which are 65 and 55 °C lower than the degradation temperature of the control samples. In these pyrolysis stages, only 54 and 66 % mass loss were observed in the case of SJ and BPS treated samples, respectively. In the plant extract treated samples, the combustion temperature was found to reduce with the dilution of flammable volatiles by formation of more non-oxidizable molecules, such as $CO_2$ or $H_2O$, at a relatively low temperature. In the third stage of the TG curves, both the treated fabrics showed char formation. The quantity of char residue remained higher compared to the untreated samples, even at that higher temperature. A similar result was also observed for the BPS treated jute fabric. From the results, it can be said that the SJ and BPS have the potential to impart flame retardancy, in both cotton and jute fabrics.

*Mass Spectroscopy (ToF-SIMS) Analysis of BPS*

Figure 6 shows the negative and positive time of flight secondary ion mass spectra (ToF-SIMS) of the pure BPS. The different molecules detected have been calculated based on their mass/charge (m/z) ratio and are presented in Table 4 Basak et al. [4]. The negative ToF-SIMS of the BPS showed the presence of the major molecules at different mass units, such as $H^-$ (1 amu), $C^-$ (12 amu), $CH^-$ (13 amu), $N^-$ (14 amu), $O^-$ (16 amu), $OH^-$ (17 amu), $F^-$ (19 amu), $Cl^-$ (35, 37 amu), $PO_2^-$ (62, 63 amu), $PO_3^-$ (79 amu), $KCl^-$ (74, 76 amu), $Cl_2^-$ (70,71 amu), etc. On the other hand, the positive mass spectrum mostly showed the presence of various metal ions, such as $Mg^+$ (24, 25 amu), $K^+$ (39 amu), $Fe^+$ (55, 56), etc. Therefore the flame retardant properties in terms of higher LOI value and more amount of char formation in the BPS treated cotton and jute fabrics were caused by the presence of free metal ions and various salts such as potassium chloride, potassium fluoride, calcium chloride, phosphate, etc.

*Mechanism of Imparting Flame Retardant Properties*

The flame retardant functionality imparted by BPS may be attributed to the presence of phosphate and other mineral salts. Different metals present in the form of metal chlorides and phosphates were detected in positive and negative mass spectra. The elemental peaks of chlorine, phosphorus, magnesium, etc., were also detected in the energy dispersive X-ray (EDX) analysis. Fourier Transform Infrared Spectroscopy (FTIR) analysis of the BPS confirmed the presence of inorganic salts. One recent study on pure BPS reported that 10.5 g inorganic salts was obtained by evaporation of 500 mL aqueous ash extract collected from burning the banana pseudostem. It was found that potassium chloride, sodium chloride, and metal phosphates are the major composition of that salt Neog and Deka [25]. On the other hand, the flame retardant property of the SJ treated cotton fabric was possibly

