Environmental Footprints and Eco-design
of Products and Processes

Subramanian Senthilkannan Muthu
Miguel Angel Gardetti *Editors*

Sustainable Fibres for Fashion Industry

Volume 1

Springer

Environmental Footprints and Eco-design of Products and Processes

Series editor

Subramanian Senthilkannan Muthu, SGS Hong Kong Limited,
Hong Kong, Hong Kong SAR

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ISSN 2345-7651 ISSN 2345-766X (electronic)
Environmental Footprints and Eco-design of Products and Processes
ISBN 978-981-10-0520-6 ISBN 978-981-10-0522-0 (eBook)
DOI 10.1007/978-981-10-0522-0

Library of Congress Control Number: 2016930270

Printed on acid-free paper

This Springer imprint is published by SpringerNature
The registered company is Springer Science+Business Media Singapore Pte Ltd.

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Introduction

The concept of sustainability is widely used in every industrial sector including textiles and clothing. According to Muthu (2014, p. v) *a sustainable textile product is the one that is created, produced, transported, used and disposed of with due consideration of environmental impacts, social aspects and economic implications.*

The social and environmental impacts from textile production are varied and evidence a mosaic of interconnected flows of the resources affected. According to Kate Fletcher and Lynda Grose (2012), fibers visibly connect us to many of the major issues of our time: Somehow we can relate climate change, waste production, and water shortage to material use, treatment, and demand. More specifically, Gardetti and Torres (2013, p. 7) state that the impacts of fiber extraction are *the use of pesticides during this process leads to workers' health issues, causes soil degradation and biodiversity loss. Water is vital in the processing of cotton, in particular, that this crop has been called the "thirsty crop." While the use of agrochemicals tends to be reduced, the use of genetically modified organisms for such purposes could lead to another type of impacts. Abuses on working conditions are also commonly presented in other stages of these industries; many times, human rights are violated in the so-called sweatshops which are characterized by low wages and long working hours. The risks are even greater if safety and health care systems are not appropriate. In turn, many of the synthetic fibers are derived from a non-renewable resource such as oil. In general, environmental abuse combines with ethical issues when water is overused, and when land for food production is usurped.*

Fibers (materials) are an essential element in fashion: They turn symbolic into real production while providing us with the physical means to build our identity and act as social beings as individuals. (Fletcher 2008 and 2014).

Fletcher (2008) explained very clearly that one of the first tasks is to acknowledge this complexity and to build expertise with a portfolio of more sustainable fibers because of their appropriateness to both product and user. Indeed, perhaps one of the greatest challenges of sustainability is to become skilled at this task. We should be able to translate the *system* "big-picture" issues (e.g., diversity, ethics, or consumption) and the *product* "small-picture" detail (e.g., fiber life-cycle analysis profile) and transfer such knowledge to our daily work so as to be able to make decisions that are simple and practical.

The fashion and textile industry's future success will depend on us reducing its environmental and social burden across the *entire* life cycle. And, for such purpose, we should develop a more pluralist, decentralized, and diverse approach. That is the hallmark of this first volume of Sustainable Fibers for Fashion Industry.

This book begins with a chapter written by Ammayappan Lakshmanan, Seiko Jose, and Sujay Chakraborty, titled "Luxury Hair Fibers for Fashion Industry". Their work analyzes animal hair fibers with limited production and unique characteristics that are used in the fashion industry to enhance the aesthetic and prestige look of garments. To sustain the luxury hair fiber industry, the authors look into existing luxury hair fibers in the fashion market and their potential applications.

Along this line, the chapter titled "Mainstreaming of Sustainable Cotton in the German Clothing Industry", by Erik G. Hansen, analyzes the sustainability-oriented transformation of clothing industries. While sustainability pioneers introduce new products in niche markets, incumbents advance them into the mass market. Together this can lead to the transformation of industries, markets, and consumer habits. This chapter reviews the German clothing retail industry with a focus on organic cotton and related sustainable fibers. The analysis also covers 4 of the 10 largest German textile retailers.

Moreover, in the third chapter titled "Possum Fiber—A Wonderful Creation of Nature", Mohammad Mahbubul Hassan analyzes possum fiber, which is harvested from a rodent called the "possum." The fiber is very soft and smooth unlike merino wool fiber. In addition, it is quite different from other animal fibers because of its unique shape and morphology. Over the past 15 years, the possum fur industry has grown in New Zealand, and when the fiber is blended with merino wool it produces various luxury apparels including coats, jackets, scarves, and cloaks. However, it poses some challenges due to its color (reddish brown). Therefore, in this chapter, the following are both analyzed and discussed: the brushtail possum and their habitat and food; the harvesting of possum fur; the physical and mechanical properties of possum fiber; and the mechanical and chemical processing methods, including bleaching and dyeing, of possum fur. Sanjoy Debnath explains, in the work "Natural Fibres for Sustainable Development in Fashion Industry", the large number of natural fibers available in nature from plants, animals, insects, and minerals. Accordingly, these fibres—alone or mixed with other fibres—are used in the design and development of specific fashion products. Different fashion industries have been developed all over the world to produce different fiber-based fashion products. These fashion industries have a huge potential for value addition with the intervention of newer product design. Recent trends also show the use of these natural fibers for sustainable growth in the fashion industry. This chapter also deals with future aspects of the use of uncommon natural fiber for sustainable fashion industry.

The next chapter, "Sustainable Bio Polymer Fibers—Production, Properties and Applications", by Karthik Thangavelu and Krishna Bala Subramani, deals with the less investigated and emerging biopolymer fibers, which will have huge impact on the sustainable luxury fashion going forward. The bio-fibers from animal protein (spider silk, hag fish slime), regenerated cellulose (seaweed), regenerated protein (milk fiber), and biopolymers synthesized from bio-derived monomers (PLA, PTT) are discussed in depth. The raw materials for the production and extraction of fibers, the properties and application of fibers, and the ecological impact of fibers are analyzed as well.

The last chapter of this first volume, developed by Y.A. Lee, is a case study titled "Case Study of Renewable Bacteria Cellulose Fiber and Biopolymer Composites in Sustainable Design Practices". This case study challenges researchers and practitioners to rethink what constitutes sustainable consumer products in a world of increasingly stressed natural resources by exploring innovative ways to develop renewable biocomposite materials, such as leather-like nonwoven fabrics, which can be used for apparel and footwear products.

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Luxury Hair Fibers for Fashion Industry

Ammayappan Lakshmanan, Seiko Jose and Sujay Chakraborty

Abstract The fashion industry has been captivated by natural fibers, particularly animal hair fibers due to their specific characteristics—such as fineness, warmth, suppleness, visual appearance, and finally mystique—since ancient times. Animal hair fibers protect the animal from extreme weather particularly at high altitude/low temperature, and thus generally their production is not as high as fine wool fiber from sheep. The limited production and unique characteristics lead them to be used in the fashion industry to enhance the aesthetic and prestige look of garments. Being utilized in luxurious fashion industry, they are also known as luxury or exotic fibers. To reduce the cost of the end product and impart novelty, these hair fibers are used often in conjunction with either sheep's wool or other natural fibers. These blends produce special effects, such as additional beauty, texture, colour, softness, resilience, durability, and luster, on garments. Luxury hair fibers are exceptionally fine (8–16 μ) and are in high demand for the production of fashion garments and accessories, which led to brink of extinction of luxury hair fibre-producing animals such as antelope in Tibet. To help sustain the luxury hair fiber industry, this chapter considers the existing luxury hair fibers in the fashion market and their potential applications.

Keywords Animal hair · Luxury hair · Fashion clothing · Fineness · Yield

1 Introduction

Clothing was introduced by mankind to protect him from the environment. After civilization was more developed, mankind introduced different clothing, and the western culture developed fashion clothing, particularly to differentiate royal people from common people. Designers of fashion textiles are always fascinated with

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S.S. Muthu and M.A. Gardetti (eds.), *Sustainable Fibres for Fashion Industry*,
Environmental Footprints and Eco-design of Products and Processes,
DOI 10.1007/978-981-10-0522-0_1

Table 1 Important luxury hair fiber properties, yield, annual production, and prices

Hair	Family	Diameter (m)	Fiber length (mm)	Price ($USD/kg)	Resource	Annual production (tons)	Trend	Yield/animal (kg)
Mohair hair	Angora goat	24–40	84–130	7.5–8	South Africa, Turkey, USA	20,000–22,000	Increasing	4–10
Cashmere hair	Cashmere goat	12.5–19	35–90	100–130	Asia, Russia, Australia, New Zealand	6500–15,000	Increasing	0.1–0.16
Pashmina hair	Chanthangi/cheru	9–14	40–60	100–150	India, Nepal, Tibet	40–50	Stable	0.5–0.45
Cashgora hair	Angora goat × cashmere goat	18–23	30–90	45	Australia, New Zealand	50	Increasing	50 % of fleece
Camel hair	Camel	18–26	30–120	9.5–24	China, Mongolia, East Asia	4500	Stable	3.5–5.0
Alpaca hair	Lama glama pacos	20–36	200–550	2–10	South America, USA, Canada	4000–6500	Increasing	3–5
Llama hair	Lama glama glama	19–30	80–250	2–4	South America, USA, Canada	2500–2700	Increasing	2–5
Vicuna hair	Lama vicuña	12–15	30–50	360	Peru, Chile	5–6	Direct consume	0.2
Guanaco hair	Lama guanacos	14–16	30–60	125–150	South America	1.5–2	Direct consume	0.7–1.0
Angora rabbit hair	Angora rabbit	11–15	25–60	20–30	China, France, South America, Turkey	2500–3000	Stable	0.4–0.8
Musk ox hair	Bovine	11–20	40–70	15	USA, Canada, Asia	4–5	Stable	0.9
Bison hair	Bovine	12–19	50–70	300	USA, Canada	5	Stable	1–2
Yak hair	Bovine	15–17	30–35	20	China, Mongolia, India, Tibet	1000	Stable	0.1

Koztowski (2012), Atav et al. (2015), Atav (2010), Berger (1963), Bobswen (2001), Cardellino and Mueller (2008, 2009), Franck (2001), Townsend and Sette (2013), Watkins and Buxton (1992), Ammayappan and Moses (2005) colour, design, and material. Designers believe that rich colour, aesthetic design, and luxurious fibers make ordinary cloth into prestigious fashion cloth. Rich colour is derived from fast natural dyes; aesthetic designs are developed by craft people; and luxury hair fibers are harvested from rare animals (Gardetti and Muthu 2015). In ancient times, hair-bearing animals were not domesticated; harvesting hair fiber from those animals was considered a hobby; it was not until later that technocrats found that animal hair fiber has softness, warmness, and fineness. These characteristics are suitable for making fashion clothing.

Wool is an important animal fiber and has been used for the development of fashion apparel for long time; however, traditionally other animal hair fibers, such as pashmina, angora goat, angora rabbit, and vicuna, have been used in the manufacture of textile clothing and fashion garments. Development of fashion textiles from luxury hair fiber can also remunerate farmers due to their high price in the market. Due to high cost, they have been generally used in conjunction with sheep's wool to produce special effects. Worldwide demand for total textile fiber was approximately 75 million tons in 2013, to which the contribution of natural fiber was estimated at 33 million tons (Atav et al. 2003; Atav 2010).

The annual production of natural fibers other than cotton fiber and wool fiber is reported approximately 1.6 million tons and they worth approximately $3 billion (Townsend and Sette 2013). For example, the share of angora goat hair is <0.05 % of the total world fiber production, and the important luxury fiber annual production and properties are given in Table 1. The low production of luxury hair fiber is due to less productivity per animal, which ranges from 20 to 500 g of greasy hair per shearing; however, this still plays an important role in the fashion textile industry. Recently the production of luxury hair fiber for supply of the fashion industry has also declined due to a reduction in the population of the animals, global warming, less availability of manpower for animal grazing, poor supplementary nutrition, and the introduction of synthetic fibers with similar properties. A group of fashion textile industries existing in European countries, Japan, and America focuses on the development of products from luxury hair fibers, and thus there is still a demand for the luxury hair fibers. This chapter will give a roadmap to the availability of luxury hair fiber, their properties, their processing and potential applications, their market, and their future perspectives.

2 Luxury Hair Fibers

Fine hair fibers obtained from animals other than sheep, such as goat, camel, and the camelid family, are used in the manufacture of fashion textile products. Due to their high cost, they are used often in conjunction with fine wool fiber (20–30 μm,) or other textiles fibers, such as silk, viscose rayon, nylon, and cotton, to impart novelty effects. The largest groups of these fine hair fibers are known as "*luxury hair fibers*," and they generally are classified based on the source of the hair (Fig. 1). The annual production of greasy hair fiber was approximately 50,000 tons

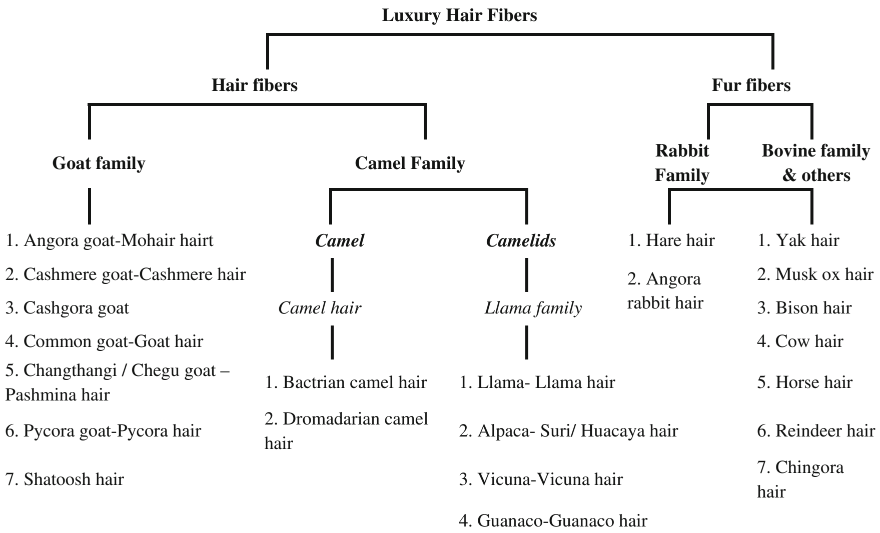

Fig. 1 Classification of luxury hair fibers based on their source

in 2012, and it contributed nearly a 0.15 % share of the total natural fiber production, i.e., 33.45 million tons, in the world. Due to their limited contribution in a specialized market, they also called "*specialty hair fibers*." The classification of luxury hair fibers based on their source is given below (Bobswen 2001; Dalton and Franck 2001; Koztowski 2012). Among luxury hair fibers, cashmere, mohair, and alpaca hair occupy the first three ranks in terms of production. Due to less availability, vicuna is the most expensive hair fiber followed by qiviut, guanaco, cashmere, and pashmina. Luxury hair fiber-based products, made by experienced artisans, are relatively more expensive than fine wool products. For example, cashmere sweater costs £100; cashmere suit fabric costs approximately £1200; guanaco fabric costs approximately £500/m; a vicuna scarf costs approximately $1500; and a men's vicuna coat costs $20,000 (Atav 2011; Atav et al. 2015).

2.1 Goat Family

Based on the quality of hair obtained from the goat family, they are classified as mohair/angora, cashmere, pashmina, pygora, cashgora (*crossbreed*), and common goat hair. Mohair fiber is obtained from the long, lustrous coat of the angora goat; cashmere fiber is obtained from the cashmere goat of family *Capra hircus* (McGregor 1990); pashmina hair obtained from Indian changthangi/chegu goat (Wani et al. 2007); Cashgora hair is obtained from a cross-breed of the cashmere and angora goat and was developed in New Zealand (James 2000); and common goat hair is generally obtained from the local goats of each country and used by farmers (Westhuysen 2005).

2.1.1 Mohair Hair

Mohair is one of important luxury hair fibers and is obtained from the long, lustrous coat of the angora goat, which originated in Turkey. This beautiful fiber is famous for its luster, softness, and strength. South Africa accounts for 60 % of total production, and other producers include the United States, Turkey, Argentina, Australia, and New Zealand. It has also been reported that genetic breeding programs in Australia are resulting in a dramatic reduction in the level of kemp fiber, which reduces the value of mohair fleece. Mohair fleece from the angora goat is white, smooth, and lustrous, and it has high tensile strength. A good mohair fleece will be characterized by locks or bunches of mohair hair held together by the curl of the fleece with a light sheen of oil and a good long staple. The average fleece yield is approximately 2.5–3.0 kg/shearing with a staple length between 12 and 15 cm; the animal is usually sheared twice a year (Hunter 1993).

Mohair hair ranges from very fine and soft to coarse and scratchy. Goat kids produce the finest fiber, and the first shearing (or fall clip) is the finest of all. These fleeces generally have very little oil, are soft, and are in the fiber fineness range of 20–24 μm. Progressively, as the animal ages, the mohair becomes coarser, and the average fiber diameter increases. The value of the fleece is determined by fiber diameter, luster, softness, and free from kemps (Hunter et al. 2008). Mohair hair is similar to wool in chemical composition, but it is more crystalline than wool. Mohair hair is a strong fiber that is elastic, has considerable luster, and takes dye very well. The cross-section form of mohair is round. The scales are larger than those of wool and lie flatter, thus making for a smoother fiber surface. The resultant greater reflection of light gives mohair its characteristic luster. The scale number is 5/100 μm, and the scale length ranges from 18 to 22 μm (Van Rensburg and Maasdorp 1985). The annual production is estimated to be approximately 22,000 tons and is mainly used for clothing and furnishings. The spinning of mohair hair is not easy, especially in drawing and spinning, due to low cohesion and the generation of static electricity. Blending mohair with wool is preferred to reduce static-electricity problem as well as allows the use of lubricants and additives. Fabrics made of mohair are very light in weight and have excellent insulation.

Mohair-based fabric provides warmth during the winter months but also makes a cool suiting fabric for the humidity of summer; hence, it is popular in Japan. Mohair is considered very valuable as an upholstering material for the making of plushes and other covering materials where strength, beauty, and durability are desired. It is used to make the knitting yarn used for hand or machine knitting to make lightweight suiting, fabric for stoles and scarves, warm blankets, and durable velour upholstery. It is often blended with wool for making top-quality blankets, in which the mohair content makes the fabric warmer and at the same time lighter (Harmsworth and Day 1990; Hess 1931; Appleyard 1978; Watkins and Buxton 1992; Franck 2001). Luxury products made from angora hair are given in Fig. 2.

Adult mohair goat

Relaxed Navy jumper with round neck & long sleeves (65% Cotton: 35% Mohair)

100% Mohair hair printed top (Mohair South Africa, 2015)

Socks from 75% Kid Mohair hair: 25% Nylon of Thermohair (Stilleagle, 2015)

Wool: Mohair hair blended Navy Tuxedo Jacket (Kingsman, 2015)

100% Mohair hair over coat (Mohair South Africa, 2015)

Fig. 2 Mohair goat and luxury products made from mohair

2.1.2 Cashmere Hair

Cashmere hair is referred to as the fine-bottom hair of the cashmere goat (*Capra hircus laniger*). The cashmere goat originated in the Himalayan regions of central and southwest Asia; later on cashmere goats spread, most notably to China and Mongolia. The annual production of cashmere hair is estimated to be between 15,000 and 20,000 tons with a yield of 6500 tons of “pure cashmere.” The major cashmere-producing countries are China (70 %), Mongolia (20 %), Iran, Afghanistan, and India. China produces the best-quality cashmere fiber (<17 μm) and is used for woven and knitted cloth. Iranian and Afghan cashmere is of lower quality, and Indian cashmere hair is 14–19 μm and is used for making a wide variety of shawls, stoles, scarves, and sweaters. It is one of the finest and softest luxury hair fibers. Its visual appearance, extreme softness, scarcity, and image or mystique character gives cashmere an unrivalled status as a luxury hair fiber (McGregor and Butler 2009; McGregor 2003).

Chemically, cashmere is identical to fine wool and mohair fiber. It has higher micro fibril-packing density, and this may be associated with the low crimp exhibited by cashmere fiber. It has a bilateral structure, and the percentage of ortho and para cortex is 50.4 and 49.6 %, respectively. There are 6.5–7 scales/100 μm. The scale edges of cashmere fiber do not protrude as much as those of wool; this leads to smoothness and lower shrinkage. Cashmere fiber is approximately 10 % weaker than the finest wool and approximately 40 % weaker than mohair fiber.

Adult cashmere goat

100% Cashmere stole of Johnstons of Elgin

Silk/ Nylon/ Cashmere blended Julia Shimmer Jacquard Stole of Gucci

100% Cashmere hand knitted scarf of Cianti Cashmere

100% Cashmere chunky knit wrap with suede Fringe of Willow Cashmere

100% cashmere hand woven glitter shawl of Willow Cashmere

Fig. 3 Mohair goat and luxury products from mohair hair

It has a superbly textural feel, drapes beautifully, feels soft, warm, and light to the touch, and will serve a user well for years. Cashmere hair offers lightweight insulation without bulk. The fibers are highly adaptable and appropriate for all climates. Its high moisture content allows insulation to change with the relative humidity of atmosphere (Patil et al. 2012).

The knitwear industry is the largest consumer of cashmere hair. Scottish knitters comprise the largest market for cashmere fiber outside of China. The weaving sector is a small consumer of cashmere followed by the knitwear industry. After shearing wool from the animal, the greasy and coarse outer hair can be removed. De-haired fine hair can be dyed with suitable dyes, and then the dyed hair is carded and spun into yarn. Dyed cashmere yarn from reputable spinners is knitted into pieces on knitting machines with suitable designs. Knitted fabrics are washed with great care in formulated soap in soft water at low temperatures. Washed scarves are pressed and undergo a final inspection before tabbing, folding, and bagging. A significant amount of cashmere hair is used to make accessories, e.g., shawls, stoles, scarves, throws, and wraps. The low-grade hair is used in carpets and under felts and interlining for men's suits and jackets (McGregor and Postle 2004; Meech 1997). Cashmere/Silk blend is also used for the development of high-cost suiting, and it has been reported that Richard Jewels, a famous designer, developed a suit costing approximately $900,000 USD and bedazzled with 480 half-carat diamonds. Brooks Brothers, a famous suit manufacture from the United Kingdom, made suiting fabric from a blend of super 200s merino wool and Mongolian cashmere (Esteban 2012).