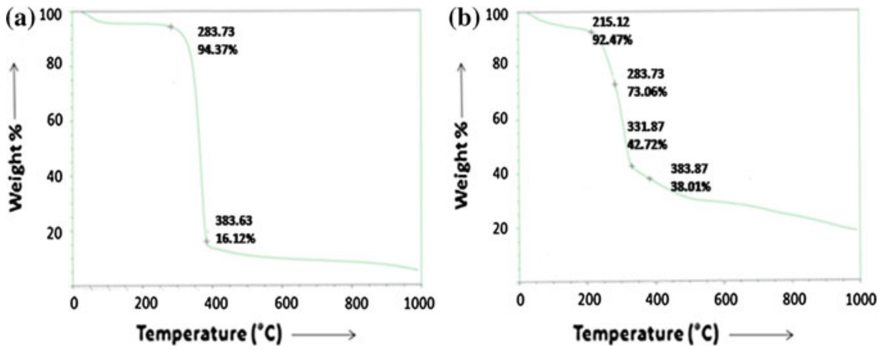


**Fig. 4** TGA curves of **a** control and **b** SJ treated cotton fabrics [4]

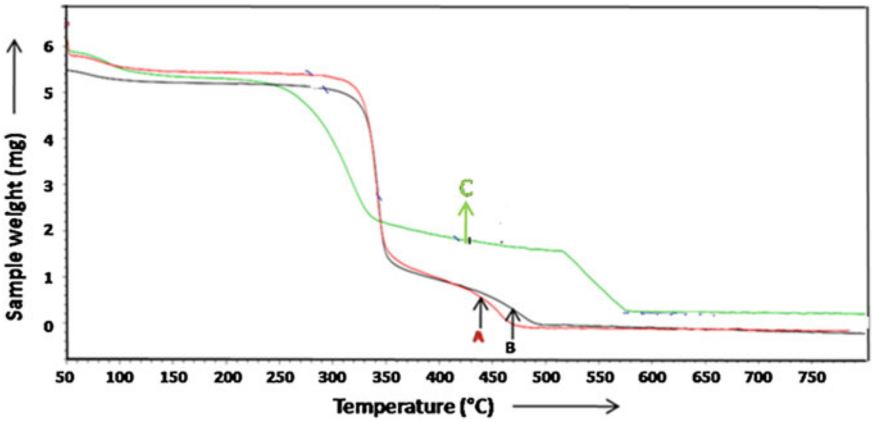


**Fig. 5** TGA curves of **a** control, **b** mordanted, and **c** BPS treated cotton fabrics [4]

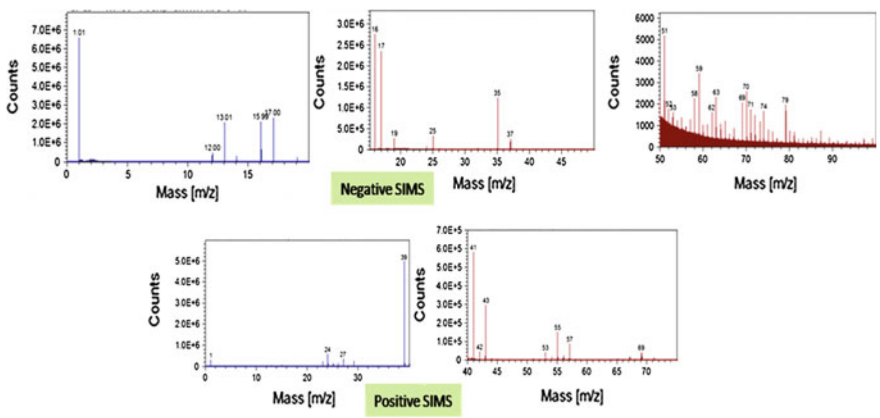


**Fig. 6** Negative and positive ion mass spectra of pure banana pseudostem sap (*BPS*) [4]

**Table 4** Different molecules detected in positive and negative ion mass spectra

| Serial no | Different molecules | Molecular formula | Mass/charge (M/Z) ratio |
|---|---|---|---|
| 1 | Hydrogen | H | 1 |
| 2 | Carbon | C | 12 |
| 3 | Nitrogen | N | 14 |
| 4 | Oxygen | O | 16 |
| 5 | Hydroxyl | OH | 17 |
| 6 | Fluorine | F | 19 |
| 7 | Chlorine | Cl | 35, 37 |
| 8 | Chloride | $Cl_2$ | 70, 71 |
| 9 | Phosphate | $PO_2$ | 62, 63 |
| 10 | Phosphite | $PO_3$ | 79 |
| 11 | Potassium chloride | KCl | 74, 76 |
| 12 | Potassium | K | 39 |
| 13 | Magnesium | Mg | 24, 25 |
| 14 | Aluminum | Al | 27 |
| 15 | Calcium | Ca | 40, 41 |
| 16 | Iron | Fe | 55, 56 |

caused by the presence of silicate and phosphate, which could be detected by elemental (EDX) and FTIR analyses. From their various characterizations, it has been reported that phosphate, silicate, chloride, and other mineral salts present in the BPS and SJ might have increased the thermal stability of cotton and jute fabric by forming more char and producing less-flammable gases. A similar observation has been made that the presence of organo-metallic additives in cellulosic textile could increase char formation while reducing formation of tar, i.e., volatile gases [41].