Recently the requirement for cashmere products has increased, and it is believed that the rearing of cashmere goats is environmentally catastrophic because the grasslands in China and Magnolia cannot support the necessary fodder for hungry goats. To sustain the supply of cashmere hair to the fashion industry, breeders have introduced a cashmere cross-breed to yield a good quantity hair rather than quality hair. Alternatively, the demand for ultra-soft, lightweight, candy-colored cashmere sweaters has increased recently, and this has lead to the selection of an alternative luxury hair fibre, particularly camelid hair fibers, in the UK fashion market (Avins 2014). Some of the luxury clothing based on cashmere hair fiber are given in Fig. 3. (Willow Cashmere Ltd 2015; Sustainable Cashmere 2015; James Johnston & Company of Elgin 2015).

Environmental sustainability means that the end product consumes less energy than it produces. M/s Chianti Cashmere, Italy, is a famous fashion outlet for cashmere hair, and they have adopted sustainable techniques starting from sustainably harvesting cashmere hair to finishing it. They believed that sustainable processes can protect the environment, improve the landscape for animals, and promote sustainable rural development. They have introduced a wide range of fashion products such as hand-knit scarves, mini shawls, baby hats and shoes, and neck scarves in natural colours.

2.1.3 Pashmina Hair

Pashmina hair is one of the finest hair fibers harvested from the domesticated goat from the Leh and Ladakh region of Jammu and Kashmir called *Chanthangi*; Lahul & Spitti of Himachal Pradesh called it *Chegu* (Koul et al. 1987; Thakur et al. 2005). Pashmina hair is also considered the prince of specialty hair fiber, and the name "pashmina" derives from the Persian word "pashm," which means "soft gold." It is in great demand in European fashion textiles due to its fineness (9–14 μm), warmth, lightness, softness, and dyes compared with other hair fibers (Acharya and Sharma 1980). Each goat produces 250 g of hair in a season, and the dehaired fibre sells for approximately $35/kg. Pashmina hair is identical with fine wool and has a bilateral structure of ortho and para cortex of 50.4 and 49.6 %, respectively. Because the cuticle of pashmina hair does not protrude like other fine wool, it leads to a smoother and more lustrous surface. However, it is 10 % weaker than fine wool and approximately 40 % weaker than mohair fiber. It has also been observed that pashmina fiber has more of the polar amino acids (serine, threonine, and tyrosine) than fine wool, so its cuticle is more hydrophilic than that of fine wool (Franck 2001; Berger 1963) (Fig. 4).

The appeal and matchless status of pashmina hair compared with cashmere hair is due to its fiber fineness (9–14 μm), visual appearance, extreme softness, scarcity, and mystique. The annual production of pashmina fiber from the Himalayas of India is approximately 30–40 tons (Fig. 5).

Pashmina shawls were sold into the western fashion market 20 years ago, and initially the pashmina shawl was marketed in 60/40 ratio of pashmina to silk and had a good sheen, strength, and pliability. Pashmina hair is also utilized for the production of aesthetic products such as knitwear in Scotland, blended suit fabrics

Pashmina bearing Changthangi goat

Hand crafted 100% Kashmiri Pashmina Shawl

Fig. 4 Pashmina goat and pashmina shawl

Hand-spinning of Pashmina hair in Charkha

Handloom weaving of Pashmina shawl

Block Printing of shawl for design

Hand Embroidery on Pashmina shawl

Fig. 5 Production of a pashmina Shawl by traditional process (Ammayappan et al. 2011)

in Italy and Switzerland and shawls, stoles, rumals, and other high-quality apparel in India and Nepal. The shawl prepared from fine pashmina fiber is traditionally hand woven. It mainly involves highly skilled labours sorting, spinning, and weaving the fiber on specified handlooms in the Kashmir valley. Making one quality pashmina shawl requires nearly 4 to 200 man hours with the involvement of 2–4 man powers.

Indian craftsmen traditionally made renowned pashmina shawls, which were woven on a hand loom and often embellished with fine embroidery; the cost was between \$200 and \$600. The exports of pashmina shawls fetched \$160 million in 2011–2012 per India's economic survey (Penisola 2015). The coarse outer hair is mainly used for rope, felt, blankets, and durries (Ishrat et al. 2012; Nazir et al. 2012). Some organized sectors have developed fine wool shawls that have been treated with suitable softeners and are sold as "100 % Pure pashmina." It has been found that in the UK market, from 35 to 69 % of fashion garments were mislabeled during 1995–2006. To sustain the quality of pashmina products, emphasis is given to the quantitative analysis of pashmina hair by DNA sequencing, PAGE, and chemical-staining methods (Ammayappan et al. 2011).

Recently the Changthang region of the larger Tibetan Plateau, India, envisaged a heavy snowfall, which deprived their animals of fodder and leaving grassy areas parched and barren in the summer. Such extremes of summer and winter lead to the starvation of goats, and seriously jeopardizes the sustainable rearing and harvesting of pashmina hair fiber. Ultimately farmers and their families are migrating toward neighboring cities for alternative jobs (Parvaiz 2013). To sustain pashmina hair cultivation for the fashion industry, government policy should be formed to increase or at least maintain pashmina goat population by funding subsidies to farmers to provide the necessary fodder to animals, optimize the supply of pashmina hair through co-operative systems, develop low-cost, innovative as well as eco-friendly shawl-manufacturing and processing Technologies, and provide the mandatory eco-label to final products (Arnott 2012).

2.1.4 Pygora Hair

Pygora hair is a fine hair fiber purposely bred for hand-spinning in Dalla, Canada. It is obtained from the Pygora goat, which is a cross-breed of the NPGA Pygmy goat and the white AAGBA angora goat, both bred by Katharine Jorgensen of Oregon City, Oregon, Canada. The Pygora goat has a soft and long silky fleece and produces three types of fleece with different characteristics (Anon 2015)

- ***Type* "*A*"**: (angora type) A long, lustrous fiber, up to 6 in. long <28 μm in diameter, that hangs in long, curly locks. This hair fiber has similar characteristics to those of fine mohair hair.
- ***Type* "*B*"**: (blend type) A blend of the Pygmy goat undercoat, which is cashmere, and the angora mohair. The fleece is between 3 and 6 in. long with a nice crimp (curl), and the fiber diameter is <4 μm. Type "B" fleece can either be lustrous or have a matte (dull) finish.
- ***Type* "*C*"**: (cashmere type) A very fine fiber, with no luster, and a length of 1–3 in. It is acceptable as an equivalent to commercial cashmere, and its fineness is <18.5 μm.

Pygora fleece has guard hair and soft fiber, and before spinning guard hairs are removed from the soft fiber. The B-type fleeces are usually finer than the A-type fleeces (i.e., they have a lower micron count) and are used for both worsted and

Pygora goat

Silk:Pygora blended scarf

Pygora Scarf with beads of Sweet River Range, USA

Lace Pygora wristlets kit, baby hat kit, and pygora guard-hair rug of Whistlekick Pygoras (Whistlekick Pygoras, 2015)

Fig. 6 Pygora goat and its luxury products

lustrous yarn. Type C fiber, after dehairing, is used for development of delicate cashmere yarn (Lisa 2014; Pygora Breeders Association 2013). The Pygora/silk blended scarf is famous for its design and softness (Fig. 6).

2.1.5 Cashgora Hair

Cashgora fleece is obtained by shearing from the Cashgora goat, which is a cross-breed of the angora goat with the cashmere goat. The goats are shorn twice a year; the fiber diameter ranges from 18 to 23 μm; and the length varies from 30 to 90 mm. Their morphological features are closer to those of mohair than those of cashmere. There are three types of Cashgora hair, which are marketed as Ligne Or (18.5 μm), Ligne Emeraude (20 μm), and Ligne Saphir (22 μm). New Zealand is the main producer of Cashgora hair, and it produced 200 tons of greasy hair in 1990, which declined approximately 60 tons in 2000. Cashgora hair has the appearance of cashmere hair with mean fiber diameter of 19–20 μm as well as a smoother surface and generally higher luster. Because it has good staple length and tensile strength, high-quality suiting fabric can be made by a worsted spinning process. After dehairing of the fleece, it behaves like fine wool and is mainly used for making lightweight suits, jackets, coats, scarves, and stoles. It is considered more suitable for weaving than for knitting (Scheurmann et al. 1990; Koztowski 2012).

Fig. 7 Cashgora goat and cashgora products from Tajikistan (Brent 2013)

In Tajikistan, the hair is harvested manually by the comber, sorted according to fineness, dehaired of guard hairs, combed to form clouds, spun into yarn either by hand-spinning or electric-spinning machine, followed by skein formation. Each skein is labeled with weight, yardage, and the spinner's name to ensure the quality of the final product. Skeins can be distributed to village women for the creation of different knitted products. These products can give good remuneration for village women to sustain their lives due to their eco-friendly preparation (Fig. 7).

2.1.6 Common Goat Hair

Common goat hair for textile use comes mainly from the Asiatic countries. Greece and Argentina are the leading exporters, and together they supply 2300 tons annually. The hair ranges in fineness from 7 to 20 µm for fine fibers, 50–200 µm for beard hair from a fully growth animal, and 15–19 µm for kid hair. The scale pattern is similar to that of cashmere fiber. Goat hair is mainly used as writing brush material, but it also has other uses. A large amount of this hair is used in the manufacture of cheap felt and carpets for the automobile industry; smaller quantities are used in the manufacture of interlining. Some studies have inferred that 60:20:20 blends of goat hair, wool, and proplon satisfy the Indian standards ISI: 1721-1960 for utilization as hair-belting yarns (Gupta 1988; Dellal et al. 2001). ICAR-Central Sheep and Wool Research Institute in Avikanagar, India, has developed the technology for the preparation of hand-made durry and carpets by keeping cotton yarn as warp. Long, medium, fine, and sheer goat hair can be used for the "hairy look" of certain fashion garments. Goat hair is primarily used by local artisans, and its sustainability generally depends on the marketing and eco-awareness of the products (Pokharna 2003).

Tibetan Chiru antelope

100% Shahtoosh shawl woven in handloom

A Kashmiri shawl weaver weaves a Shahtoosh shawl in Srinagar, Jammu and Kashmir, India on 2000 (Mushtaq, 2008)

Fig. 8 Tibetan chiru antelope and shahtoosh products

2.1.7 Shahtoosh Hair

"Shahtoosh" refers to shawls made from the hair of the endangered Tibetan chiru antelope (*Pantholops hodgsoni*), which yields toosh (known as Shahtoosh), and this is more delicate than pashmina hair. The Tibetan antelope lives in the Himalayas at an altitude of >5000 m, and they have down fur, which is both very light and warm (Rizvi 2015). During British rules, pashmina and Shahtoosh hair-based shawls were introduced to the fashion world and until now both have been in greater demand. However, the Tibetan antelope was hunted down specifically for its fur, and their numbers have dropped; it is now an endangered species. Shawls from Shahtoosh hair are woven by only master artisans because its fiber fineness ranges from 7 to 10 μm. Dehaired fibers from five Tibetan antelopes or Chiru are required to make a shawl that is 2 m long. It is believed that Shahtoosh shawls can be passed through a wedding ring and so are is known as "ring shawls." The cost of one Shahtoosh shawl is approximately $3000–$5000 in India and approximately $18,000 in luxury boutiques of Europe, the United States, and Gulf countries, depending on the quality (Wikipedia 2015a; Koztowski 2012) (Fig. 8).

Kashmir is the only place that produces Shahtoosh shawls; however, to sustain the antelope population, the Indian government has banned the rearing/trading of Shahtoosh products since 2000. This ban has ruined the income of Kashmiri women in the shawl industry; however, traders from Tibet reared the hair and smuggled it to India for shawl manufacturing, which increases the cost of the shawl (Mushtaq 2008).

2.2 Orenburg Hair

Orenburg hair fibre is reared from the native-breed Orenburg goat, which is found in the Orenburg, Chelyabinsk, and Aktyubinsk regions of Russia. Orenburg hair is famous for its downy texture, and the development of traditional Orenburg shawl has been followed for >300 years (Orekhov 2007). The fleece consists of long, coarse, and bright guard hair and fine undercoat hair. Each goat yields an overall

Orenburg Goat

Hand-woven Orenburg (100%) shawl

Orenburg (100%) wedding-ring shawls

Fig. 9 Orenburg hair

range of 180–400 g, and the average diameter of the hair is 15 μm. The fineness of the hair is uniform in all over the fleece. Being the finest hair fibre, the hair is famous for being made into shawls, known as Orenburg shawls/scarves/ "Orenburgskyi Platok" in Russian. It is often called the "wedding ring shawl," i.e., it is believed that a shawl knit in the traditional fashion can be pulled through a wedding ring like a pashmina shawl. The shawls are made from a blend of silk and Orenburg hair fiber, similar to cashmere or mohair. After harvesting and dehairing the guard hair, fine hair is then hand-spun using a supported spindle followed by plying against a commercial silk thread. This yarn is used for making shawls by knitting it in a variety of geometric designs. Similarly, for sustaining this luxury hair fibre, the cost of the shawl is reduced by blending it with rayon viscose/nylon or other synthetic fiber and then developed into scarves or shawls (Rusclothing 2015; Terletski 2015) (Fig. 9).

2.3 Camel Family

2.3.1 Camel Hair

Camels are part of the Camelidae grey family. There are two kinds of camels, namely, the Arabian or Syrian camel, which has one hump and is known as the "dromedary camel" (*Camelus dromedarius*), and the Eastern Asiatic camel, which has two humps and is known as the "bactrian camel" (*Camelus bactrianus*) (Fig. 10).

China is the leading producing country of camel hair followed by Mongolia, Iran, Afghanistan, Russia, New Zealand, Tibet, and Australia; 4500 tons of greasy camel hair is harvested annually (Taoufik et al. 2014). Camel hair is largely obtained from the double-humped Bactrian camel, and it produces best, softest, and finest hair fiber. Camel hair is normally "willowed" to remove most of the dirt, dust, and vegetable matter and dehaired to recover the finer hair. It contains 15–35 % sand and dust and 05–1 % wool wax. The diameter of the inner down hair varies

Fig. 10 Camel

Single hump adult camel

Double hump adult camel

from 19 to 24 µm, and the fiber length varies from 25 to 125 mm. The outer coat hair is coarse with a fiber length of 375 mm and a fiber diameter of 20–120 µm.

The colour of the hair varies from reddish to light brown, and it is sorted according to colour and age of the animal. The scale edges are generally smooth and vertical to the fiber axis. The number of scales varies from 4 to 9/100 µm. It is capable being dyed with a broad range of dyes and accepts dye equally as well as fine wool fiber (Msahli et al. 2008). Camel hair is blended with fine wool for overcoating, tops, sportswear, and sports hosiery. Nylon/virgin-quality camel hair blends are used in hosiery and in knitted products. The hairs are also used in the preparation of worsted yarn for making industrial fabrics such as press cloth used in the extraction of oil from seeds. The long hair is removed by a dehairing process and is used to make felts. Camel hair-based felts are used for tents and Mongolian herdsman's winter coats due to its warmth and waterproof character. It is also used in the manufacturing of men's and women's coats, jackets, and blazers, skirts, hosiery, sweaters, gloves, scarves, mufflers, caps, and robes. Camel hair/wool blends in combination with polyester staple/silk waste can improve the utilization of available camel hairs for overcoats, knit wear, blankets, and carpets (Gupta et al. 1989; Pokharna 2003) (Fig. 11).

Similar to fine/medium wool fiber, camel hair is covered with fine scales, and fibers have air-filled matrix called the "medulla" in the center of the fiber, which affords warmth to camel hair-based garments. To enhance the look of the camel hair-based coats and jackets for fall and winter garments, they are brushed. Fine camel hair and camel hair/fine wool-blended coats and suits were introduced by UK-based clothing company Jaeger in the nineteenth century followed by being popularized by polo players in the United States. A camel hair blazer from the American fashion label Bill Blass is shown in the figure (Wikipedia 2015b; Petrie 1995).

Longer camel hair is typically blended with fine sheep's wool and used for upholstery or coats and flippers, such as Zakhs, which was developed by artisan cooperatives in the Asian Steppes. Being reared in the interior of hilly region of China and Mongolia and semi-arid regions of Asian countries, camel hair is an asset for local farmer communities, and a multi-purpose camel hair can sustain their lives by producing income for them (Oijala 2012; Allen Edmonds Corporation 2015).

100% Camel Hair Pullover of Fashion Classics, UK

100% fine camel hair cap and scarf of Fashion Classics, UK

Camel Hair Blazer of Jos. A. Bank, USA

100% Camel Hair Sport Coat of Allen Edmonds, USA

100% Fine camel hair Polo Coat of Ben Silver, UK

Camel hair based slipper by Zakhs

Fig. 11 Camel hair based luxury products

2.4 Camelid Family

South American camelids exist in four forms, all of which live in the high altitude of the western coast of the Andes region in South America. Llamas (*Lama glama glama*), alpacas (*Lama glama pacos*), guanacos (*Lama guanicoe*), and vicunas (*Vicugna vicugna*) are collectively known as “new world camelids.” They are all members of the camelid family and are related to bactrian and dromedary camels. These animals can endure the climate of the highest Andean altitude from 2500 to 5000 m and from tropical areas to sub-polar regions by adapting to the rarefied atmosphere and being able to survive on the tough natural vegetation of the steppes (Rodriguez and Quispe 2007; Quispe et al. 2009).

Compared with camel hair, goat hair, and fine wool fibers, camelid hair fibers are considered a sustainable fiber because they do not contain lanolin and thus do not require any chemical treatments. These animals are believed to be better for the pastures during grazing than goats, i.e., they are gentler on their food sources. These fibers often afford incomes for local communities; in addition, locals develop different fashions using traditional hand-made items, which are then sold through cooperatives to European and American markets. This sustainable supply chain makes for a strong ethical and fair trade component. The poaching of vicuna and guanaco for the illegal marketing of the luxury hair fiber is the only threat to their sustainability (Alex 2011).

2.4.1 Llama Hair

The llama is a domesticated South American camelid that has been widely used as meat and a pack animal by Andean cultures since pre-Hispanic times. They are very social animals, and are also called “camels of the clouds,” “Peruvian sheep,” and “silent brother.” The wool produced by a llama is very soft and lanolin-free. There are two types of llama: kcara, a light-fleeced animal used mainly as a beast of burden, and chaku, a heavy-fleeced animal used for its hair (Cardellino and Mueller 2008).

Like other fleece, llama fleece has a double coat: an outer coat of coarse guard hair and an undercoat of soft, fine down. Llama fleece contains 0–20 % guard hair. The failure to utilize llama fiber for high-quality garments resulted from the inability of South American Indians to successfully dehair the fleeces. Modern technology has enabled full use of llama fiber. Greasy hair annual production ranges between 2500 and 3300 tons with a clean hair yield of 85–90 % (Fig. 12).

Llama hair fiber is fine, strong, comfortable, warm, lightweight (good warmth-to-weight ratio), and is available in 22 natural colors such as white, black, brown, red, gray, spotted, and tricolor. Negative characteristics of llama hair are little elasticity, easily attacked by moths, and less resistance to sunlight. Because llama hair lacks natural oils, it is very light and thus has 90–93 % yields. Fiber diameter ranges from 20 to 40 μm, and fiber lengths range from 80 to 250 mm (Cardellino and Mueller 2009; Frank et al. 2012). Llama hair has medullation, and the degree of medullation decreases with fiber diameter. Llama wool is used mostly for utilitarian items such as outer clothing, blankets, ropes, hats, scarves, vests, jackets, ponchos, blankets, fishing flies, and batting for quilts, whereas guard hairs can be used for making wall hangings, rugs, and felts (Gamze and Nilgun 2014) (Fig. 13).

M/s Altiplano Insulation, Inc., has established a sustainable methodology to develop a winter coat from state-of-the art equipment and craftsmanship of natives of the Altiplano. Shepherds believe that llama hair is one of the most sustainable

Fig. 12 Different breeds of llama camelids

100% Llama scarf from authentic knitting board (Rayannsom, 2011)

Woman's coat from Llama/ Wool, Polyamide / Lining Polyester of Doncaster, England

Alpaca/ Llama hair blended hooded Poncho Rustic with Ethnic Andean Designs from Bolivia

100% Sustainable Llama suiting of Altiplano Insulation

Fig. 13 Llama hair based luxury products

fibers because the respective garments do not retain odours and can be cleaned under moderate conditions. Low energy is consumed for the cleaning of llama products and so has a low impact on the environment. No harm chemicals are used for processing llama hair, and the hair can be made into yarns, fabrics, and garments using traditional methods. A fashion product made from 100 % luxury hair fibre is also naturally biodegradable and eliminates disposal problems. Luxury hair animals graze native plants and yield organic fibres because they are a natural part of the ecology of the region. Because llama hair fibre has natural colors such as white, grey, reddish brown, brown, dark brown, and black, it may not require additional dyeing (Altiplano 2015).

2.4.2 Alpaca Hair

Alpacas are native to the high Andes Mountain countries of Peru, Chile, and Bolivia, and Peru is the major alpaca hair-producing country with 90 % of the world trade; South America produces nearly 4055 tons of greasy alpaca hair annually representing a 0.04 % share of world natural fiber production (Quispe et al. 2009) (Fig. 14).

Eighty percent of alpaca hair is exported to fashion industries of China, Germany, and Italy as raw fleece, and Peru earned approximately $50 million in sales/year. Alpaca produces single-coated fleece; thus it does not require dehairing process. There are two breeds of alpaca—called suri and huacaya—which produce different hair. Their cross-breeds are also known as huarizo and misti. The huacaya is the "teddy bear" alpaca, whose full coat presents a round and wooly appearance. Huacaya fleece is crimped, very dense, and comes in eight basic colors: natural white, natural light fawn, natural fawn, natural light grey, natural grey, natural rose grey, natural dark brown, and black and most often come in five solid colors (The British Alpaca Society 2015; Ammayappan and Moses 2005).

The Suri is the Alpaca hair resembling dreadlocks but without matted hair fibers. Suri are very rare in the world and have extraordinary lustrous fiber, which makes

Fig. 14 Alpaca camelid

Alpaca Suri

Alpaca Huacayo

this fleece more sought after and expensive. Suri is long and straight hair, and Huacaya hair is short and curly hair. The annual production per animal is ranged from 0.9 to 3.6 kg with a mean of 1.8 kg. Alpaca hair is highly medullated; the fiber diameter ranges from 20 to 30 μm; and the staple hair length for Suri and Huacaya ranges from 10 to 12 in. and 8 to 10 in., respectively. The tensile strength and the elongation at break in Huacaya are greater than those in Suri. Alpaca hair has a higher cystine content, especially in Suri. The chemical composition of Huacaya is more closely related to wool, whereas Suri hair is more closely related to mohair. The Suri variety is more affected due to its open fleece and straightness of the hair (McColl et al. 2004).

Spinners are generally delighted with alpaca hair fleece because it comes in >22 different colors, which reduces the need to dye, which further protects and enhances the resilience, softness, flexibility, and hypoallergenic qualities of the fiber. The primary end use for alpaca hair is knitwear, but it is also goes into woven cloth for clothing, accessories such as shawls and stoles, and rugs. Alpaca hair has been blended with wool, cotton, and silk in knitwear and woven cloth as a means of broadening its use. People often describe alpaca clothing as being finer than cashmere, smoother than silk, softer than cotton, warmer than goose down, and more “breathability” than thermal knitted products (McGregor 2006) (Fig. 15).

Alpaca hair is naturally water-repellent due to the presence of natural resin, which makes it difficult to ignite. Huacaya hair has natural crimp, thus making a naturally elastic yarn that is well-suited for knitting. Alpaca hair has less lanolin, and so it does not require scouring before spinning. The Peruvian Society of Registered Alpaca (SPAR) exports high-quality alpaca hair fiber to the Italian wool industry for making high-quality garments. Alpaca hair is also utilized for outdoor sports clothing due to its lighter weight and better insulation during cold weather (Alpaca Canada 2015).

Recently knitters have come to admire alpaca hair fiber due to its softness and the quality of the yarns. In South America, it is sold in both dark and bright colours suitable for garments, whereas in the UK market it is sold in wide range of natural colours. Because this fiber comes in natural colours, it is very attractive to the fashion industry as a sustainable and environmentally fiber. The consumption of products made from this luxury hair fibre has increased in the European fashion market due to its sustainable rearing. It is reported that alpacas are also more efficient than

Acrylic/alpaca merino wool (45/40/15 blend) poncho by Alfredo Falcon, Peru

Baby alpaca (100%) knitted poncho with fur trim of Alicia Adams Alpaca, USA

Alpaca/merino wool (50/50 blend) throw by Woolme, Lithuania

Crewneck made from baby alpaca/wool/nylon (55/25/20 blend) with ribbed trim of Baltic, Peru

Baby alpaca/short silk (80/20 blend) scarf of Inis Meain, Ireland

Donegal weave suit of lambswool/alpaca (65/35 blend) by Magee of Ireland

Alpaca (100%) hand-knitted wrap of Mayu, Peru

Alpaca hair (100%) based woven scarf by Alfredo Falcon, Peru

Fig. 15 Alpaca hair based luxury products

cashmere/pashmina goats, i.e., they drink less water than a goat and can yield four to five time more hair than a goat in 1 year. An alpaca sweater costing \$150–\$200 and is less likely to pill and is more durable than a sweater made of other luxury hair fibers, which decreases the generation of textile waste each year (NRDC 2011).

2.4.3 Vicuna Hair

Vicuna hair is obtained from the vicuna, also known as the “bearer of the golden fleece,” the smallest and most agile species of llama. vicuna yields the rarest and finest fiber; in ancient times only royalty was allowed to wear this precious fiber. The greasy fleece yield varies from 85 to 550 g with an average of 200 g/year. Peru is the leading producer of vicuna fiber followed by Bolivia and Chile, and the annual greasy hair production is approximately 5500–6000 kg (Quispe et al. 2009). Vicuna fleece is mixed type containing approximately 10 % beard hair intermingled with fine hair, and the clean yield is approximately 70 %. The hair fineness of hair ranges from 13 to 14 µm, and the number of scales averages 10 (range 7–14)/100 µm. Fine hair fibers <18 µm are nonmedullated and those ≤30 µm possess interrupted to fragmented medullas. The fine fibers vary in length from 12 to 65 mm

Fig. 16 Vicuna camelid

(Quispe et al. 2010). Vicuna hair color ranges from red-brown to light tan to yellow-red, and the fine hair has softness, luster, strength, and warmth without weight, and it is highly desirable for fashion fabrics. Raw vicuña fleece can sell for $200/pound (Fig. 16).

The tensile strength of vicuna hair is equal to that of cashmere hair, and its chemical properties are similar to those of alpaca hair. Vicuna wool is finer than any other wool and as such is softer, lighter, and warmer than any other wool. The fibers of vicuna wool are so sensitive to chemical treatment that the wool is normally used in its natural golden color. Because of the shorter fiber length, vicuna hair is usually woolen spun, and the woolen yarns are woven into lightweight suiting, jackets, overcoats, and scarves. It has been blended with fine wool and used for making high-quality suiting. Vicuña hair is amazingly soft and has a natural cinnamon shade. Garments, such as sport coats, made from vicuna hair costs $21,000 and are marketed by Italian tailoring house Kiton; the high price is due to the fact that they make only 100 pieces a year. Similarly, a vicuña hair scarf from Loro Piana costs approximately $4000. Ermenegildo Zegna sold vicuna suits for $46,500 because they produce only 30 vicuña suits/year (Coggines 2013). The Italian fashion outlet Brioni sold fashion suits made from blend of vicuna, qiviuk, and pashmina that fetched approximately $43,000/piece. It is reported that UK designer Alexander Amosu has developed a Vanquish II Bespoke Suit, made from mixture of vicuna and qiviuk wools, that sold for $103,000 (Esteban 2012) (Fig. 17).

Because vicuña is an endangered species, the hair is traded by shearing the hair from a live vicuña at an officially authorized facility. Fashion industries carefully examine the source of the fiber and follow government regulations to develop the products for the sustainability of the fiber (Braaten 2015).

2.4.4 Guanaco Hair

Guanacos are the smallest camelids and roam in small herds in the High Andes. Guanaco hair has recently been introduced as one a luxury hair fiber by the wool sector, and the production is lower than that of vicuna hair. It is reported that from

Vicuna/qiviuk blend suit Vanquish II of Alexander Amosu

Handloom-woven men's scarf made from natural dyed vicuna hair (100%) in Peru

Vicuña sport coat of Ermenegildo Zegna, Italy (Coggins, 2012)

Vicuña/baby cashmere blend scarf of Loro Piana, Italy (Coggins, 2012)

Fig. 17 Vicuna hair based luxury products

South America, the greasy hair production is approximately 1500 kg (Quispe et al. 2009). The fleece is usually long and wooly, especially on the chest and thighs. The fur is mainly a reddish-brown colour and usually white underneath the animal. Like the llama, the guanaco is double-coated with coarse guard hair and a soft undercoat, which is even more highly prized than that of the alpaca, although guanaco carry far less of it. The colour varies very little, ranging from a light brown to dark cinnamon and shading to white underneath. The fleece is very fine and silky and contains 10–20 % beard hair and 50 % medullated fibers. Dehaired fleece that has a clean yield is approximately 70 %. The fiber diameter ranges from 18 to 20 μm with 118 scales/mm, and its physical structure makes it much softer and more lustrous. The fur of baby guanaco is famous for pelt, which resembles those of the almost copper-coloured red fox. It is also blended with fine wool, silk, and cotton for making high-quality fashion garments (Bas and González 2000; Anon 2011; Cardellino and Mueller 2008; Apu Kuntur 2015) (Fig. 18).

Fig. 18 Adult guanaco camelid

Guanaco fibre (100%) scarf of Guna, Peru

Guanaco fibre (100%) stole of Guna, Peru

Guanaco/silk (70%/30% blend) scarf (Esgyrn Guanaco, 2015)

Hand-woven scarf made from guanaco fibre (100%)

Fig. 19 Guanaco hair based luxury products

To sustain guanaco hair-based fashion products, the hair is often blended with other fine hair fiber in order to reduce the cost and enhance the novelty of the final products. Ultra-luxurious fabric, called “guanashina,” is used for making men’s suit, and it is produced by France’s cloth maker Dormeuil. The name is the amalgamation of guanaco (“guan”), baby cashmere (“ash”), and kid pashmina (“ina”), and suits are priced at ≥$50,000 (Nicksbespoke 2015) (Fig. 19).

2.5 *Rabbit Family*

2.5.1 Angora Rabbit Hair

The hair of the angora rabbit (*Oryctolagus cuniculus*) has been used in the textile industry since the nineteeth century. It is believed that French country women first developed hand-knitted products from angora rabbit hair, and today it is in high demand among an elite group of fashion consumers. Four angora breeds are used to harvest hair: English angora, French angora, German angora, and Satin angora. The annual production of angora rabbit hair is estimated at approximately 2500–3000 tons. China produces 90 % of the world trade, whereas Chile, the USA, and Eastern Europe are also significant producers (Schlink and Liu 2003; Ammayappan 2014). Angora rabbit hair has special characteristics such as excellent whiteness, superb softness, lightness, and warmth. The staple length of angora rabbit hair varies from 25 to 55 mm; the fiber diameter varies from 11 to 20 μm; and the fiber medullation ranges from 80 to 100 % (Fig. 20).

Due to the presence of a ladder-type medulla, products from angora rabbit hair have good insulating properties. Angora rabbit hair poses a problem in spinning due to its lesser scale height and medulla because they reduce interfiber cohesion. During spinning, angora rabbit hair tends to slip out of the yarn and also sheds away from the fabric (Perincek et al. 2008). It is primarily used for items such as

Fig. 20 Angora rabbit

sweaters, mittens, baby clothes, shawls, and millinery. Its chemical properties are similar to those of wool and other keratin fibers. The tip end of the fiber has the ability to curl, which encourages felting. It absorbs considerably less dye than wool fiber because of the medulla and its fineness. Angora rabbits come in many colours from pure white to peachy cream to black. To enhance its utilization, is the hair is chemically modified at the fiber stage and blended with other natural fibers, such as fine wool, cotton, and silk, for the development of knitted fabrics, shawls, and fancy woven fabrics (Nida et al. 2009; Ammayappan et al. 2009; Raja et al. 2011).

There are five grades of angora rabbit hair, and first four grades are classified based on their fiber length: grade one is 2–3 in. long, grade two is 1.5–2 in. long, grade three is 1–1.5 in. long, and grade four is any length. These first four grades must be white, clean, and without tangles or mats. Grade five is of any color and can be soiled and matted or unmatted. Naturally colored angora rabbit hair is used for mélange garments by small-scale manufacturers (Spalding and McLelland 1991) (Fig. 21).

Angora rabbit hair fibre is a by-product after the meat and fur. Angora rabbit hair is famous for its utilization in sweaters for its soft and fuzzy clothing look as well as warmth. It is reported that angora rabbit hair is plucked, and so rearing of angora rabbits has been banned by animal rights organizations since 2013 (Alex 2011). As a result, major retailers—such as Marks and Spencer, Top Shop, H&M, Primark, and Next—have agreed to postpone the use of angora products. Now it is difficult to

Sam Edelman Scott Club Monaco Etsy

Fig. 21 Angora rabbit hair based luxury products from different brands find angora rabbit hair sweaters. However to sustain angora rabbit hair-based fashion products, it is common to find angora rabbit hair blended products sold by famous fashion retailers such as Club Monaco (a mix of cotton, alpaca, cashmere, and angora rabbit hair), Sam Edelman (64 % nylon/30 % angora/6 % wool), Scott's Sweaters ($325), and Etsy (45 % angora rabbit/36 % cotton/13 % lambswool/6 % nylon) (Ang 2015; Etsy Inc 2015).

2.5.2 Hare Hair

A typical hare is larger than a rabbit and has longer ears with characteristic black markings. The hair texture is woolly. Hare have short hairs compared with angora rabbit hair. Their entire hair is pigmented from reddish brown to brown. Hare and rabbit hairs can be distinguished by their respective felting and milling property. It is largely used for making felts, hat making, and gloves, and for blending with other fibers (Ammayappan and Moses 2005).

2.6 Bovine Family

2.6.1 Musk Ox Hair

Musk oxen (*Ovibos moschatus*) are similar to yaks, but they live in the Arctic tundra. The musk ox is an Arctic mammal of the family *Bovidae* noted for its thick coat and for the strong odor emitted during the seasonal rut by males. Musk oxen primarily live in the Canadian Arctic, Greenland, Sweden, Siberia, Norway, and Alaska (Fig. 22).

Musk ox hair and products are commonly sold under the Eskimo name "qiviut" (pronounced kiv-ee-ute). Each animal produces approximately 1.5 kg of down hair, of which perhaps 60 % is recoverable by conventional dehairing. Fine hair of the musk ox is sold under the name of qiviut, and it has average fiber diameter of 15.2 μm and a fiber range of 17–22 μm without medullation. It is comparatively

Fig. 22 Musk oxen

100% Qiviut hand-woven scarf of Treadlers, USA

cashmere/qiviut (50/50 blend) hand-woven scarf of Treadlers, USA

Cashmere/qiviut (50/50 blend) hand-knitted wrist warmers of Vancouver, Canada

100% Qiviut blanket of Qiveut Designs, USA

Fig. 23 Qiviut hair based luxury products

smooth with low crimp, and the fiber length is 40–70 mm (Rowell et al. 2001). Scoured and dehaired hair is light brown to chocolate brown in colour. qiviut, the downy soft under-wool from the Arctic musk ox, is shed naturally each year during the spring months. Native Alaskan women from remote coastal villages of Alaska knit items by hand. Each village has a signature pattern derived from the traditional aspects of village life and the Eskimo culture. The caps and scarves made by the knitters are as comfortable to wear on cool days in a warm climate as they are in chilly weather. Qiviut is most commonly used for hats and scarves and a high-quality knitted scarf can cost >$300 USD. Qiviut hair yarn is eight times warmer than wool, is softer and more valuable than cashmere, and is mainly used by knitters and weavers (Arctic Qiviut 2015; Rowell et al. 2001) (Fig. 23).

Undercoat qiviut hair is smooth compared with fine wool and does not shrink in hot water, i.e., it does not felt. Qiviut clothing may be cleaned by hand washing gently in warm water, and is believed that qiviut is a sustainable fashion products. In Alaska, Musk Ox Producers' Co-Op helped to procure and develop products such as 100 % qiviut hair and qiviut/silk (80/20 blend) scarves, stoles, head band smokerings (Nachaq), tunics, and baby caps by traditional hand spinning and knitting in the trade name "Oomingmak." This supply chain gives supplemental income and helps sustain the local farmers' community (Oomingmak 2015).

2.6.2 Bison Hair

Bison are molting animals that shed their coats in the spring of each year. Native Americans have used this luxury hair for rope and as stuffing for insulation. They harvested 4–5 tons of greasy hair worth of $600 USD/kg. Bison hair fleece is made up of course guard hairs and fine downy hairs. The guard hairs are hollow and range from 21 to 110 qiviut in diameter with an average 59.0 qiviut. The fine downy hairs are solid and are covered with fine scales (Fig. 24).

Downy fibers range in diameter from 12 to 29 qiviut. The fiber diameter of downy bison fiber is similar to that of fine- and medium-grade sheep's wool. The moisture regain of bison hair ranges from 15 to 30 %, a property that is helpful to

Fig. 24 Adult bison

absorb away from the skin quickly. United by Blue, an outdoor goods company, developed socks from a blend of bison hair and merino wool, which is sturdy yarn, and they found that the products are ultra soft, temperature regulating, hypo-allergenic, and antimicrobial, and are easy to care for. They are used in making felts and blankets (Kailus 2014; McGregor 2012) (Fig. 25).

2.6.3 Yak Hair

The yak (*Bos [poephagus] grunniens*) is related to the bison and is a bovine. They live in the high Tibetan Plateau where they are often domesticated and used as transport animals. Yak hair is regarded by some as being an acceptable alternative to cashmere. China is the leading producer followed by Mongolia, Russia, India, and Nepal. Yak coats are black and consist of long coarse hairs and an undercoat of quite soft, silky wool, which is available in the form of dehaired combed tops. The outer coat resists wind, snow, and rain, and the inner fine hair fiber maintains warmth and provides insulation. The annual yield per animal is an average of 100 g. The hair is ≤50 mm in length and of 15- to 17-μm fineness in young animals and 18- to 19-μm fineness in adult animals. The colour of yak hair varies and depends on the breed. The interesting shades of yak hair are red, white, black, and blackish

Bison/merino (50/50 blend) cable-knit scarf of The Buffalo Wool Co, USA

Bison down/silk (50/50 blend) scarf of The Buffalo Wool Co, USA

Merino wool/bison down/nylon/spandex (56/24/18/2 blend) socks of United by Blue, USA

Fig. 25 Bison hair based luxury products

Fig. 26 Yak hair

Aduly Yak

Hand spun of yarn from 100% Fine Yak hair

brown. Coarse hair has a narrow medulla, and fine hair has no medulla. The outer guard hair of the yak fleece is the longer, coarser, and stronger, and it is mainly used locally for floor covering in huts and for mats. Strong ropes are made from the tail hair and felted fabrics from the down hair (Watson 2010; Pokharna 2003; Anon 2014) (Fig. 26).

Fine yak hair is blended with cashmere hair for making fashion shawls and scarves by German fashion brand "edelziege." In the mid-twentieth century, designers from Lyle and Scott introduced yak hair followed by French luxury brand Louis Vuitton, who produced a yak hair-based cape-cum-neck cushion. Later on suiting made from a blend of yak hair and merino wool was introduced by Dunhill, Eileen Fisher, and Vince. The fashion industry, for different luxury hair fibers, takes care about the sustainability of their manufacturing and supply chain of each product. Because luxury hair fibers are costlier and rare, much of the fashion industry prefers either alpaca or cashmere for making high-quality products. Some designers prefer some alternative sustainable natural fibers for the fashion industry. Paola Vanzo, the founder of Myak, introduced a woven stole made of 100 % baby yak wool, a textured cable-stitch scarf with rib finish at the bottom, and different fashion knit products (Vingan 2015; Myak 2014). Paola Vanzo also co-operated with nomads in the Himalayan region for the direct procurement of baby yak hair, which helps to sustain farmers by paying suitable remuneration. Exploring yak hair as an alternative to cashmere hair/alpaca hair creates a steady wage for and improves the living standards of farmers, particularly nomadic herders, who are world's poorest inhabitants as well farmers of sustainable hair-producing animals (Fig. 27).

Fig. 27 Yak hair based luxury products (Vingan 2015; Myak 2014)

2.6.4 Cow Hair

The United States is probably the largest consumer of pulled cow hair. A cow's hair coat is made up of outside hair and inside down fiber. The hair fiber varies widely in diameter. The average diameter for carpet grade is 36 μm. The fiber length varies from 12 to 50 mm. The number of scales is 12/100 μm. The fibers are medullated and are relatively narrow and unbroken. Cow hair, although harsh and coarse, can be made up into blankets, felts, mattresses, and carpets, but it should first be mixed with other fibers (Ammayappan and Moses 2005).

2.7 Other Hair Fibers

2.7.1 Reindeer Hair

Reindeer hair is obtained either by shearing or is a by-product from the fur of reindeer found in polar regions. Its fleece has coarse outer guard hairs and fine under hairs. Its fiber diameter varies from 20 to 30 μm; the hair length varies from 20 to 50 mm; and the colour ranges from white to brownish. It is mainly used as a stuffing fiber for toys and sports materials and is used to give special appearance in its blend with fine wool (Koztowski 2012).

2.7.2 Horse Hair

Horse hair is obtained from the tail of the horse (60- to 80-cm length and 80- to 400-μm fineness) as well as the mane (25- to 45-cm length and 50- to 200-μm fineness). Horse tail hair can be sorted into black, white, grey, brown, and mixed according to natural colors. Horse tail hair can be divided into 11 sizes according to length. Clothes made with horse tail hair lining cloth are stiff, beautiful, durable, and lasting and keep their shape. The average fiber diameter ranges from 75 to 280 μm. It is used mainly for making interlining for men's jacket, violin bows, and industrial and domestic brushes (Fig. 28).

Horse hair | Horse hair bracelets | Horse hair pendant | Horse hair stuffed mattress

Fig. 28 Luxury/fashion products made from horse hair

Horse hair is also used for making seat covers for top-grade sofas and car seat covers, superior handbags, and all sorts of cases and bags. It is generally smooth, stiff, well-ventilated, washable, and resists wear. Horse hair cotton union fabric is usually used as interlining or stiffening for tailored garments and millinery. This type of fabric was made into shirts worn by religious penitents and later became a popular upholstery material in the nineteenth century. By the end of the nineteenth century, horsehair was used as covering for parlour sofas (Abdurrahman 2014). It is now widely used in the manufacturing of top-grade sofas, car seat covers, and superior handbags. Argentina, Canada, Mongolia, China, and Australia are the main exporters of horse hair for the textile industry.

2.7.3 Chiengora Hair

Chiengora is the yarn developed from dog hair. “Chien” is French for dog and “gora” comes from “angora,” the fiber that dog hair most closely resembles. Chiengora is mainly used for hats, mittens, and sweaters. These products are soft and fluffy like angora; they are incredibly warm; and they shed water well. Garments made of this hair have been worn proudly by the rich and famous for generations. Chiengora yarns are also used in hand knitting, machine knitting, crocheting, and even as weft yarns by hand weavers (Greer 2003).

3 Conclusion

Natural fibers provide employment to 4 % of the world’s population particularly for the farmers, the growers, and the industry; similarly luxury hair fibers provide employment for farmers who live under extreme conditions for whom this income mitigates poverty. Business and fashion sector people wear clothes made of luxury hair fibers, which is a status symbol in their society; synthetic fibers do not offer the same effect (Fig. 29).