## 8 UV Protective Textiles Using Plant Extracts

UV protective finishing of textiles is important in our day to day life, as about 7 % of the total solar emissions reaching the Earth is composed of UV radiation. It can cause skin ageing, sunburn, weak immune system, tanning, photocarcinogenesis, and even skin cancer. In the past, various chemicals such as silicate and metal nanoparticles such as $TiO_2$ and ZnO have been explored for imparting UV protective finishing on textiles as they are non-toxic, environmentally friendly, and low in price. UV radiation is categorized in three zones based on their wavelength namely, (1) UVC (200–280 nm), mostly absorbed in the ozone layer, (2) UVB (280–320 nm), which penetrates the top layer of skin and causes skin ageing, sunburn, etc., and (3) UVA (320–400 nm), which penetrates through the skin and causes skin ageing. Therefore, in UV protective finishing, the textile has to be designed and finished in such a way as to block the transmission of UVA and UVB. The UV protective performance of a textile is defined by the ultraviolet

**Table 5** UV protective performance of different fabrics treated with plant extracts

| Different samples | UPF | | UPF rating | UVA (% transmittance) | UVB (% transmittance) |
|---|---|---|---|---|---|
| | Mean | SD | | | |
| Bleached jute fabric | 16 | 2.5 | 10 | 10.7 | 7.1 |
| Mordant treated jute fabric | 17 | 3.9 | 15 | 7.2 | 5.7 |
| Babool treated jute fabric | 43 | 5.2 | 40 | 2.7 | 2.4 |
| Manjistha + mordant treated jute fabric | 44 | 4.8 | 35 | 2.9 | 2.4 |
| Annatto + mordant treated jute fabric | 36 | 3.9 | 25 | 3.8 | 3.0 |
| Ratanjot + mordant treated jute fabric | 21 | 5.8 | 20 | 5.6 | 4.8 |
| Grape oil treated cotton fabric | – | – | 50+ | – | – |
| Bleached cotton fabric | 11 | 3.2 | 10 | 9.5 | 7.2 |
| Mordant treated cotton fabric | 14 | 4.2 | 10 | 7.5 | 6.2 |
| BPS treated cotton fabric | 43 | 5.2 | 40 | 2.7 | 2.4 |
| BPS + mordant treated cotton fabric | 145 | 8.2 | 50+ | 1.2 | 1.0 |
| SJ treated cotton fabric | 125 | 9.0 | 50+ | 2.0 | 1.8 |

protection factor (UPF). Any textile having a UPF value of $\leq$10 is considered as offering no protection from UV radiation. On the other hand, if the fabric has a UPF value of $\geq$50, it is considered to be an excellent UV protective textile. The UPF value of a fabric depends on the fabric properties, such as weave, yarn count, areal density, thickness, and chemical parameters such as type of dye molecule present, chemistry of fiber, and type of finish imparted. As discussed earlier, because of global awareness of green/eco-textile products, current research has been intensified in the area of development of UV protective textiles using plant extracts. A few recent studies have reported that some natural dyes have active molecules which can absorb UV light and block its passage through the fabric. Earlier, European researchers reported that dyes extracted from the madder wodes, knotgrass, fenugreek, and marigold possess very good UV protective properties. They have dyed linen, hemp, and silk fabrics with those natural plant extracts. The linen fabric was dyed with India madder which showed a UPF rating of more than 50, which is considered as excellent so far as the UV protection is concerned Sun and Tang [44]. Similarly, a few recent studies from India reported that grapefruit oil enhanced the UV protective properties of bamboo, Tencel fiber, and regenerated blended fabrics. Honeysuckle extracted molecules also provide good UV protective attributes to wool fabric. Other types of textile, such as ligno-cellulosic bleached jute fabric, was made UV protective using pomegranate, alum mordanting, and dyeing with extracts of babool, manjistha, annatto, and ratanjot. The UV protective results of these textiles are reported in Table 5. The naturally dyed textile from babool extract showed a good UPF factor compared to other natural dyes used in this study [5].