Due to their decline in the production, the sustainability of luxury hair fiber is the need of the hour because luxury hair fibers are source of “high-class” status and fashion clothing. This sector is in a position to procure the hair fibres required to maintain their societal status. Sustaining the harvesting of luxury hair fiber can also add more employment and enhance the economic activity of the country. The greatest threat to the sustainability of the luxury hair fiber sector is the extinction of hair-producing animals (Fletcher 2008; Gardetti and Muthu 2016).

Luxury hair fibers have a discriminate position in the textile clothing sector; however, it competes with other fibers even they are costly. Imitators sell fake products by mislabeling their products as luxury hair. Such fake products are sold at a low price, and consumers buy these products without knowing their real value. Thus, the grower of luxury hair fiber, i.e., the farmer community, is not remunerated. Fashioner prefer to spend their money as worth as possible, and they also want

100% Nepal Pashmina product (Go International Project, 2015)

100% Kashmir Pashmina product (Livemint, 2015)

100% Mohair hair product (Mohair South Africa, 2015)

100% Baby Alpaca hair product (Bri Cain, 2014)

70% Alpaca hair blended product (Bri Cain, 2014)

Luxury brand Kinross cashmere products of Scotland (Bēhance, 2015)

Mongolian Pure Cashmere (ipaustralia.com.au, 2015)

Product from 100% Alpaca from Australia

100% cashgora hair from New Zealand (LegalForce,2015)

Fig. 29 Different trademark for fashion products developed from 100 % luxury hair fiber

quality products. To sustain the luxury hair fiber sector, this is the right time to create appropriate policies for reforming the marketing of pure products, identify cost-effective technologies for value addition, and develop diversified clothing from such fibres. These strategies can improve the economic status of growers. Some possible ways to sustain luxury hair fiber are given below.

1. All luxury hair fibers are costly, and therefore 100 % pure luxury hair products are not affordable by common people. It is better to develop diversified or novelty products by blending them with other natural fibers such as fine wool fiber. This can reduce the cost of products and increase the consumption of luxury hair fibers over a shorter duration. This can enhance awareness of and demand for luxury hair fiber (Ammayappan et al. 2009).

2. Luxury hair fibers are soft fibres, and processors are not preferred to provide advanced finishing such as nano and aroma finishing. Advanced finishing can be standardized, and such value addition can be used to increase the demand for luxury hair fiber products.
3. Each luxury hair fiber is geo-specific, and each region should create suitable rules and regulations to identify and explore pure luxury hair fiber products in the markets by providing a unique label such as Woolmark. This can reduce the adulteration of other wool products in the market.
4. Spinning and weaving of luxury hair fiber is traditional and manual work. Suitable technology intervention is required to reduce the processing time by modifying conventional spinning and weaving either for semi-automation or to reduce wear and tear in the development of quality products.
5. Sustainable rearing of luxury hair producing animals also mainly depends on the support of the local farmers' community because they live and share natural resources with animals. It is vital to involve the local farmers' community in the management of natural resources, in order to make it available to the animals when needed, with the help necessary infrastructural and financial support from the government and technical expertise from nongovernment organizations (Namgail et al. 2010).
6. Luxury fiber-producing animals are reared under extreme weather conditions, and so they are limited in population and their hair high in price. This situation lends to poaching, whereby poachers illegally procure and trade fiber as well duplicate products in the market. To sustain the animal population, the following steps must be implemented at the farmers' location (Brent 2013).

(a) Organize a community-breeding structure to increase the animal population
(b) Train women ed to spin perfect yarn on advanced spinning and weaving systems for qualitative and quantitative production
(c) Convey awareness of natural dyes and their market potential through workshops
(d) Organize craft persons in a effective co-operative mode
(e) Train the weavers per the market needs
(f) Implement a micro-loan system so product developers can purchase fiber
(g) Establish a direct supply chain to exporters to obtain their products.

Luxury hair-based products still dominate the market and must meet the requirements of customers, particularly for specific end uses. Diversified products, innovative value addition, and proper labeling could improve the demand for luxury hair products, which will ultimately enhance the economic status of growers involved in harvesting luxury hair fiber.

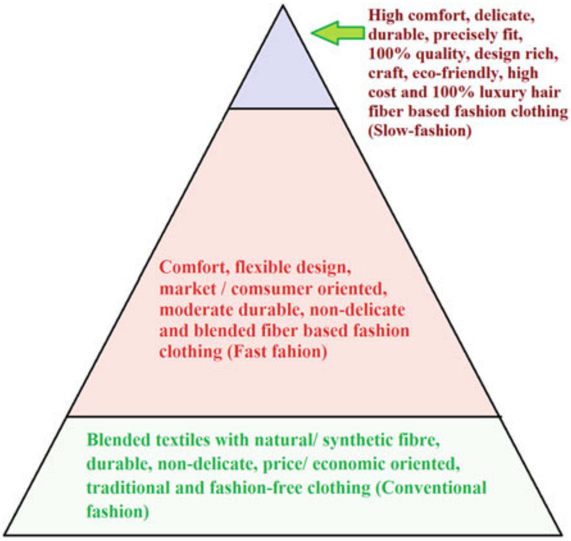

Fig. 30 Fashion triangle

4 Conclusive Remarks

Consumption pattern of fashion clothing is similar to a triangle, in which the voluminous lower portion indicates regular clothing with less quality/design/comfort/price in high quantity; middle portion occupies with the fast-fashion industry with semi-durable quality/comfort in moderate price; the tiny-top rules by high quality design and costliest luxury brands as mentioned in the Fig. 30. Fast-fashion companies target middle class families and they are marketing in high quantity with moderate quality clothing and it generally leads to mechanical dumping of used clothing. It is reported that fashion and textiles industry is the second most polluting industry in the world after oil industry.

There are nearly 8,000 different chemicals are used in dyeing and finishing process to make single fashion apparel under fast-fashion products. Mechanical dumping of used clothing can pollute the environment and pose many ecological problems and now many fast-fashion industries switched towards the quality-fashion companies with sustainable focus. It is also called as ‘slow fashion’ i.e. clothing manufactured under safe labour conditions, skilled manpower, sustainable materials, eco-friendly processing with satisfaction of both ethical and aesthetic desires. However luxury hair based fashion industry sells resource-dependent and costliest products, which increases their need to sustain. Being craftsmanship involved in the production, luxury fashion industry promote specialized skills and train employees to enhance and sustain their skills. Luxury fashion industry is less anxious about cost reduction and enhancing the value of the final product by novelty design. To keep their market values, they spot themselves as green brands by labeling like “Mohair Mark”. They can redefine the concept of quality by taking all environmental friendly steps i.e, most of the luxury fashion brands follow eco-packaging, eco-friendly raw materials, sustainable processing with lower water and energy consumption as well as supporting various environmental initiatives (Joy 2013).

To sustain the production of luxury hair fiber, it is necessary to standardize the supply chain of the luxury hair based fashion clothing by implementing sustainable harvesting, environmental free processing, high skilled crafting, quality assurance by eco-labeling and eco-friendly technologies in every step. Sustaining can be implemented by taking responsibility of each person’s starting from farmer to consumer. Such sustainability make the luxury hair fiber can also give a chance for its utilization for our future generation.

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Mainstreaming of Sustainable Cotton in the German Clothing Industry

Erik G. Hansen and Stefan Schaltegger

Abstract This chapter analyses the sustainability-oriented transformation of clothing industries. Although sustainability pioneers introduce new products in niche markets, incumbents advance them into the mass market. Together this can lead to the transformation of industries, markets, and consumer habits. We examine the German clothing retail industry with a focus on organic cotton and related sustainable fibres. The analysis covers some of the largest German textile retailers. Data collection is based on publicly available sources. We find that in the late 1970s, Hess Natur pioneered organic cotton practices and supported the development of sustainability standards in the clothing industry. Although in the beginning this was largely a phenomenon in niche markets, some of the organic practices have now diffused amongst mainstream retailers. This is counterintuitive because previous theory suggests that incumbents only adopt practices with significantly lower sustainability standards than do niche companies. The findings can support managers to better understand their organization's role in the transformation of industries and markets toward sustainability, and—vice versa—understand how the transformation may affect them. Leading the transformation challenge by adopting organic and other sustainable supply chain practices can be an important measure for market success.

Keywords Sustainability-oriented innovation · Corporate sustainability · CSR · Organic cotton · Integrated production · Certification · Environmental quality standards · Eco labels · Transformation · Textile industry · Clothing industry · Supply chain

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S.S. Muthu and M.A. Gardetti (eds.), *Sustainable Fibres for Fashion Industry*,
Environmental Footprints and Eco-design of Products and Processes,
DOI 10.1007/978-981-10-0522-0_2

1 Introduction

The key idea of a sustainable economy is the lasting, world-wide guarantee of individual opportunities to secure basic needs as well as attain a greater quality of life while at the same time preserving nature and promoting humane social relationships (cf. for example WCED 1987). Changed and changing markets and legal, political, and social conditions challenge companies to take greater account of sustainability. The degree of sustainability-oriented industry transformation varies from one country to the next; however, it is always influenced or even shaped by changes made within and by corporations. In this context, corporate sustainability does not mean a (superficial) "repair" or "correction" of corporate activities but rather making deep changes, i.e., making sustainability principles an integral element of corporate value creation by knowing that engagement is most credible when it is comprehensive and lasting and contributes not only to social and ecological development but also to corporate success.

Industry transformation toward sustainability in the textile and clothing industries has been studied in the literature from diverse perspectives (e.g. Illge and Preuss 2012; Villiger et al. 2000). Here we focus on an illustrative examination with a focus on the diffusion of organic cotton through incumbent clothing retailers. The change from conventional cotton to organic and other more sustainable forms of cotton indeed represents a strategic innovation to incumbent retailers because they must (a) develop the sustainability consciousness and purchasing patterns of consumers or enter new consumer segments; (b) build up new competencies in managing the upstream supply chain (i.e., cotton cultivation); and (c) create or engage in co-operations to increase the cultivation of more sustainable cotton.

The chapter is structured as follows. Section 2 gives an overview of sustainability issues and the important aspects of sustainability management in the clothing industry. Section 3 presents the case study method. Section 4 presents the findings of the illustrative case study in the clothing industry. Finally, Sect. 5 discusses the findings.

2 Sustainability Challenges and Developments in the German Clothing Industry

2.1 *Overview of Industry*

Clothing is a basic human need and the textile and clothing industry (in the following text simply "clothing industry") delivers goods in response to this demand. At the same time, the clothing industry is subject to severe ecological and social problems in most of the phases of the supply chain spanning from fibre production, spinning, fabric production and dyeing/finishing to clothing production (cf. Goldbach et al. 2003). During the last few decades, the clothing industry has faced price pressure exacerbating its efforts to become more sustainable. The pursuit of a comparative cost advantage has led to the outsourcing of much of European and US clothing production to emerging and developing countries in Asia. This covers most of the value chain. The value creation remaining in Western countries is mostly limited to value-added services such as design and overall brand management (exceptions are some new entrepreneurial firms experimenting with new business models based on local production; e.g., Plieth et al. 2012). This relocation of value-chain activities to low-wage countries has increased the sustainability challenges because it becomes ever more difficult to manage or even oversee labour and ecological practices at supplier sites in these supply chains (Harms et al. 2013).

More generally, taking a product innovation perspective, sustainability improvements can occur across all life-cycle phases (Hansen et al. 2009). In the clothing industry this has led to a plethora of standards, certification systems, and labels covering different parts of the value chain (see Fig. 1). These approaches aim, for example, at better inputs (particularly fibres), the control of production regarding various chemicals and other risky substances (threatening the natural environment and the health of workers and other stakeholders), the extension of product lifespans, or closing the loops at the product's end-of-life (either by reusing/repairing/recycling or, in case of biodegradable products, by reintroducing them into the biological metabolism). In this chapter, we focus on the sustainability at the beginning of the value chain, i.e., the provision and use of fibres. While the improvements of fibre production is predominantly perceived as an environmental measure, it is in fact also linked to

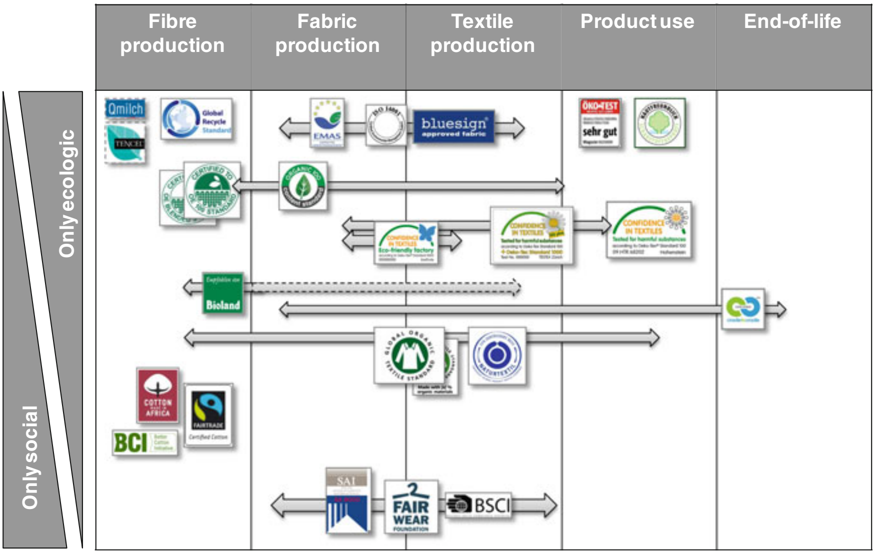

Fig. 1 Ecological and social quality standards, certification systems, and labels covering different life-cycle phases in the textile industry (Hansen and Schaltegger 2013, p. 586)

both direct social effects (i.e. health of farmers and of nearby communities) and indirect social effects (i.e. consumers' health).

The textile and clothing industry uses various natural and man-made fibres—such as cotton, wool, polyester, and nylon—which all have advantages and disadvantages regarding environmental impact (Chouinard and Brown 1997; see also the detailed classification of fibres in Sanches et al. 2015, p. 694). Still, cotton is the main natural fibre used in the clothing industry globally accounting for 38 % of the world's textile consumption (DU 2009b; Sanches et al. 2015).

2.2 Sustainability Challenges Associated with Cotton

Cotton fibre production is a sustainability "hot spot" in textile production (Gminder 2006, p. 126; Villiger et al. 2000, p.159) both concerning the general characteristics of the fibre (e.g., land use, water footprint) as well as the specific cultivation practices used in today's widely spread intensive agro-industrial farming (e.g., pesticide use). Overall cotton production is linked to many challenges to sustainability (e.g., DU 2009b; Gminder 2006; Goldbach et al. 2003; Illge and Preuss 2012) covering "degraded land as a result of salinisation and erosion; water depletion by excessive use of soil and surface water; natural habitat conversion due to cutting of forests and dam constructions; eutrophication of surface water; wildlife contamination by pesticides (insects, fish, mammals, birds); and human health due to direct pesticide intake primarily by farm worker (Kooistra and Termorshuizen 2006, p. 33)." Excessive land use is also linked to displacement of the local or indigenous population.

The major issues of cotton cultivation are usually considered to be land and water use on the one hand and synthetic pesticide use and related toxic effects on humans, other species, and the natural environment on the other. Conventional cotton production uses very large quantities of synthetic pesticides and chemical fertilizer, which not only contaminate soil and water and decrease biodiversity but also have significant health impacts on farmers and local inhabitants, particularly in developing countries where usually the most toxic pesticides are applied without proper protection of workers. Due to residues, this can even affect consumers (e.g., those with allergic reactions). Approximately 10–16 % of worldwide pesticides and 25 % of insecticides are used on conventional cotton production while this covers only 2–4 % of the global agricultural land (Gminder 2006; Sanches et al. 2015). With the aim of solving some of these problems, genetically modified plants have been on the rise; however, this is with severe negative side effects such as loss of farmer rights to collect their own seeds (due to patents), heavy dependence on (sometimes monopolistic) seed firms, increased cost of seeds, and negative impact on alternative crops and wild plant populations (e.g., cross-pollination) (DU 2009b; Gminder 2006). The price pressure on raw materials and particularly fibres has further intensified agricultural production systems and their negative environmental impacts (Goldbach et al. 2003).

2.3 General Approaches for Improved Sustainability of Fibres

Two groups of alternatives to conventional cotton can be distinguished: alternative farming systems for cotton can be pursued or alternative fibres can be sought.

2.3.1 Improving Sustainability of Cotton

A first set of options for sustainability-oriented improvement is to look at alternative farming systems such as integrated or organic production:

- *Integrated production of natural fibres*. Integrated production or integrated pest management (IPM) aims at the provision of a more sustainable production system for natural fibres. The integrated production system (IOBC/WPRS 2004) is an *efficiency* approach and deals with the reduction of environmental impacts by using less pesticides and fungicides, chemical fertilizers, and water, and this was already called for in the Brundtland Report (WCED 1987, p. 67). We will use the term “improved cotton (IC)” in the remainder of the chapter to refer to this type of ecological (and partly social) improved cotton. Integrated production, including improved cotton, is often criticised for unclear standards and missing certification systems, which leave too much room for uncertainty. However, certification standards such as Cotton Made in Africa (AbTF 2012) or initiatives such as the Better Cotton Initiative (BCI 2009) are exemplary certification systems promoting the idea of improved cotton. Some researchers and practitioners also see genetically modified fibres as a solution to excess pesticide use and thus as a contribution to sustainability. However, against the background of lack of knowledge of long-term effectiveness as well as the many ecological, social, and ethical risks associated with the new technology, we emphasize the precautionary principle and question the instrumentality of genetic engineered plants for sustainability until the doubts are reasonably resolved (Makoni and Mohamed-Katerere 2006).[1] This debate is also reflected

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[1] The most prominent GMO fibre is Monsanto’s “Bt Cotton” plant which incorporates genes of the bacterium “*Bacillus thuringiensis*” for the production of a biological insecticide and thus makes the plant resistant to some insects at least in the short term. The introduction of GMO cotton in major production countries, such as the US, China, and India, has often resulted in yield increase and decreased pesticide use (e.g., Krishna and Qaim 2012) and is thus promoted by biotech proponents as a solution to sustainable development. The effectiveness, however, has been questioned as being far from fact because the technology depends on local circumstances (Qaim et al. 2006) and seems to erode over the long-term due to secondary pests (Wang et al. 2008; Zhao et al. 2011) or pesticide resistance (Tabashnik et al. 2012). However, others criticise the technology not for their (in)effectiveness but for their non-technical risks, both ethical and social (Hahn 2012). Overall, the potential benefits of GMO plants are controversially discussed and are linked to overstated benefits, missing evidence on long-term effects, narrow assessment of risks based on simplified cost-benefit analysis excluding many ethical, social and other aspects, and last but not

in the assessment criteria of the various cotton initiatives: the Better Cotton Initiative is “technically neutral” and allows GMO cotton (BCI 2009), whereas Cotton Made in Africa bans it (AbTF 2012).

- *Organic fibres.* In contrast to the integrated production system, the organic production system is a *consistency* approach (Huber 2000; Schaltegger and Burritt 2005) because it aims at producing cotton with material flow systems in harmony with the natural environment. This is achieved by crop rotation and the use of natural fertilizer (usually from animal husbandry) and natural pesticides, thus it represents a circular economy in the agricultural sector. Chemical (also called synthetic) pesticides and fertilizers are banned. Based on comparative life-cycle analysis between organic and conventional crops (including cotton), organic produce is sometimes considered less environmentally friendly because the environmental benefits related to the organic practices are said to be overcompensated by lower yields leading to the assumption that “organic production is not necessarily any more or any less environmentally friendly than current conventional cotton production” (Wakelyn and Chaudhry 2009). However, this type of LCA study—due to the necessary system boundaries—usually does not consider all of the direct and indirect effects, e.g., the human–toxicological/biodiversity effects of pesticide use and other indirect effects of conventional industrial agriculture. In addition, the water footprint is often not fully considered in LCA studies (Kooistra and Termorshuizen 2006, p. 34). Moreover, while it is commonly accepted that the heavy use of fertilizers and pesticides in conventional agricultural practices usually leads to higher productivity (i.e. yield increases), it is often neglected that organic agricultural practices can also do so, at least in specific contexts (e.g., Gminder 2006, p. 127; Hess Natur 2009). Particularly in developing nations, the potential for yield increases with organic (Badgley et al. 2007). Although the organic system does not incorporate any regulation regarding water use, organic cotton farms are predominantly (60 %) rainfed and therefore much less prone to water depletion (Kooistra and Termorshuizen 2006, p. 34). Although organic cotton production is more cost-intensive due to a higher demand for manual labour (which leads to higher employment levels in developing nations and therefore represents a desirable social effect), this is usually financially offset or even overcompensated with price premiums for (certified) organic cotton. In the last decade, organic cotton has become an important trend in the clothing industry, particularly in Europe and the US (Willer and Kilcher 2011; Memon 2012). Organic cotton production has experienced strong growth in the past, and although it experienced a steep decrease in 2011/12 (a major problem, beside others, is the provision of organic seeds due to pollution by genetically modified cotton),

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(Footnote 1 continued)

least, unethical marketing practices of biotech companies (e.g., Makoni and Mohamed-Katerere 2006). Considering the lack of scientific knowledge on the long-term impacts and risks of GMO, the *precautionary principle* should apply (Makoni & Mohamed-Katerere 2006; Zhao et al. 2011).

future growth is forecasted (TextileExchange 2012). Still, organic cotton accounts for only approximately 1 % of worldwide cotton production (Pay 2009). Two main certification systems for organic cotton exist internationally: the Organic Exchange standard (OE 100; OE Blended) only controls for the organic content, whereas the "IVN certified BEST" and Global Organic Textile Standard (GOTS) additionally define ecological and social criteria for the entire textile supply chain (IVN-certified BEST is considered the most ecological stringent standard in the industry; although it is derived from the latter, the related GOTS standard relaxes some of the criteria). Moreover, a huge number of company-specific labelling approaches exist, which may be used in addition to or in replacement of independent certification (DU 2009a).

In summary, the three cotton-farming systems can be compared regarding their environmental impacts (Table 1). In general, the challenges of heavy land and water use do not differ much between the various farming systems, however, in practice organic farms mostly provide for a better water footprint because the majority of farms are rainfed. The major differentiator in the farming systems is the use of pesticide and chemical fertilizer, which is banned in the organic farm system, therefore eliminating toxic effects on humans, other species, and the natural environment. At the same time, organic cotton is often linked to a decrease in productivity per hectare (yield) depending on locality. However, over the long term, organic agriculture can maintain productivity over infinite time periods, whereas conventional intensive agriculture is subject to soil degradation and a decrease in productivity in the long term.

Table 1 Characteristics of organic, integrated, and conventional cotton-farming systems (based on Kooistra and Termorshuizen 2006, p. 32)

	Organic	**Integrated production**	**Conventional**
Synthetic/organic fertiliser use	Organic	Synthetic/organic	Synthetic/organic
Synthetic/natural pesticide use	Natural	Synthetic/natural	Synthetic/natural
Irrigation water use	Yes (but often rainfed)	Yes	Yes
Average yields	Rel. low (depending on locality)	Rel. high	Variable
Soil degradation	Low	Medium	High
Monocultivation/mixed-cropping systems	Mono/mixed	Mono/mixed	Mono/mixed
Continuous cultivation	No	No/yes	No/yes
Land-clearing allowed	Yes	Yes	Yes
Burning organic material (weeds, plants, etc.)	No	Yes	Yes
Mechanised labour	Yes	Yes	Yes
Share of world production (%)	1	20	79

2.3.2 Alternatives to Cotton Fibres

A second set of options covers alternative fibres, both natural and man-made, as well as recycled fibres:

- *Switch to alternative natural fibres*. One approach is to switch to alternative natural fibres such as hemp or flax. Compared with cotton, hemp has much lower environmental impacts because it requires almost no pesticides as well as only a modest amount of fertilizer (van der Werf 2004) and has much higher productivity levels per unit of land (Cherrett et al. 2005). Indeed, an LCA analysis showed that organically grown hemp is much more environmentally friendly than cotton (and polyester) (Cherrett et al. 2005). At the same time, however, hemp is very much constrained regarding its diffusion in the clothing industry because its fibre characteristics make textile production more difficult and less appealing to consumers (Cherrett et al. 2005).
- *Replacement of natural fibres with man-made fibres*. Cotton can also be replaced by manufactured (man-made) fibres. An increasing share of clothing uses synthetic fabrics such as polyester (Shishoo 2007) which are also highlighted due to their durability. However, petrochemical-based (nonrenewable) materials cause many environmental and health problems in all phases of the product life-cycle and thus do not necessarily represent a more sustainable alternative to clothing made from conventional cotton. A long overlooked fact is that the use of synthetic materials in consumables such as clothes, shoes, tires etc. leads to abrasion and, hence, leakage of non-biodegradable plastic particles into the natural environment ultimately harming natural systems and species (including humans) living therein (EMF 2016). It is for this reason that consumables should be designed in harmony with the biological metabolism (Braungart et al. 2007). A more promising alternative might be the substitution of natural fibres with man-made fibres from renewable sources such as lyocell fibres based on cellulose (Shishoo 2007; TextileExchange 2011), "qmilch" based on milk proteins (Schölch 2013), or soybean protein fiber (Sanches et al. 2015). However, these fibres are currently representing only small niches in the clothing industry, and their diffusion still needs to be proven.
- *Use of recycled fibres*. A further approach is the use of recycled fibres. Cotton recycling is so far rarely used with one exceptions being H&M, which intends to increase the use of recycled fibres of both cotton and polyester; however, detailed information is given only on polyester (H&M 2011). Overall, polyester occupies the lion's share of recycled fibres, and cotton recycling is only slowly gaining more attention (TextileExchange 2011). Certification systems are increasingly available to guarantee recycled contents in the finished good, e.g., the Global Recycling Standard (GRS). However, the contribution of recycling to increase the industry's sustainability is often overstated. In fact, recycling is mostly "downcycling" (Braungart et al. 2007), i.e., collected materials (e.g., from plastic bottles) are of lower value and are not used for the same purpose again (i.e., plastic bottle) but for "more forgiving purposes" (e.g., carpets). Also,

> products with recycled contents can often not be recycled again because of the mix of different plastics. The diverse and sometimes unspecified sources of the recycled content can also lead to a new problem: lower or uncertain human-toxicological characteristics—or "material health" (Braungart et al. 2007)—of the recycled fabric. Some may even consider the term "plastic recycling" to be misleading because the diffusion of recycled plastics in industry applications also cements the demand for virgin plastic and thus further stabilizes the existing (plastics) regime (e.g., Geels 2002).

Although all of the presented approaches can play a role in advancing sustainability, natural fibres—particularly cotton—are considered to be the most popular fibres with overall very good fibre characteristics regarding their use in clothing (DU 2009b). It is thus unlikely that cotton will be generally replaced at least in the near future. It is thus of major importance to consider sustainability strategies for cotton, which is the topic of this chapter. Although we have introduced other improvement approaches, it is *not* the aim of the chapter to compare the sustainability of cotton versus noncotton fibres.

Given the chosen focus on cotton, we have explained *organic* and *improved* cotton strategies as alternatives that are linked to *organic* production and *integrated* production systems, respectively. As an umbrella category, practitioners and researchers often refer to them as "sustainable cotton" (e.g., Goldbach et al. 2003; H&M 2011; Illge and Preuss 2012) although, to be more precise, it should be called "*more* sustainable cotton" (or "less unsustainable cotton"). Although we focus on organic cotton in this chapter, empirically (as we will see later in the text) the two approaches are closely interrelated, and thus it is not always practicable to deal with the two production systems in a separate manner (it should also be mentioned that organic and improved cotton often simultaneously lead to social benefits, such as eliminated health threats of pesticides, higher incomes of farmers due to price premiums, and better working conditions in production due to additional social criteria in certification systems such as GOTS).

3 Method

We followed a case study research approach (Yin 2003) with the focus on the clothing industry. The case is "illustrative," emphasizing the dynamics of the industry, rather than an "in-depth" case on a single company. It is an embedded single-case design (Yin 2003, p. 43) using two units of analysis: The analysis focuses on the industry level, although we also specifically consider individual companies (incumbents) and how they respond to sustainability challenges. We selected the clothing industry for its high relevance to society and severe negative sustainability impacts. First, clothing is a basic human need. Second, the current practices in the industry are mostly unsustainable in all phases of the product life cycle from cotton plantation to fibre production, production of clothing, finishing of

Table 2 Top 10 textile retailers in Germany (Hansen and Schaltegger 2013, p. 589)

Company	Sales revenue (textiles) 2010 [Mio EUR]	Rank in global organic cotton sourcing 2010	Organic products	Availability of public data	Selected for case study
Otto	4.158	10	Own collection ("PURE WEAR")	High	+
H&M	3.211	1	Own collection ("Organic cotton")	High	+
C&A	3011	2	Own collection ("Bio cotton")	High	+
Metro (incl. Galeria Kaufhof)	2.418	–	Selected items	Low	–
Karstadt	1.973	–	n.a.	Low	–
P&C	1.334	–	n.a.	Low	–
Tengelmann (includes Kik)	1.195	–	Selected items	Low	–
Lidl	1.049	–	Selected items	Low	–
Aldi group	1.034	–	Selected items	Low	–
Tchibo (textiles)	945	–	Selected items	High	+

clothing, and end-of-life treatment (see previous above). As we focus on incumbents' responses to sustainability challenges, we have chosen 4 of the 10 largest players in the German clothing retail sector (TextilWirtschaft 2011), of which 3 belong to the top 10 organic cotton buyers (TextileExchange 2012). The selection was also based on information availability and the related knowledge about the scope of organic textile practices (Table 2).

The four companies in focus can be briefly characterised as follows:

- Otto is a major mail-order business belonging to the Otto Group, a family business founded in Germany. The company operates in mainstream markets but has aimed for integrating sustainability strategically for several decades.
- H&M, a Swedish company, is one of the global top players in fashion retail focusing on fast fashion.

- C&A is Dutch fashion retail company with headquarters in the Netherlands and Germany. It is fully family owned through its holding company. For many decades associated with a low-budget image, the company has recently moved toward higher quality and prices.
- Tchibo, based in Hamburg, Germany, is one of the largest German consumer-goods retail companies. Through a shop-in-shop system and its own stores, Tchibo sells a diverse product portfolio including coffee, textiles/clothing, furniture, and mobile phone contracts, amongst others. The company is known for its weekly changing assortment of goods.

For the following case study, we collected data from secondary sources such as previously published research, industry studies and reports, market reports, and company reports. For the sake of data availability (e.g., sustainability reports), the data collection was based mainly on a snapshot from the year 2011, but it also covered broader historical accounts where necessary.

4 Illustrative Case Study: Transformation in the German Clothing Industry

4.1 Pioneering the Organic Market in Germany

The German market for ecological textiles and clothing was mainly pioneered by Hess Natur. In 1976, Hess Natur was founded by Hans Hess as a mail-order business in Germany with the aim of developing healthy and eco-friendly clothing free of pesticides and other chemical residues (Hess Natur 2009, 2011; Illge and Preuss 2012; Paulitsch 2001; Schaltegge 2002). Thus, they banned polyester and other synthetic fibres (today this has partly changed) and focused on natural fibres instead. They also exerted rigorous control of the clothing supply chain with regard to the use (and ban) of chemicals and other health-threatening substances. Hess Natur also focused on more regional sourcing and production (e.g., in Europe instead of Asia) to spur local economic cycles, keep transportation impacts low, and improve supply-chain transparency (Paulitsch 2001).

Although in the beginning the focus was on producing clothing without negative health impacts, a next step further upstream the supply chain led to the questioning of existing cultivation practices of natural fibres and hence to investigate the impact of organic cotton. Because the supply for organic cotton was virtually non-existent, Hess Natur, partly in cooperation with development aid institutions or NGOs, invested in development projects aimed to increase organic cotton cultivation (e.g., in Africa). In 1991, in partnership with the Sekem farm in Egypt, Hess Natur was the first company worldwide to invest in organic cotton cultivation (Hess Natur 2009). Ultimately, Hess Natur developed its own market for textiles and clothing based on organic cotton. In 2008, Hess Natur was still the global number 10 organic cotton user in the world, although its relative share dropped considerably with the market entrance of large incumbents; hence, it is no longer part of the top 10 TextileExchange 2011).

Hess Natur probably developed the world's most stringent sustainability criteria for clothing and the textile supply chain and cofounded the International Natural Textile Association in 1999, which issued organic textile standards and certification schemes in Germany (Paulitsch 2001) and subsequently led to the GOTS standard, which is now applied on a global level (Pay 2009, p. 4).[2]

While in the beginning the development of organic markets was the task of early pioneers, mainstreaming was only possible through incumbents who followed and reinforced this trend.

4.2 Mainstreaming the Organic Market in Germany

4.2.1 Overview

An "early follower" in the organic cotton trend was the Otto Group, the largest textile retailer (mail-order business) in Germany (cf. Table 1). The company's engagement is strongly driven by the (family) majority owner and CEO Michael Otto. Already in the 1980s, Otto acknowledged the importance of environmental protection and formulated it as a corporate goal (Goldbach et al. 2003; Seuring et al. 2004). Otto confirmed its engagement by purchasing organic cotton and developing its own label, "Pure Wear." In 2010, Otto has become the 10th largest buyer of organic cotton worldwide (TextileExchange 2012).

In the last few years, other conventional retailers have entered the market for organic cotton clothing (Table 3). The retail sales volume of organic cotton products has grown steadily for the last decade (Fig. 2). For example, C&A has purchased organic cotton since 2006 and in 2009 founded its own brand, "Bio Cotton," for 100 % organic clothing (C&A 2012a). Today C&A, the second largest textile retailer in Germany, has taken a leading role in the purchase of organic cotton making it one of the world's largest buyers of organic cotton. In terms of quantity, it has long overtaken the pioneers Hess Natur, Patagonia and Otto (TextileExchange 2011). In 2011, C&A sold approximately 32 million items made from organic cotton, and the company plans to double this number in the short term. This strong diffusion into the mass market is only possible because C&A did not pass the higher resource costs of organic cotton (compared with conventional cotton) on to the consumers but rather accepts a smaller profit margin (C&A 2012a, b, p. 104).

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[2] Internationally, the US-based outdoor clothing company Patagonia was another small pioneer replacing conventional with organic cotton in 1996 (Fowler and Hope 2007). The company was one of the largest organic cotton buyers in the world until 2006 (TextileExchange 2011).

Table 3 Organic cotton (OC) and improved cotton (IC) use by large German retailers (based on Hansen and Schaltegger 2013, p. 591 and Schaltegger and Hansen 2013, p. 187)

		C&A	H&M	Otto	Tchibo
Organic cotton (OC) history	First documented use:	2007	2004	1995	2006
	Own collection since	2008	2007	~1999	2008
	Collection name	Bio cotton	Conscious collection	PURE WEAR	n.a.
Use of organic cotton (2011)	Global sourcing of OC (Rank)	#2	#1	#10	–
	OC (tons)	12.500[1]	15.000	450	210
	OC items sold (Mio items)	32	n.a.	n.a.	3.4 (OC + IC)
	OC (% of total business)	13 %[a]	7.6 %[b]	1.5 %[a]	0.5 %[b]
	OC + IC/Sustainable cotton (% of total business)	13 %[a]	7.6 %[b]	2.2 %[a]	5 %[b]
Corporate goals	By 2012/2013	– Double sales of OC items	– Use 5 % IC (BCI)	– 5 % OC – 10 % IC (CmiA) (in own brands only)	– Maintain OC – Sell 8.5 Mio sustainable textiles (OC + IC) which equals 15 % of total cotton products
	By 2020	– Promoting OC through Cotton Connect initiative – 100 % sustainable cotton (OC + IC)	– 100 % sustainable cotton (OC + IC + recycled cotton)	– 100 % sustainable cotton (OC + IC)	n.a.

[1] Data from 2008
[a] items
[b] tons

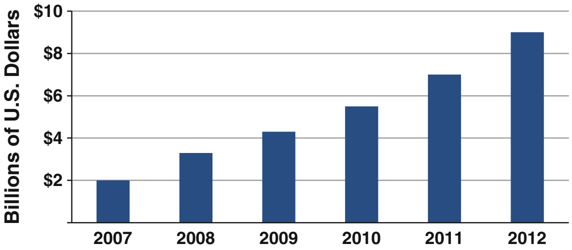

Fig. 2 Global retail sales of organic cotton products. *Source* TextileExchange 2012, p. 22

4.2.2 Marketing Strategies, Long-Term Strategies, and Supply Management

The strategies of the textile retailers in Germany to market organic cotton follow different paths, which can be described by the following characteristics:

- First, retailers may sell *only a selected item in organic quality* for piloting or experimentation (e.g., Tchibo), introduce a new organic collection (e.g., C&A, H&M, Otto), or transform the entire product portfolio (the latter is limited to pioneering companies such as Hess Natur and Patagonia; however, the future will show whether incumbents such as C&A also take this route as planned in the long-term).
- Second, *differences exist with regard to certification.* All retailers mention the use of certification standards GOTS and/or OE. The actual certification is very important because they differ with regard to whether they only control for the organic content (OE) or additionally for production characteristics in the entire supply chain (GOTS). However, detailed information on the share of certification in relation to overall organic cotton use is very difficult to obtain.
- Third, not all retailers analysed use labels of independent certification systems (e.g., GOTS) *at the point of sales*. Often they only use their own proprietary label such as PURE Wear (Otto) or Bio Cotton (C&A). Reasons for this may vary, but probably they include increased flexibility of retailers, desire to reduce their dependency on a single certification system, and desire to simplify communication to consumers in case several (competing) certification systems are used simultaneously.
- Fourth, retailers do not always use either integrated or organic qualities in a pure manner. Organic cotton is also used in *blending strategies* where integrated or organic fibres are mixed with conventional cotton (Hustvedt and Dickson 2009). Although all organic certification systems allow for a tolerance of ≤5 % of conventional material in the final goods, specific blending certification allows to vary the degree of organic cotton and other fibres (e.g., the minimum amount of organic cotton in the final good is 5 and 70 % in the OE blended and the GOTS "made with x % organic" standards, respectively). For example, H&M sells both 100 % organic and blended organic clothes (H&M 2013). With the blended-cotton strategy, incumbents can transform the entire product portfolio more easily because only a minimum amount of cotton needs to be mixed into the clothes (although it is not part of this analysis, Nike now sells 90 % of brand items with a minimum of 5 % organic cotton; Nike 2011, p. 27).

For future development, it will be interesting to investigate both the short- and long-term goals of retailers more closely. Two of the four retailers aim to considerably increase the share of organic cotton (C&A and Otto). H&M and Tchibo set goals on increasing or introducing cotton from integrated production. As a response to Greenpeace's "Detox" campaign, C&A and H&M, together with other retailers, have adopted the long-term goal of using 100 % sustainable cotton by 2020 (C&A 2012a, b, p. 100). To what extent this will include cotton with organic or integrated quality remains open, but possibly both strategies could be pursued simultaneously, and the specifics could depend on how quickly the different cotton-production systems can be extended at which cost.

Because the strongly growing demand faces a very limited supply, C&A has had problems similar to those Hess Natur had three decades earlier as the industry was beginning to change. Their response was to found the initiative "Cotton Connect" to promote the cultivation of organic cotton (C&A 2012a, p. 106). According to a recent press release, C&A is planning to double the sales of certified organic clothing (C&A 2012b). Other large retailers have also invested in more sustainable cotton cultivation, although this was not with a specific focus on organic quality but rather on integrated production. For instance, Otto founded and invested in the initiative "Cotton made in Africa," whereas H&M and Tchibo invested in the "Better Cotton Initiative."

In sum, the market observation shows that innovative pioneer companies and conventional global retailers, who have often borrowed their strategies from the pioneers, have initiated a notable change in the German clothing industry. This can be seen in the forecasts of most of the market studies predicting strong growth of the cultivated area for organic cotton as well as in an increasing need for retailers to rethink their strategy in terms of sustainability (cf. Memon 2012; Pay 2009; Textile Exchange 2011; Willer and Kilcher 2011). The currently low share of organic cotton in the global cotton market of about 1 % (Pay 2009, p. 5) is thus expected to grow considerably.

5 Discussion and Implications

5.1 Discussion

The example of the clothing industry shows how the diffusion of the certification of organic cotton and the transformation of the market is driven by the efforts of market actors alone. Regulatory aspects do not play a decisive role in this market. The extraordinary efforts of an early pioneer and the related success in a niche market led to new technological possibilities (organic cotton; healthy and eco-friendly clothes) and related production and certification standards. Conventional mass market retailers (e.g., C&A) have only recently engaged in this trend, but are already leading purchasers of organic cotton and sometimes even have ambitious goals for their further transformation. This rapid transformation of a few conventional players in the market has taken place for at least four reasons:

- *Value through healthy products*: The introduction of organic textiles can, in cases where a high level of health awareness exists and the intangible value of the product is increased through sustainability attributes, represent additional customer benefits (e.g., Hustvedt and Dickson 2009).

- *Reputational risk*: The risk of scandal accompanying conventional clothing products can have a significant effect on brand value. The Detox campaign of Greenpeace and the numerous responses on YouTube films and activities in retailer stores may have spurred the transformational activities of the large clothing retailers.
- *Continuous use of existing production processes*: Even if the scarcity of organic cotton is a huge challenge and requires a strong and fast expansion of areas of organic cotton cultivation, the change from conventional to organic cotton is relatively simple and does not require new, expensive production technologies (e.g., new machines) or work processes (this will change once the sustainability focus is expanded from regular cotton production and use to the whole supply chain as is done under certification systems such as GOTS).
- *No sunk costs of transformation strategy*: To switch to organic instead of conventional cotton does not cause new substantial investments in production technologies (e.g., for spinning, weaving, etc.) and thus neither endangers existing sunk costs in production, warehouses, logistical systems, etc. nor causes new ones. In case of missing demand for organic cotton, most costs do not have a sunk cost character, but they can be seen as investments in improved supply chain partner relationships, quality management, and efficiency improvements.

Extant research in sustainable entrepreneurship usually emphasizes that incumbents use lower-level standards of sustainability for their innovations in the mass market (e.g., Hockerts and Wüstenhagen 2010). The analysis of the organic cotton transformation of the clothing market in Germany, however, shows that not only lower-level standards (i.e., “improved cotton”) but also the highest level (i.e., organic cotton) is being diffused in and by incumbents. This should not hide the fact that many differences can still exist with regard to pioneering and incumbent companies. For example, whereas pioneer Hess Natur rigorously controlled the entire textile value chain, incumbents differ in their ambition. Depending on the specific certification standard, the control is often limited to fibre quality (e.g., OE 100) and does not account for chemical treatments during fabric and clothing production (and thus, ironically, cannot say anything about the ecological and health characteristics of the end product). We also did not explicitly examine the social standards in the value chain besides those already integrated in the considered certification systems. Further research should investigate the contingencies involved in which specific organic (and social) standards are adopted by incumbents.

The change from conventional to organic cotton presents a case of strategic innovation for large German clothing retailers because they are challenged to (a) address new customer segments or develop the consciousness of their existing customers, (b) develop new competencies for the tighter coordination of the upstream supply chain (particularly regarding the organic quality of fibres through a chain of custody), and (c) develop strategic partnerships with NGOs, multi-stakeholder initiatives, or industry initiatives for developing the organic and other forms of more sustainable cotton supply. This reflects the move from anonymous price-based to negotiation-based coordination mechanisms in the supply chain, at least for the time that sustainable cotton fibres are scarce (Goldbach et al. 2003).

Still, while switching to higher quality fibres is a good start for the sustainability-oriented transformation of the industry, other ecological and social improvements in later phases of the value chain—or its complete redesign—is also necessary. One interesting development is the upsurge of new brand manufacturers such as manomama in Germany (Plieth et al. 2012), Switcher in Switzerland, and American Clothing in the USA, operating with innovative business models based on regional value creation through vertical integration and thereby offer entirely different solutions to broader social (and ecological) problems—together demonstrating the importance of new business models for sustainability (Schaltegger et al. 2012, 2016). Another is of course to deal with (planned) fashion obsolescence as the root cause for the every accelerating take-make-waste cycles in "fast fashion".