From Table 5 it can also be seen that plain woven bleached cotton fabric showed a poor UPF value of 10. As a result, the majority of incident UV rays can easily pass through the fabric. After mordanting with tannic acid and alum, the UPF value does not improve much. However, when the mordanted fabric was treated with BPS in alkaline conditions, it showed a UPF value greater than 100, i.e., a UPF rating of 50+ (excellent category). Further, the UVA and UVB transmittance percentages were reduced drastically in this sample compared to the untreated sample. On the other hand, if the bleached fabric was directly treated with alkaline BPS without the mordant, it showed the lower UPF value (40). From these two facts, it can be seen that the improved UPF value, i.e., the lowering of UV (A&B) transmission percentage, is happening because of the synergistic effect of the BPS and mordant. The UV protection of BPS may be caused by the presence of *N,N*-alkyl benzeneamine as confirmed by the GC-MS analysis of BPS Katarzyna and Prezewozna [15], Sayed et al. [40]. The UPF value of the treated fabric was also calculated after washing (ISO 1) the sample. It was found that the UPF value was 70 after the first washing, and 55 after the second. Similarly, the SJ treated bleached cotton fabric in alkaline condition showed a UPF value of $\geq$50, which may be caused by the presence of organic color and silicate molecules. The research group of Egypt has also used the alkaline extract of banana fruits peel for natural dyeing and UV protective finishing of fine quality Egyptian cotton textile [33]. The fabric was mordanted with ferrous sulfate and showed a UPF value of 7. On the other hand, the banana fruit peel extract treated sample showed an excellent UV protective performance. The observed high UPF value was possibly caused by complex formation between the dye molecules and the mordant. Sarkar [37] reported that dyeing of cotton with madder and indigo could also improve UV protective performance. It was observed that, by increasing the percentage of natural dye from 2 to 6 %, the UPF value increased to 50.

## 9 Conclusion

Wet chemical processing of textiles, such as desizing, scouring, and bleaching, are important for cleaning the fiber surfaces and making them free from dirt and impurities, besides making the textile fashionable and acceptable through dyeing, printing, and finishing. A large quantity of chemicals and auxiliaries are used in textile processing, dyeing, and finishing which can adversely affect the environment. Textile chemical processes also consume high volumes of water and discharge a huge amount of effluent. They cause water and air pollution besides adversely affecting the fertility of agricultural land. In the past, several technological advances have been made in the textile sector, either to reduce the pollution load or cost of production, such as (1) spray and foam finishing, (2) digital printing, (3) infrared and radio-frequency heating/drying, (4) use of ultrasound energy, (5) super-critical carbon di-oxide for dyeing, and (6) implementation of plasma technology for dry processing. Because of global awareness of the environment and the demand for healthier life styles, efforts have been made of late to explore various plant molecules (extract) to develop sustainable textile processing and also to meet the demand of eco/green textiles for new markets. In this context, the most successful and commercialized technologies are (1) enzyme application in textile and (2) use of natural dyes for coloration.

Natural fiber-based apparel and home textiles can be dyed with natural coloring molecules extracted from indigo, turmeric, manjistha, annatto, babool, marigold, dahlia, tesu, kusum, etc. Natural coloring molecules can produce different color shades on textiles in the presence of different mordants. Many of the traditional mordants are metal salts, but recently plant-based bio-mordants, such as pomegranate rind, natural lodhra, kenduka, and fruit extracts of haritak have also been developed. Many of the natural dyes have active molecules which can absorb UV light; hence, by using them appropriately, UV protective textile can be developed. Babool, manjistha, annatto, ratanjot honeysuckle extract, and grapefruit oil have been used to impart UV protective functionality in cotton, jute, wool, bamboo, Tencel, and blended textiles. Recently, BPS, an agro-waste, has also been used to impart excellent UV protective properties with ratings of >50 in cotton textiles. BPS treatment also showed excellent flame retardancy on cellulosic as well as ligno-cellulosic textiles. In the treated samples, the LOI was found to increase to >30 from a value of <21 in the untreated samples. The total heat of combustion was found to decrease from 16.4 to 13.1 MJ/kg in the untreated to the treated samples. The spinach extract has also shown similar results in terms of UV protection and flame retardancy. Antimicrobial and mosquito repellent textiles have been developed using medicinal plant extracts, such as neem, aloe vera, tulsi leaf, tea oil, and eucalyptus oil, and most of these fabrics showed antibacterial efficacy against both Gram positive and Gram negative bacteria. Such plant molecules (extract) and a few more, such as drumstick extract, sandalwood oil, bark of the arjuna tree, and nirgundi leaves have been explored to develop well-being, aroma, and cosmeto textiles. As many of the plant extract (molecule)-based finishes did not remain stable during washing, microencapsulation and other techniques have been explored to improve the durability of the finishes. It is felt that the extraction and use of various plant molecules for textile coloration and functionalization help to develop an eco-friendly textile which ensure adding value to the agro-waste/residue and plant extract.

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