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Possum Fiber—A Wonderful Creation of Nature

Mohammad Mahbubul Hassan

Abstract Possum fiber is harvested from a rodent called the "possum." The fiber is very soft and smooth, unlike merino wool fiber. The fiber is quite different from other animal fibers because of its unique shape and morphology: The fiber is hollow lengthwise, which provides high warmth. Possum fiber is mainly harvested in New Zealand from brushtail possum (*Trichosurus vulpecula*). During the past 15 years, the possum fur industry has grown in New Zealand, and the fiber, when blended with merino wool, produces various luxury apparel including coats, jackets, scarves, and cloaks. However, the inherent color of possum fiber (reddish brown) could be a problem because the fabric made from it needs to be white or other lighter colors. It is difficult to bleach possum fiber by traditional bleaching methods with hydrogen peroxide and chlorine. In this chapter, brushtail possum and their habitat and food, the harvesting of fur from possum, the physical and mechanical properties of possum fiber, and the mechanical and chemical processing methods, including bleaching and dyeing, will be discussed.

Keywords Possum fibre · Animal fibre · New Zealand

1 Introduction

Possum fiber is obtained from the Australian brushtail possum (*Trichosurus vulpecula*), a small, nocturnal, cat-size rodent animal. Brushtail possums are available throughout the main islands of New Zealand except for some Alpine areas and parts of South Westland and Fiordland. They are sometimes confused with the American opossum (they are under the family Didelphidae). Opossums are found only in North America, although there is another marsupial called the "water possum" (also known as the "yapok"), which is found in Central and South

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S.S. Muthu and M.A. Gardetti (eds.), *Sustainable Fibres for Fashion Industry*,
Environmental Footprints and Eco-design of Products and Processes,
DOI 10.1007/978-981-10-0522-0_3

America. The size of possum is double of the size of opossum. Possums are native to Australia and produce fur far better than other marsupials. These Australian possums were introduced in New Zealand in 1850s to establish an animal fur industry, and their number in New Zealand now reaches 60–70 million. It is claimed that possum fabrics are 55 % warmer than merino and 35 % warmer than cashmere fabrics of the same weight and knit structure. Possum is a largely arboreal, nocturnal species that is generally found in dry eucalypt forests and woodlands. Large populations of this species can be found in pine plantations as well as suburban and urban areas. The possums breeding behavior depends on their habitat environment: Some breeds year round in some areas, and in others possums will breed in one or two seasons. Females begin breeding at approximately year of age; a single young is born after a gestation period of 16–18 days; and young have a pouch life of 4–5 months.

This species is commercially produced in Tasmania. On Kangaroo Island, possum is treated as a pest species (to humans and other threatened species), and killing them is permitted by a law. Possum is major a pest species in pine plantations in Australia where it can do considerable damage, and it acts as a host of bovine tuberculosis in New Zealand. Therefore, to control their population in New Zealand, killing them is permitted by law.

2 Characteristics, Habitat, Food and Reproduction of Possum

2.1 Physical Description

Possum are usually 320–580 mm long, and they have quite long tail (i.e., more than half of their body length [usually 240–350 mm]). They have large eyes and tall, rounded ears. Its fur is short but dense, and its tail is typically long and covered in long, bushy fur. In some subspecies, the fur on possum tail is the same length as on the rest of the body. Throughout its range, there is considerable variation in the coat color of *T. vulpecula*. Color seems to vary according to habitat, and several subspecies have been identified. Three of the subspecies are typically grey in color. Of them, *T. vulpecula*, is found throughout southern Australia and New Zealand.

In all subspecies, the underside is lighter in color (almost cream) than the upper side, which is blackish-grey with some fibers being black. Figure 1 shows a fleece collected from a dead possum and also possum fiber collected from under the belly of the possum. A scent gland located on the chest is used to mark territories. The reddish secretions from this gland give the fur around it a brown or reddish appearance. Like most marsupials, the females have a small, forward opening pouch that is used in reproduction.

Fig. 1 A possum fleece (**a**) and possum fur (**b**) collected from the skin under the belly of the animal. *Source* The author's own collection

2.2 Habitat

T. vulpecula (Fig. 2) usually resides in forested or woodland areas. These habitats vary greatly throughout its range. In Tasmania, *T. vulpecula* can be found throughout the rainforests and the dry woodlands that cover over 60 % of the area. In the Australian northwest, it prefers eucalyptus forests and mangroves. In southern Australia, they also reside in wooded areas but are sometimes found living a semi-terrestrial life where they den in rock crevasses and termite mounds. In New Zealand, *T. vulpecula* can be found in most forested areas. The common brushtail

Fig. 2 A possum in natural habitat. *Source* The author's own collection

possum is a social animal and remains in contact with its group through sound and scents. At times, particularly during the breeding season, it makes piercing screeches in the middle of the night to establish territories and warn of danger.

2.3 Food Habits

Possums have low metabolic rates and can maintain themselves on 30 % less food than comparably sized eutherians such as rabbits. Captive adult possums housed indoors consume 80 g digestible dry matter per day when feed either a diet of commercial pellets or one containing natural foliar foods. Mean retention times of digests are 1.5–3.0 days for both synthetic and natural foliar diets (Nugent et al. 2000). Possums usually spent <25 % of each night feeding (MacLennan 1984) in one to three bouts with 2–3 h between bouts. Possums are omnivorous and live by eating leaves, shoots, flowers, fungi, both invertebrates and vertebrates, and plant material. Possum diets also routinely include insects and other animal material. Possums also readily eat raw and cooked meat. Researchers found that they have excellent adaptability in terms of foods and they can even eat highly toxic flowers and leaves. Their preferable food is flowers of the eucalyptus plant, but they also eat other plants and shrubs. They also eat clover grasses, garden fruits, and turnips.

2.4 Behavior

Possums are strictly nocturnal animals in terms of their activity; they spend the daytime in hollowed-out logs or trees, but in more urban areas they find shelter wherever they can find it. Possums awaken and start to become active in their shelters approximately 1–2 h before sunset, but they do not usually come out of their shelter until about 30 min after sunset (Ward 1978). They mark their territories using secretions from both anal gland and the scent gland on their chests. Although they do not leave in groups, clear dominance hierarchies have been observed where co-dominants of the same sex purposely avoid one another. There appears to be very little direct aggression among individuals. They use deep guttural vocalizations to communicate territory location and to attract mates during the breeding season.

2.5 Reproduction

There are typically two breeding seasons for *T. vulpecula* throughout the year. It is rare for a female to give birth twice in 1 year. The highest number of births occurs in the fall with fewer occurring in the spring. The females’ estrous cycle lasts for approximately 25 days. The gestation period is approximately 18 days, and a single young emerges from the pouch in approximately 4 months. The young are typically weaned by approximately 6 months, and disperse anytime between 8 and 18 months. Females can reproduce by approximately 12 months of age, and males typically reach sexual maturity by age 2. They have an average life span of 7 years in the wild. The mortality rate for *T. vulpecula* is 75 % in individuals around 1 year of age. That number drops considerably as the young mature, and in adult *T. vulpecula*, the mortality rate is only approximately 20 %.

3 Harvesting of Fiber from Possum

Possum fur is usually machine or hand plucked from the skin of possum.

3.1 Hand Plucking

Hand plucking is a laborious job. Hand plucking cannot be done for all possums. Hand plucking is easy if plucking is carried out immediately after killing; otherwise it become quite difficult to remove fur from the skin by hand. Possum is held for stripping in a manner to enable efficient stripping. Fur is removed from the back quarter to the front of the possum by holding the back legs by gently pulling fur forward. Fur is not collected from the tail of the animal. During plucking, care must be taken so that fur not becomes dirty. It is less likely that fiber breakage would occur by hand plucking.

3.2 Machine Plucking

A number of portable or stationary plucking machines are available in the market to pluck possum fur. This method is suitable for possums that have been poisoned and the carcasses cold. Plucking machines can electrical or petrol driven (Fig. 3). In this

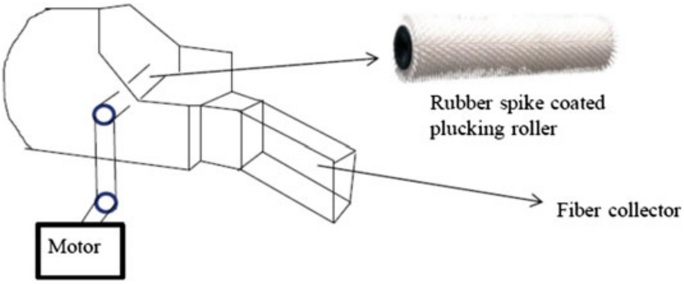


Fig. 3 Schematic diagram of an electrical possum fiber plucking machine

method, the animal skin is brought into contact with a rotating drum covered with rubber spikes, which remove the fur without affecting the animal skin. Machine plucking is more economical and faster compared with hand plucking.

4 Sustainability of Possum Production

The concept of sustainability was developed in the 1970s mainly to combat various problems including climate change, damage to the environment, energy shortage, human population, and exploitation of resources. Sustainability issues are based mainly on four pillars: economical, environmental, social, and ethical. Sustainable production means production of a product by using the least resources without harming the environment and also by following ethical and social practices.

4.1 Social and Economic Impact

Killing animals to get their fur by unethical and cruel methods is an issue that has been heavily criticized by animal rights and welfare activists. Possums are either poisoned or killed to harvest their fiber. However, since its introduction to New Zealand forests by fur traders in the late nineteenth century to develop a possum fur industry, the nonnative brushtail possum population has reached such a level that they are now treated as a pest because they destroy crops, native flora, and fauna. Possum can lower productivity or add to costs in other areas of primary production. Possums also damage newly planted willows and poplars commonly used for catchment protection and erosion control. Therefore, control of possum population is a necessity. In New Zealand, the population of possum is sustainably controlled. Some possum-control options require compliance with complex local legislations. The use of poisons in possum control is implemented various legislations such as the Biosecurity Act 1993, the Civil Aviation Act 1990, the Pesticides Act 1979 and the resource-management Act 1991. The possum population is controlled either by killing with poison (sodium monofluoroacetate, phosphorous paste, brodifacoum, cholecalciferol, and pindone) or by nontoxic but cruel techniques such as using various possum traps as shown in Fig. 4.

However, it is necessary to improve the current techniques used to trap and kill possum. Some of the traps that suffocate or cause significant damage to the legs of the animals should be outlawed. The killing process also should be more humane than the current practices. Possum could be stunned or the toxins that incapacitate the nerve system of the animal should be applied before killing, or toxins that quickly kill the animal should be used. The suggested approaches may overcome the ethical issues related to possum-fiber harvesting.

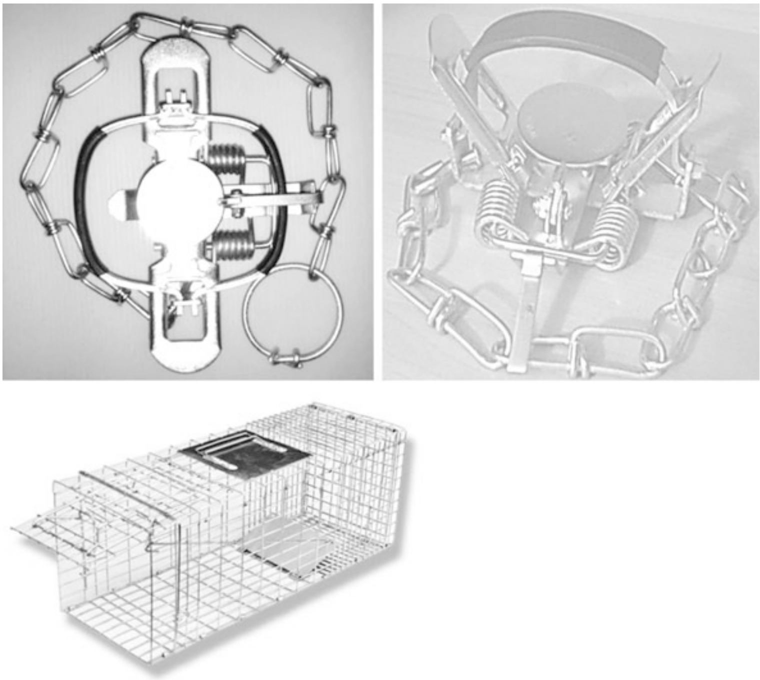


Fig. 4 Various types of possum traps used in the possum industry. *Source* The author's personal collection

4.2 *Environmental Impact*

One of the measurements used to assess the environmental impact of a product/process is calculation of the carbon footprint. The carbon footprint of a fiber is the sum of all emissions of greenhouse gases, such as carbon dioxide, caused from cradle-to-grave production of that fiber. Calculation of the total carbon footprint is a complex process and requires a large number of data. The carbon footprint of possum fiber could be smaller than that of other animal fibers. They are minimally chemically processed, and only in rare cases are they are dyed, which minimizes their carbon footprint.

5 Physical Properties of Possum Fiber

Possum fiber is very smooth and soft and has better luster than wool fiber. The diameter of possum fiber is quite variable, from 10 to 45 μm, depending on the area of the animal's body from where the fiber is collected. The fibers are mainly made of keratin protein, similar to wool fibers, although amino acid compositions could be slightly different from wool. Generally the underside fibers are thinner (14–25 μm) than the topside fibers (20–45 μm). Figure 5 shows optical microscopic images of possum fibers harvested from the top and underside of the animal. The surface topologies of top and underside possum fibers are quite distinct, and their morphologies are more resembles those of European beaver hair.

Scanning electron microscopic images (Fig. 6) shows that the fibers collected from the back (top side) of the animals more closely resembles human hair, but the fibers of the underside of belly more closely resembles wool fibers; however, the geometry of the shape of the scales is different from the scales of wool fibers. However, the scale height of possum fiber is shorter compared with the height wool

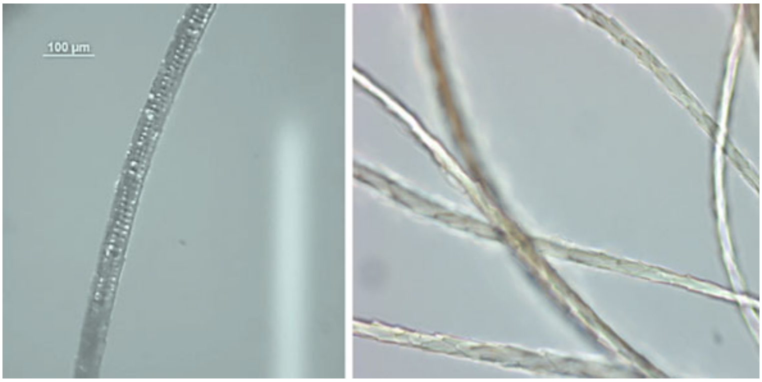


Fig. 5 Optical microscopic images of fur collected from the top side (*left*) of the animal and also from underneath the belly (*right*). *Source* The author's personal collection

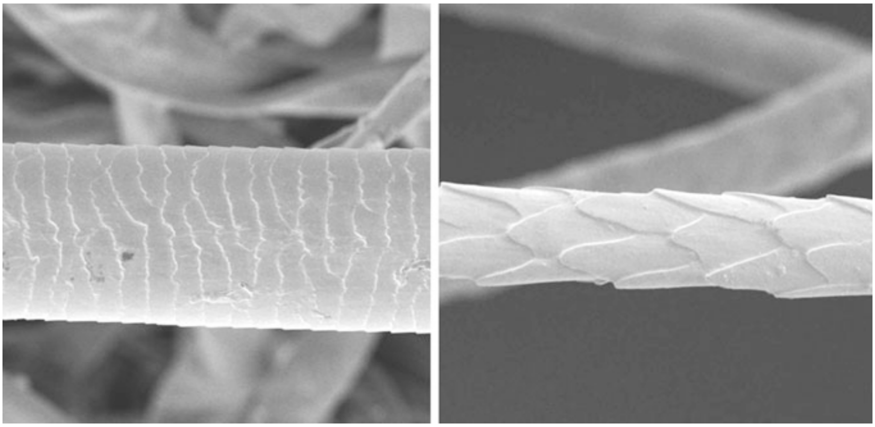


Fig. 6 Scanning electron micrographs of possum fibers collected from the top side of the animal (*left*) and from underneath the belly (*right*). *Source* The author's personal collection

Fig. 7 Optical microscopic image of a lengthwise bisected possum fiber. *Source* The author's personal collection

fiber scales. Therefore, they have less tendency to felt, but felting of possum fiber does occur under some conditions, such as agitation in a highly alkaline aqueous solution.

Like wool fiber, the surface of possum fiber is also hydrophobic because of the presence of 18-methyl eicosanoic acid (18-MEA), which is bound to the wool fiber surface through thioester bonding. Because of the long hydrophobic tail of 18-MEA, the fiber surface is strongly hydrophobic.

The unique characteristic of possum fiber is that the inside of the fiber is hollow in the direction of the length of the fiber, which makes is lightweight and very warm. It is the third warmest natural fiber in the world after polar bear and the Arctic fox fibers. Because of its hollow structure, which traps air, which in turn works as a heat insulator, possum fiber is warmer than wool fiber. Figure 7 shows magnified image of a lengthwise-bisected possum fiber.

6 Mechanical Processing

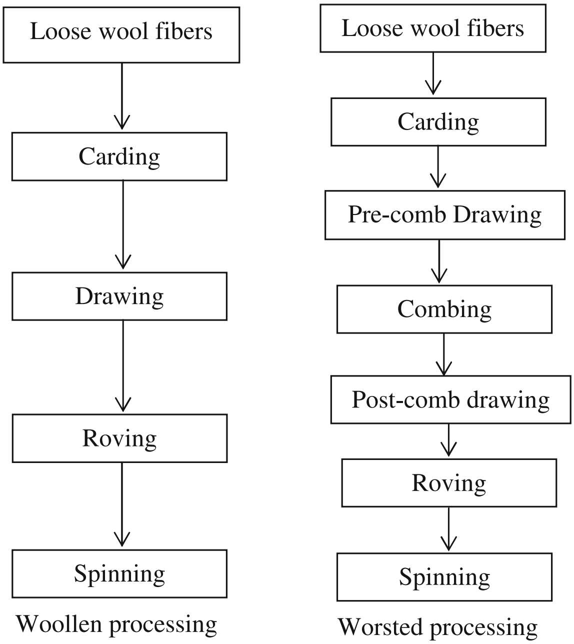
Mechanical processing may include yarn and fabric manufacturing from possum fiber.

6.1 Manufacturing of Possum Yarn

Possum fibers are usually blended with merino wool and or silk at 20–30 % levels, and the blending with wool and or silk is carried out during the drawing stage. Following are the typical spinning routes for wool-fiber spinning (Fig. 8):

Sliver of possum fiber is made after carding, similar to wool-fiber carding. Loose wool fibers are converted into yarn by two processes, namely, woollen and worsted spinning processes. Scoured wool fibers are opened and passed through a process called "carding" where the fibers are straitened and placed in parallel to each other in a rope-like bundle of fibers called a "sliver."

Fig. 8 Wool-fiber processing: loose wool fiber to yarn



A carding machine is a large machine, approximately ≥20 m long, with large-diameter pin rollers (pins are in opposite direction) that tease the fibers, open them up, and produce a nice even sliver. In the woolen-spinning process, this carded silver is fed into a simplex machine (also called s "roving" machine) to form rovings, and then these rovings are spun into yarn by a ring spinning machine. The carded silver is fed to the simplex machine to reduce the linear density of the silver and also to form a roving. In the worsted system, further parallelization and straightening of fibers are carried by three extra processing steps: gill-drawing (pre-comb drawing), combing, and finisher drawing (post-comb drawing). Figure 9 shows a carding machine (top) and a gill-drawing machine (bottom).

In the gill-drawing process, four to eight carded slivers are feed together, blended, and their linear decreased by 4× to 8×. The fibers in the sliver are further aligned and parallelized. At this stage, the sliver still contains particles of vegetable matter as well as short fibers. Carded sliver of possum fiber is usually blended with merino wool fibers at this stage. Then combing is carried out. short fibers are removed, and further parallelization of fibers is carried out. Short fibers are hard to control in a yarn and they affect the yarn's tensile strength and other performances. Further parallelization and alignment of fibers is carried out by the finisher drawing, which also levels thick and thin areas of slivers. The slivers coming out from the finisher drawing machine are then fed into the simplex/roving machine (Fig. 10) to further reduce their liner density, and then spinning is carried out.

Fig. 9 A high-speed carding machine (*top*) and a gill-drawing machine. *Source* The top image is from Melliand International 3 (2011) 133. Published with the authorization of Deutscher Fachverlag GmbH, Germany. The *bottom* image is from the author's personal collection

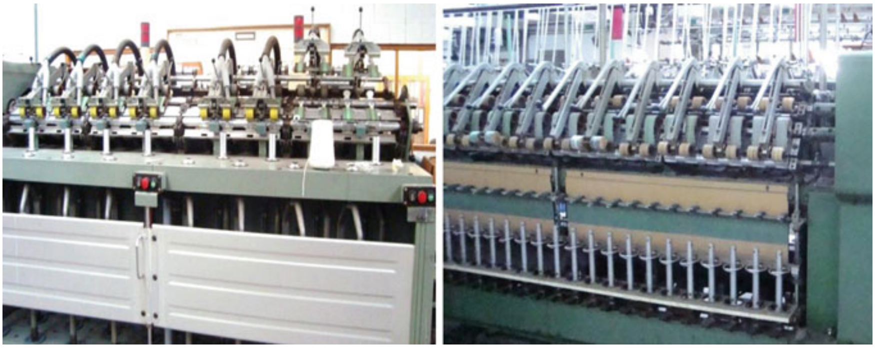


Fig. 10 A roving machine (*left*) and a ring-spinning machine (*right*). *Source* The author's own collection

Spinning of wool/possum fibre blended roving is carried out by a ring-spinning machine (Fig. 10) to convert the rovings into yarns. The yarn loop rotating rapidly at a speed of 30,000–40,000 rpm around a fixed axis, which generates a surface referred to as a "balloon." Ring spinning is popular because ring-spun yarns have the highest tensile strength compared with yarns manufactured by any other spinning process. In a ring-spun yarn, fibers are almost completely aligned to one another; therefore, when these aligned fibers are twisted, they provide high strength. A ring-spinning machine is suitable for staple fibers and therefore is also appropriate for spinning animal fibers because of their short length.

6.2 *Manufacturing of Possum Fabric*

Yarns made from possum fiber blended with merino wool or other fibers are converted into either knitted or woven fabrics. For most of the fibers, fabric manufacturing is carried out before any chemical processing (e.g., scouring, bleaching, dyeing, and finishing). However, luxury fibers, such as possum, wool, and alpaca, are at least scoured (sometimes even dyed) in loose stock form before into conversion to fabric. Possum fibers are mainly used in knitted fabrics, and knitting is carried out either by hand or by a knitting machine.

Several types of knitting machines are used for making fabric from possum-blended yarns such as single-jersey and double-jersey knitting machines and V-bed knitting machines (Fig. 11). Sometimes rovings are used directly for making thick garments (sweaters, cardigans, etc.) by hand knitting. For the manufacturing of fabric from wool/possum yarns, sometimes hand looms (Fig. 11) and, for high-quality suitings, power looms are used. Rapier and air-jet looms are quite popular for weaving wool and wool/possum fabrics.

Hand loom Circular knittingmachine V-bed knittingmachine

Fig. 11 A handloom, a circular single-jersey knitting machine, and a V-bed knitting machine. *Source* The author's personal collection

7 Chemical Processing of Possum Fiber

7.1 Bleaching of Possum Fiber

Possum fibers harvested from the top side of the animals are dark brown, which will be visible when blended with wool fiber and dyed in pastel shades. Therefore, bleaching is essential if the fibers will be used in materials intended to be dyed in pastel shades. However, if the fabric material will be dyed a deep black or deep navy color, then possum fibers are not usually bleached.

The fiber is dark colored because of the presence of pigments called “eumelanin” (which causes black, dark brown, and grey colors of the fiber) and “pheomelanin” (which causes yellow, reddish-brown, and red color of the fiber) pigment in the fiber cortex (Bereck 1994). Eumelanin and pheomelanin are formed by different mechanisms because their chemical structure is quite different. Eumelanin is formed by the enzymatic oxidation of tyrosine and by polymerization of several oxidation products (Swan 1974). It is a highly heterogeneous polymer consisting of different monomer units linked by a variety of bonds (Korytowski and Sarna 1990). On the other hand, pheomelanin is composed of several yellow-red pigments such as trichosiderin, trichoxanthin, pyrrotricholes, trichochromes, and gallopheomelanin (Stoves 1976). Because they are highly cross-linked as well as insoluble in water, they are extremely stable against any kind of chemical attack. Melanins are practically impervious to reducing agents, and therefore their bleaching is extremely tricky. If care is not taken during bleaching, the treatments may cause substantial damage to the fiber. Traditional peroxide bleaching at alkaline conditions does not have any effect on the reduction or decolorization of these melanins. Strong oxidizing agents, such as sodium peroxide and chlorine, used at high doses (10 % on the weight of the possum fiber) also have a minimal effect on the color of melanin as shown in Fig. 12.


pH 4 pH 8.5

Fig. 12 Possum fiber beached with 5 % potassium persulfate at pH 4 and pH 8.5. *Source* The author’s own collection

With sodium dithionite With sodium sulfite

Fig. 13 Possum fibers beached with sodium dithionite and sodium sulfite reducing agents. *Source* The author's own collection

It is evident that a strong oxidizing agent, even at high concentrations, only slightly changes the color when oxidation treatment is carried at low pH (pH 4), but at high pH, no change in color takes place. Reducing agents, such as sodium dithionite and sodium sulfite, have no effect on the color of possum fiber even at high doses (10 % of the weight of the fiber) as shown in Fig. 13.

The only way to decompose and decolorize these melanin pigments is the oxidation at alkaline conditions in the presence of iron or copper salt, which causes at least some level of damage to possum fiber. During the bleaching process, some oxidation of keratin occurs, which causes damage to the fiber, which is often referred to as "oxidative" damage. The damage arises from the attack on amino acids in the keratin fiber, particularly cysteine, which is converted into cysteic acid. It has been postulated that oxidative bleach reagents rupture the disulfide bonds causing cross-linking components of proteins and possibly the polypeptide chains (Holmes 1933; Wolfram 1970; Cegarra and Gacen 1983) as well as the modification of other side chains (tyrosine, tryptophane, lysine, and arginine) (Zahn 1966). Rinsing after the mordanting step proved to be critical with regard to fiber damage. The rinsing step is to remove excess iron from the keratin fiber matrix which is not bound to a melanin pigment.

If excess iron is present in the fiber, then over-bleaching occurs throughout the whole fiber rather than at the pigment source, thus causing a reduction in fiber strength.

Pigmented fibers, such as possum fiber, require a specific mordant bleaching process (doped peroxide bleaching) if the dark melanin pigment needs to be decolorized (Duffield 1986). An efficient melanin decolorization with minimum possum fiber damage is provided by the use of metal catalysts, such as iron and copper, in the mordanting step before bleaching with alkaline hydrogen peroxide. Melanin has a high affinity for metal ions (Hong and Simon 2007). Because the electron density of native melanin is higher than that of keratin, the metal cations are preferentially absorbed by the melanin (Liu et al. 2003). The doped metals work as an activator for hydrogen peroxide and produce hydroxyl radicals, which decompose melanin. It was found that the bleaching with this method is enhanced by illumination from ultraviolet A (UVA) and Ferrous (II) or copper (II) bonded to melanin also accelerates the bleaching of melanin by a Fenton-like oxidation (Perez-Benito 2004). The industrial practice with possum fiber is to initially treat it with ferrous sulfate and then bleach it with hydrogen peroxide. Typical bleaching conditions for possum fiber are as follows:

Mordanting bath

11 g/l Ferrous sulfate
11 g/l Ammonium chloride
2 g/l Tartaric acid
0.5 g/l Sodium pyrophosphate
2 ml/l Formaldehyde

The fiber is soaked in the above-mentioned solution at 40 °C overnight and then hydro-extracted without any washing or rinsing. Then the fiber is soaked in the bleaching bath at 30 °C overnight. The bleaching bath composition is as follows:

Bleaching bath

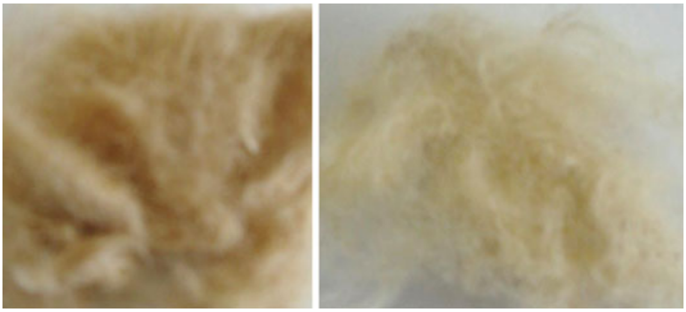
2 g/l Oxalic acid
8 g/l Ammonium chloride
8 g/l Sodium pyrophosphate
35 ml/l Hydrogen peroxide (50 %)
2 g/l Sodium carbonate
2 g/l Sodium bicarbonate

The fiber is then washed several times in water and neutralized with acetic acid. Some of the chemicals used in this process, such as oxalic acid and formaldehyde, are toxic and therefore should not be used. Moreover, this treatment would cause considerable loss of tensile strength of the fiber due to damage. A simpler method than the one mentioned previously was used by Chen et al. (2001) for alpaca fiber bleaching, which is as follows:

Mordanting bath

10 g/l Ferrous sulfate
6 ml/l Formic acid
0.5 g/l Cibaflow CIR (Huntsman Chemicals)

The bath is filled with cold water, and the above-mentioned chemicals are added. The fiber is then introduced in the bath, and the bath pH is set at 2.9. The bath is then heated to 80 °C at 3 °C/min and held for 60 min. The bath is then cooled, and the liquor is drained. The bath is then filled again, and 4 g/l formic acid is added. The bath is then heated to 80 °C at 3 °C/min and held for 20 min. Then bath is then cooled to 70 °C; the bath is drained; and the fiber is rinsed several at 50 °C. The bath is again filled with water, and the following chemicals are added:



1 ml H_2O_2/ g possum fiber 4 ml H_2O_2/ g possum fiber

Fig. 14 Possum fibers bleached with two different concentrations of hydrogen peroxide in the mordant bleaching process. *Source* The author's own collection

28 g/l Hydrogen peroxide
10 g/l Tetrasodium pyrophosphate
4 g/l Oxalic acid
5 g/l Sodium carbonate
0.5 g/l Cibaflow CIR

The bath is then set at pH 8.5 with ammonium hydroxide and then heated to 70 °C at 3 °C/min and held for 50 min, after which the bath is drained and again refilled and run for 20 min at 50 °C. Toxic oxalic acid can be replaced with the same quantity of ethyelendiaminetetraacetic acid or eco-friendly citric acid. Figure 14 shows bleached possum fibers using two different concentrations of hydrogen peroxide in this mordant bleaching process. It is evident that the concentration of hydrogen peroxide in the bleaching solution has great effect on the bleaching performance of possum fiber. In the case of low concentration of peroxide, it degrades the melanin compound to golden yellow, but increasing the concentration to 4 ml H_2O_2/g possum fiber decolorizes the fiber to almost white.

7.2 *Dyeing of Possum Fiber*

Like other animal fibers, possum fiber is a keratin protein fiber similar to wool and silk fibers; therefore, it can be dyed with the same class of dyes used for dyeing animal fibers. Keratin fibers are composed of a variety of amino acids. These amino acids are amphoteric in nature because they have cationic amino groups as well as anionic carboxylic and hydroxyl groups. In an aqueous bath, they are usually cationic above pH 4.5, and below that pH they are anionic. Animal fibers are usually dyed in acidic conditions to protect them from alkaline damage; therefore, dyeing is usually carried out under acidic conditions. Because they are anionic at acidic conditions lower than pH 4.5, animal fibers are usually dyed with anionic dyes such as sulfonate groups containing acid, reactive, and direct dyes. The acid dyes used in animal fiber dying usually contain one to three sulfonate groups in each dye molecule. These sulfonate groups not only provide solubility in water but also provide substantivity toward amino groups of animal fibers. Possum fibers are dyed in an aqueous dye baths.

7.2.1 Dyeing with Acid Dyes

Acid dyes are quite popular for dyeing animal fibers because of easy dyeing process, high dye exhaustion, and dyes are less expensive compared with reactive dyes. The dyed fibers have quite good fastness to washing as well as rubbing. Acid dyes are called this because they are applied to animal fibers from dye baths under acidic conditions because they are anionic in nature. The dyes contain solubilizing groups, mostly sulfonic acid (in some cases carboxylic acid) groups. The number of these substituent groups in the dye molecule determines their solubility in water and also the dyeing properties (Duffield 1992). Acid dyes mainly have azo chromophore groups, but some acid dyes may have xanthene, anthraquinone, pyrazolone, triphenyl methane, and metal-phthalocyanine chromophore groups. Depending on their dyeing behavior, acid dyes are of three classes, namely, level dyeing, fast acid, and milling/supermilling.

Dyeing behavior of acid dyes are very much controlled by their relative molecular weight; with an increase in relative molecular weight, dye migration from dye bath to fiber decreases, and substantivity and wet fastness increase. The dyeing of possum fibers with reactive dyes must use a range of dyeing auxiliaries including a dye-levelling agent (to control the absorption of dyes into fiber), a wetting agent (to wet the surface of hydrophobic possum and wool fibers), an electrolyte (to increase the absorption of dyes into fiber), an anti-setting agent (to prevent damage of fiber at boil), a crease-protecting agent (to prevent the formation of crease marks), and an antifoaming agent. Failure to use appropriate auxiliaries can cause poor depth of shade, unlevel dyeing, and a crease mark in the dyed fabric along with fiber damage.

Dyeing with level-dyeing acid dyes

The dyeing of animal fibers with level-dyeing acid dyes requires the no levelling agent be used in dyeing. Mainly salt, acid, antifoaming agent, and wetting agent must be used. The typical dye bath composition is as follows for the Tectilon levelling acid dyes (Fig. 15):

Dye 0.05–10 % (depends on the shade desired)
Sodium sulfate 5–10 %
Sulfuric acid 4 % (to set the pH at 2.5–3.5)
Wetting agent 0.25–0.50 g/l
Defoamer 0.5 g/l

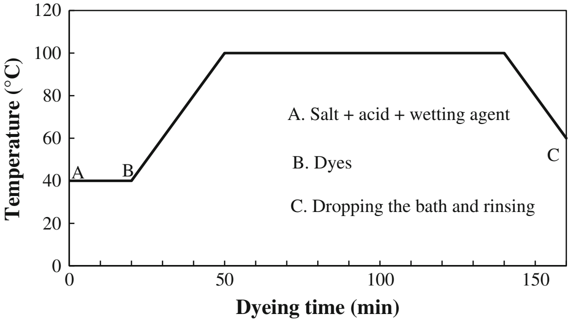


Fig. 15 Temperature profile for levelling acid dyes

TectilonBlue F-3R Tectilon Red F-2G

Fig. 16 Possum fiber dyed with TECTILON levelling acid dyes. *Source* The author's personal collection

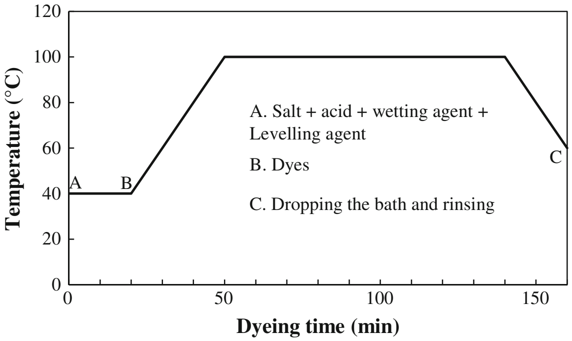
The dye bath is filled water and salt, acid, and wetting agents are added at 40 °C. The fabric is introduced in the dye bath, and running dyes are added after 10 min. The temperature of the bath is raised to 100 °C at 2 °C/in and is held for 60–90 min. The bath is then cooled to 60 °C and is dropped. The fabric is then rinsed and soaped at 50 °C for 20 min using a 1 g/l nonionic detergent. Figure 16 shows fabric samples dyed with two levelling acid dyes.

Dyeing with fast acid dyes

This group of acid dyes is generally monosulfonated, and they exhibit wet fastness superior to levelling acid dyes. The shade range available in this dye group is narrow compared with levelling and milling acid dyes.

Dye 0.05–10 % (depends on the shade require)
Sodium sulfate 5–10 %
Acetic acid 1–3 % (to set the pH at 4.5–5.0)
Wetting agent 0.25–0.50 g/l
Anti-setting agent 1 g/l

Fig. 17 Temperature profile for fast acid dyes (Sandolan P dyes)



The dye bath is filled water and at 40 °C, salt, acid, levelling and wetting agents are added. The fabric is introduced in the dye bath and after 10 min running dyes are added. The temperature of the bath is raised to 100 °C at 2 °C/in and is held for 60–90 min. The bath is then cooled to 60 °C and is dropped. The fabric is then rinsed and soaped at 50 °C for 20 min using 1 g/l a non-ionic detergent. Figure 16 shows fabric samples dyed with two levelling acid dyes.

Dyeing with milling acid dyes

Acid milling dyes are called this because of their high degree of fastness to milling processes, i.e., they have higher degree of wet fastness compared with levelling or fast acid dyes. The dyes have different substantivity toward tip and the bulk of the fiber; therefore, highly substantive dyes may create uneven dyeing between the tip and the bulk of the fiber. Levelling agents are used to slow down the migration of dye from the dye bath to the fiber so that the tip and the bulk of the fiber are uniformly dyed. Milling dyes are used for those applications where high wet-fatness properties are required. The typical dye bath composition is as follows (Fig. 17):

Dye	0.05–10 %
Levelling agent	1.0–2.0 %
Sodium acetate	1.0–2.0 ml/l
Wetting agent	0.25–0.50 g/l
Acetic acid to adjust the pH at	5.0–7.5

The dye bath is filled water, and salt, acid and, wetting agents are added at 40 °C. The fabric is introduced in the dye bath, and running dyes are added after 10 min. The temperature of the bath is raised to 100 °C at 2 °C/in and is held for 60–90 min. The bath is then cooled to 60 °C and is dropped. The fabric is rinsed and soaped at 50 °C for 20 min using a 1 g/l nonionic detergent. Figure 16 shows fabric samples dyed with two levelling acid dyes.

7.2.2 Dyeing with Reactive Dyes

As the name suggests, reactive dyes have reactive groups that can react with the functional groups (e.g., hydroxyl, amino and thiol groups) of the substrate forming a covalent bond. The energy required to break this bond is of the same order as that required to break carbon carbon bonds in the substrate itself, and they provide the highest degree of wet fastness. In the case of animal fibers, reactive dyes mainly bond to the amino groups (in the case of wool fibers they also react with thiols). Reactive dyes are not very popular for dyeing animal fibers because the bonding between the dye and the fiber takes place under alkaline conditions, which causes degradation of the wool fiber. Actually, certain classes of reactive dyes have a positive effect on the amount of wool damage produced when dyeing at the boil and higher (Lewis 2014). However, some manufacturers dye animal fiber, such as silk and wool, with reactive dyes because of their high degree of wet and light fastness. In the case of reactive dyeing, a high degree of dye fiber covalent bonding is achieved, which gives maximum wet fastness. The reactive dyeing has two stages: adsorption and fixation (dye fiber bonding). The rate of adsorption always should be higher than the rate of fixation; otherwise dyeing will be uneven (Lewis 1992) (Fig. 18).

Structurally, reactive dyes used for wool are little bit different than ordinary reactive dyes because in the case of wool dyeing, the dyes react with the amino groups of wool; therefore, fiber-reactive groups of wool-reactive dyes are selected to achieve maximum bonding with amino and thiol groups of wool fiber. Reactive dyes used for dyeing cellulosic fibers have monochlorotriazine (Procion M) or dichlorotriazine (Procion H), dichloroquinoxaline (Levafix E), and vinyl sulfone (Remazol) groups, whereas typical wool-reactive dyes mainly have α-bromoacrylamido (Lanasol dyes), 5-chloro-2,4-difluoropyrimidyl (Drimalan F), and N-methyltaurine-ethyl sulfone (Hostalan) reactive groups with the first one being the most popular for dyeing animal fibers (Bühler et al. 1995). However, modern reactive dyes have more than one reactive group, and some recent reactive dyes have three reactive groups (either the same type or different types of reactive groups in the same molecule of dye) to

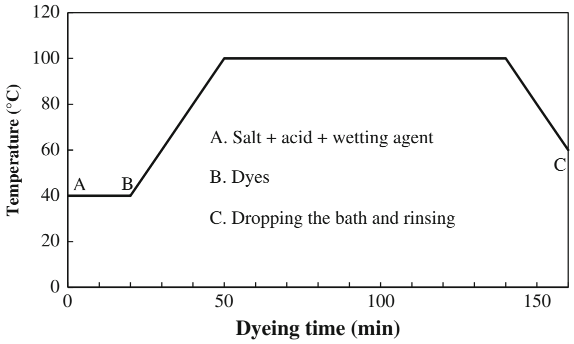


Fig. 18 Temperature profile for milling acid dyes (polar dyes)

maximize their fixation with the substrates. Reactive groups in commercially available reactive dyes used for wool dyeing mainly react by two systems: nucleophilic substitution reaction and Michael addition reaction (Duffield 1992).

Because of increasing environmental concerns with heavy metals (e.g., chromium, copper, etc.) related to metal-complexed acid dyes, it is now usual to use reactive dyes to match deep shades of black and navy blue (usually dyed with chrome dyes) in order to offer textile dyers a real alternative to chrome dyes. It is expected that textiles dyed with chromium dyes in a landfill or effluent containing chromium dyes will liberate chromium due to the degradation of the dyes in the environment. Although trivalent chromium does not appear to be carcinogenic, its hexavalent form is highly toxic as well as carcinogenic (Norseth 1981; Mayfield et al. 2000). Recently, several dye manufacturers marketed ranges of reactive dyes that are free from heavy metals and that can match the shades produced by chrome dyes. These dyes are not only attractively priced, their application can give a dyer huge environmental benefits including compliance with various eco-labelling as well as decreased effluent treatment cost. Such dyes include Lanasol CE dyes from Huntsman, Realan dyes from DyStar, and Drimalan dyes from Clariant.

Dyeing methods

The dyeing method of animal fibers using reactive dyes is quite complicated compared with the dyeing method using acid dyes. The affinity of reactive dyes to cellulose is not high; therefore, a large quantity of salt is used to increase the dye absorption, but no levelling agent is needed. On the other hand, the affinity of reactive dyes to animal fiber is very high under acidic conditions; therefore, controlling the absorption of reactive dyes by using wool a combination of salt and dye-levelling agent is required. Levelling agents either form a complex with the dyes used, or they temporarily bind to dyeing sites. At an elevated temperature, this dye levelling agent complex is either slowly broken down or the high molecular weight dye molecules slowly kick out the levelling agent from the dyeing sites and then binds to those sites. In this way, the absorption of dye into fiber is controlled to accomplish level dyeing. The application level of dye very much depends on the required depth of shade. For pale shades, 0.05–1 % dye of the weight of fiber is used, but a deeper black or navy shade, sometimes even 10 % dye of the weight of fiber is used. Dyeing is usually carried out in a slightly acid dye bath at pH 5.5–6.0 for pale shades and 5.0–5.5 for deep shades. The temperature of dyeing depends on the reactive groups of the dyes used. Depending on the depth of dyeing, an alkaline treatment is necessary to achieve a high level of wet fastness (Fig. 19).

The dye bath is filled water, and salt, ammonium sulfate, acetic acid, and wetting agents are added at 40 °C. The fabric is introduced in the dye bath, and running dyes are added after 10 min. The temperature of the bath is raised to 65 °C (55 °C for chlorinated wool) in 20 min and is held for 30 min. The temperature is again raised to 98 °C in 30 min and is held for 30–45 min (depending on the depth of shade required). The bath is then cooled to 85 °C in 10 min, and the pH is set at 8.5

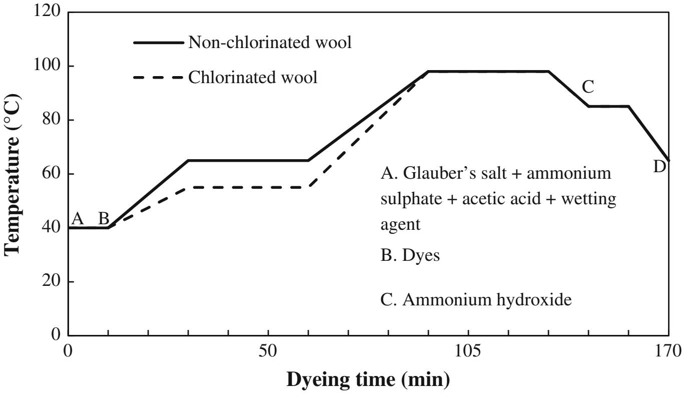


Fig. 19 Temperature profile for reactive dyes (Drimalan F) for possum-fiber dyeing

with ammonium hydroxide. After 15 min, the bath is further cooled 60 °C and dropped. The fabric is rinsed and soaped at 50 °C for 20 min using a 1 g/l nonionic detergent. Figure 16 shows fabric samples dyed with two levelling acid dyes.

7.2.3 Dyeing with Natural Dyes

People have used natural dyes since ancient times for dyeing carpets, rugs, and clothing using the roots, stems, barks, leaves, berries, insects, vegetables, and flowers of various dye plants (Yusuf et al. 2015). In recent decades, there has been a renewed interest to use eco-friendly natural materials in daily life. Natural dyes have been receiving increasing attention from researchers and dyers due to their green image, low cost, environment friendliness, and their beneficial health and safety aspects. Moreover, some of the natural dyes used in textile dyeing have antimicrobial and UV-protective properties (Shahid et al. 2012; Dev et al. 2009; Grifoni et al. 2011). Natural dye can be obtained from many plants, vegetables, and insects—such as eucalyptus leaf extract (Mongkholrattanasit et al. 2009), *Fusarium oxysporum* isolated from the roots of citrus trees (Nagia and El-Mohamedi 2007), Chinese gall extract (Zhang et al. 2014), tea extract (Moiz et al. 2010), lac (Kamel et al. 2005), and indigo carmine (Komboonchoo and Bechtold 2009)—to make a variety of shades on various animal fibers. Natural dyes are always applied on textile substrates by mordanting method, in which fiber is treated (before dyeing or after dyeing) with a mordanting agent that forms a complex with the natural dyes and provide wet-fastness properties. Tin chloride, potassium dichromate, copper chloride, potassium alum, tannin, etc., are used as mordanting agents (Räisänen et al. 2001; Smith et al. 2005; Grifoni et al. 2014; Prabhu and Teli 2014). However,

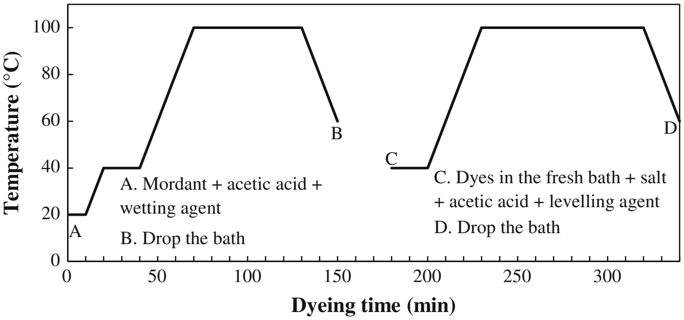


Fig. 20 Temperature profile for natural dyes in premordanting process

some of the mordants used in dyeing animal fibers with natural dyes are not only toxic but also carcinogenic or teratogenic. Copper beyond a certain limit also falls under the eco-standard norms as an objectionable heavy metal (Samanta and Konar 2011). Stannous chloride is teratogenic and genotoxic, whereas potassium dichromate is a possible carcinogen and mutagen (Sisman 2011; Gasiorowski et al. 1997; Levis et al. 1978).

Dyeing procedure

Mordanting is carried out before dyeing (pre-mordanting) or after dyeing (post-mordanting). Mordanting is carried out before dyeing (pre-mordanting) or after dyeing (post-mordanting). Mordanting agents not only increase dye uptake by the fiber but also form a complex with the dyes, thus making the dyes insoluble in water and provide good wet-fastness properties. In the pre-mordanting method, the fiber substrate is first treated with a mordanting agent at a materials-to-liquor ratio of 1:5–1:30. The dye bath is filled with water, and the required quantity of mordanting and wetting agents are added. The substrate is then introduced, and the pH of the bath is set at 3.0 with acetic/formic acid. The temperature is then raised to boil at 2 °C/min and held for 1 h. Then bath is then cooled to 60 °C, dropped, and rinsed. The bath is then filled, and pre-dissolved natural dye, leveling agent, and salt are added. The temperature is again raised to boil at 2 °C/min and held for 1 h; after which the bath is cooled to 60 °C; when the temperature reaches 60 °C, the bath is dropped. The dyed samples are then rinsed and soaped at 60 °C for 15–20 min with a 2 g/l nonionic detergent. Figure 20 shows the dyeing procedure in a schematic diagram.

In the post-mordanting method, at first dyeing with natural dyes is carried out according to the second step shown in Fig. 20. After the completion of dyeing, the bath is dropped, and a new dye bath is prepared with fresh water. Then mordanting with a mordanting agent is carried out according to the first step shown in Fig. 20. After completion of mordanting, the bath is dropped, and the dyed materials are rinsed and soaped with a nonionic detergent.

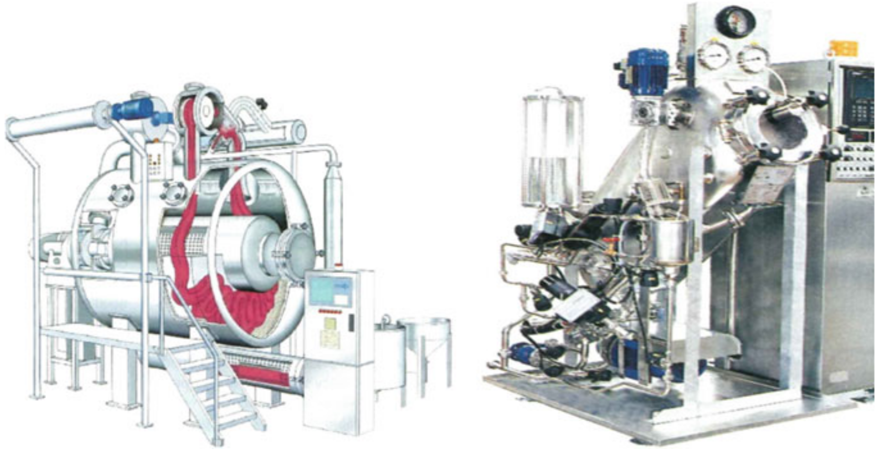


Fig. 21 A winch (*left*) and a jet-dyeing machine (*right*). *Source* Melliand International 3 (2010) 112 and 3 (2010) 120. Published with the authorization of Deutscher Fachverlag GmbH, Germany

7.3 Dyeing Machines

Luxury textiles fibers are usually dyed in loose stock form; therefore, a round-shaped, perforated basket type, loose-stock dyeing machine is used. In the case of yarn dyeing, yarns are wrapped onto spools; several columns of spools are stacked inside a yarn-dyeing machine; and dyeing is carried out. For fabric stage dyeing, winch or jet-dyeing machines are mostly used. Figure 21 shows the internal structure of a closed-loop winch-dyeing machine as well as a jet-dyeing machine.

7.4 Finishing Treatments

Finishing treatments are the last operations before marketing the fabric. Finishing treatments are carried out to enhance the aesthetic appeal and also to improve the functional performance of the fabric. However, possum fiber processing industries sell their products as a finished garment rather than as a fabric. Possum fibers are usually blended with wool; therefore, mostly wool-finishing processes are followed for possum/merino wool blended fabrics or garments. The main finishing processes are singeing, decatizing, softening, antimicrobial, antistatic, anti-shrinking, anti-shedding, etc. In the singeing process, a fabric in flat form is passed over a flame to burn out projecting fibers, which improves the aesthetic property of the fabric. Decatizing is carried out on a decatizing machine (Fig. 22) to flatten the fabric to remove creases, reduce shrinkage, and improve the stability and luster of the fabric. In this process, the fabric is wrapped on a perforated drum, and the drum is placed in a hot water bath or exposed to pressured steam. Decatizing is carried out at 110–120 °C under 1- to 2-bar pressure.

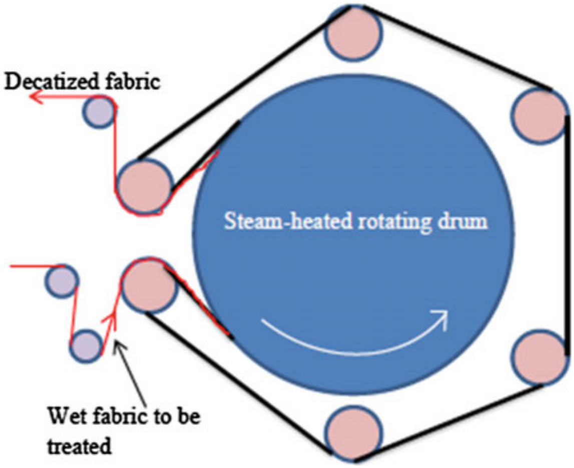


Fig. 22 Schematic diagram of a decatizing machine

To increase the softness and handling properties, the fabric is treated with aminosilicone pre-polymers. A dispersion of the polymer is taken in a padding mangle, and the fabric is passed through it and then squeezed to remove the extra liquor. The fabric is then dried in a stenter machine in a stretched condition and then cured at 150–180 °C for 60–90 s. Wool/possum blended fabrics are sometimes treated with an insect-resistant or antibacterial agent to protect them from moth or antimicrobial attack, respectively. Permethrin and imidacloprid are used as insect-resist agents, and triclosan, polyhydroxybiguanide, and quaternary ammonium compounds are used as antibacterial sgents (Goetzendorf-Grabowska et al. 2008; Hassan and Sunderland 2015). These are either added to the dye bath or to the finishing bath (padding mangle).

8 Applications of Possum Fiber

Possum fur is used in furnishings, clothing, clothing accessories, blankets, and footwear. Possum fiber made furnishings may include cushions and throws, which at various weight ranges are very soft and comfortable. Clothing and accessories made from possum fiber blends may include cardigans, jumpers, sweaters, wraps, vests, jackets, scarves, beanies, gloves, socks, wrist warmers, shawls, tunics, hats, berets, knee rugs, etc. It is also used in footwear including slippers and shoes. Possum fiber made blankets are very soft and warm. In the near future, possum fibers may find applications in duvets and pillows.

8.1 Possum Fiber in Fashion Wear

During the last 15 years, possum fibre blended with merino or cashmere has been accepted and established in the market as differentiated luxury yarn. Luxury European brand Hermes-Paris produced and commercialized ready-to-wear collections of luxury ladies wear using brushtail possum fiber/wool blend yarns made by a New Zealand-based yarn manufacturer named Woolyarns Limited. In New Zealand and overseas, several merino wool/possum blends are marketed by a number of brands including Koru, Lothlorian, Native World, Noble Wilde, Perino, and Zealana. There are always sold as a luxurious fashion wear and fashion accessories at premium prices that are much higher than those of merino wool products. MERINOMINK© is a wool/possum fiber made into apparel and accessories is marketed by Snowy Peak Limited (New Zealand) as shown in Figs. 23 and 24.

Fig. 23 Luxurious fashionable MERINOMINK© menswear and women's wear. *Source* Images are from Fiona Bretherton of Snowy Peak Limited. Published with the authorization of Snowy Peak Limited, Christchurch, New Zealand

Fig. 24 Luxurious fashionable MERINOMINK© accessories. *Source* Images are from Fiona Bretherton of Snowy Peak Limited. Published with the authorization of Snowy Peak Limited, Christchurch, New Zealand

9 Conclusions

Possum fiber is a wonderful fiber of nature with high warmth, light weight, very soft, and lustrous. The fibers are hollow in the length direction, which traps air, thus providing high warmth. The fibers are bluish grey to black and are mostly produced without any kind of chemical processing, which reduces environmental impacts and the carbon footprint of possum-fiber processing. The key sustainability issue is the trapping and killing methods used to harvest the fiber from possum. Alternatives could be stunning possum before killing or poisoning the animals with toxins that incapacitate the nerve system of the animal or toxins that quickly kill the animal. Possum fiber is rich in melanins, which give them a quite dark color. However, for dyeing in bright shades, they must be bleached, which is quite complicated and cannot be done without causing some level of damage to the fiber. Possum fiber is used in making various kinds of clothing and clothing accessories, blankets, and footwear. There is the opportunity to make the fiber further sustainable by using no harmful chemicals and also by stopping the use of dangerous toxicants to kill possum, which can endanger other forest animals and birds.

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Natural Fibres for Sustainable Development in Fashion Industry

Sanjoy Debnath

Abstract Ample numbers of natural fibres are available in nature from plants, animals, insects, and minerals. Each fibre is different from others, and that causes difference in their properties. Accordingly, these fibres alone, or in admixture with other fibres, are used in the design and development of specific fashion products. With time, different fashion industries have been developed all over the world for manufacturing different fibre-based fashion products. There is a huge potential of value addition in these fashion industries with the intervention of newer product design. Again, in this fashion industry, apart from newer design, avoiding the use of common natural fibres (cotton, wool, silk, etc.) commands more profit. Recent trends also show the use of these natural fibres for sustainable growth in this fashion industry. This chapter also deals with future aspects of the use of uncommon natural fibre for sustainable fashion industry.

Keywords Fashion industries · Natural fibres · Plant fibres · Sustainable development · Known plant fibres

1 Introduction—*Natural Fibres, Sources and Application —An Overview*

Nature has gifted humankind with a wide range of fibrous material. Based on the source, natural fibres are primarily classified into two categories: plant fibre and animal fibre. These plant fibres further classified into various categories such as leaf fibre, bast fibre, seed fibre, fruit fibre, etc.; on the other hand, animal fibres are also categorized as hair fibre, insect-secretion fibre, etc. Almost all animal fibres are protein-based, and plant fibres are cellulosic. Apart from the protein and cellulose as

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S.S. Muthu and M.A. Gardetti (eds.), *Sustainable Fibres for Fashion Industry*,
Environmental Footprints and Eco-design of Products and Processes,
DOI 10.1007/978-981-10-0522-0_4

major components for animal and plant fibres, respectively, these fibres contain many other components. Because all of these natural fibres come from biological sources, renewability or sustainability is not a big issue. For the fashion industry, along with manmade fibres, developments in the progress of the product and process of natural fibre are parallel.

Nowadays, people are more conscious about natural fibres and their uses (Debnath 2014a) due to their environmentally friendly nature because the disposal/degradation after use is not questionable. For this reason, many fashion products are now being stressed for development with natural fibres. In this chapter, most of the natural plant fibres used in the fashion industry will be covered. These fashion products are of two types: wearable and nonwearable. People are looking more for the use of uncommon/unexplored natural fibres in fashion products. Elite-class people are ready to pay more money for fashion products made out of natural fibres rather than products made out of common plant fibres such as cotton, wool, etc. Sometimes some manmade and natural fibres are blended with these known fibres to improve the functional properties of the final products (Basu and Roy 2008). The long plant fibres used most in fashion are jute, flax/linen, ramie, pineapple, sisal, nettle, coir, etc.; these fibres are sometimes blended with unconventional fibres such as cotton, viscose, polyester, acrylic, etc., to improve the look and feel of the final fashion product.

In the fashion industry, apart from manmade fibres, long plant fibres are generally extracted from different parts of the plant, viz., bark/bast/stem, seed, leaf, etc. are converted into textile yarn and fabric, which are used for fashion applications. There are many such plants in nature whose sap extracted from root, stem, leaves, barks, fruits, and seeds are used to extract natural dye used to colour fashion products. The natural fibres are cultivated; hence they are annually renewable in nature. This fact should be given more emphasis so that fashion products can be diversified. The fashion industry can be sustainable if the proper market and value of the fashion products are paid. Nevertheless, the present term “sustainable” also means taking care of mother Earth so that fibre can be green, production processes can be green, and fashion products can be free from synthetic materials. Minimal use of toxic chemicals and maximize utilization of plant extracts would sustain the fashion industry for the long term. This present chapter will cover to a great extent sustainable fashion textiles with reference to plant fibres other than cotton.

2 Fibres for the Fashion Industry—Natural and Man-Made Fibres, Blending of Fibres for Fashion Textiles, and the Importance of Using Known Fibres

Jute fibre has been a fibre known for more than a century for its industrial applications such as sacking/packaging, geotextiles, and carpet backing (Debnath et al. 2009). However, in last few decades, there have been lots of works wherein jute has been used as fashion products in different wearable and nonwearable fashion products. The demand for conventional products has declined due to the easy availability of low-cost synthetic materials. Export demand has also been reduced due to stringent norms due to presence of band residual chemical traces. Hence, many industries are now concentrating on the development jute-diversified products for fashion and jute bags for the packaging of agricultural produce. It has been found from the literature that jute with ornamentation—using suitable modifications in spinning (Debnath 2013b, 2014c), weaving, and knitting as well as nonwoven, handloom fabrics with an attractive look of elegance—can be made (Anonymous 2006a). Fashion design aspects have been considered at the fabric-manufacturing stage and others in dress making with designed fabric (garment manufacturing). Figure 1 shows a fashion shawl made from jute-based material (Anonymous 2006a). A jute-based fashion jacket and blazer are shown in Fig. 2a, b, respectively. Furthermore, jute-based fashion garments were exhibited in fashion shows at GIFTEX Stationex and Jutex 2005 in August 2005 at Mumbai (Anonymous 2006b). Models wore jute-based decorative fashion garments in the fashion parade (Figs. 3a through c). The literature also reveals that apart from these conventional products, jute can be used for the development of value-added green textiles. Some of these jute-based green textiles are fashionable, and some are of industrial application in nature. Fashionable green products from jute-based materials (Debnath et al. 2009) include fashion garments (Debnath 2013a, 2014b, 2015b) such as bulked yarns for sweaters, jute slippers, decorative and fashion products

Fig. 1 Jute-based fashion shawls

Fig. 2 **a** Jute-based fashion jacket as winter garment. **b** Jute-based fashion blazer

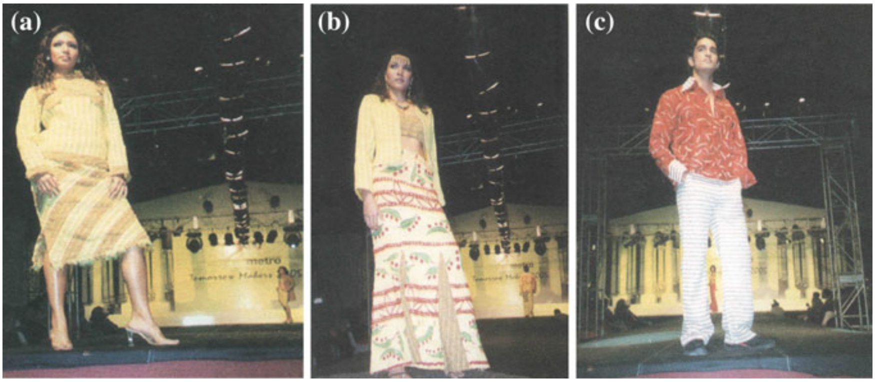

Fig. 3 **a** Jute-based fashion ladies' garment worn in fashion show. **b** Fancy jute-based ladies' wear worn in fashion show. **c** Male fashion apparel from jute used worn in fashion show

from handmade paper, fashionable shopping bags, fancy curtain materials, etc. These uncommon products are being marketed to some extent at prices that fetch good revenue.

The earliest example of preserved linen appears to be a needle-netted linen headpiece from Nahal Hemar Cave in Israel from 8500 years ago, and Swiss Lake Dwellers used a native flax to make cloth 5000–6000 years ago. Linen was the preferred textile of the ancient Egyptians who used it for clothing, bed linen, shrouds for mummies, and ships' sails. The earliest Egyptian linen cloth dates from the Old Kingdom, but flax appears to be have been grown for linen approximately 5000 years ago in the Early Dynastic period. In today's scenario, when we talk about flax fibre, it is well known as linen fashion as well as formal apparel for both males and females. Many leading manufacturers of linen-based products exist all over the world. Different blended linen products (Basu and Dutta 2014) are linen/cotton (warp cotton, weft linen or warp cotton, weft cotton/linen blend yarn), linen-based/cotton (warp cotton, weft linen/jute, linen/ramie, linen-pineapple, or linen/silk waste, etc.), linen/synthetic (warp polyester/cotton or polyester/viscose blend, weft linen, linen/jute, or linen/cotton, etc.), etc. Apart from these, there is huge scope to develop many other blended materials from linen. Elite men as well as women currently prefer linen-based apparel mainly for comfort apart from its esthetic look. Linen fibre material can absorb moisture quickly from body perspiration, and this provides cool and comfort in humid conditions. As far as the properties of the fibre are concerned, linen fibre material swells and thus improves the strength under wet conditions. This is one of the reasons linen/flax blend is normally preferred to spin under wet rather than dry conditions. As far as the international market is concerned, many pure/blended linen products are available such as ramie/linen *Kurti* for women for casual wear, linen blend trousers (50 % viscose, 35 % cotton, 15 % linen. The White label (65 % viscose, 25 % cotton, 10 % linen) by Joanna Hope, linen-mix trousers and shorts (55 % linen, 45 % cotton) by SOUTHBAY, single-breasted linen mix blazer (55 % linen, 45 % cotton; lining: polyester) by Williams and Brown: All of these are examples of lightweight fashion fabrics will keep you cool but stylish in the warm weather. Apparel (54 % cotton, 46 % linen) by Black Level Jacamo, linen mix 3/4 pants (55 % linen, 45 % cotton) by Southbay, ladies fashion linen-bow decorated straw-braid summer sun hat (linen 100 %), linen women's summer wide-brim sun hat style "Wedding Church Sea Beach" (linen 100 %) by Kentucky Derby, ladies sexy pleated criss-cross fashion linen dress, women's white linen dress (100 % linen), female slim blazer/short jacket/linen blazer/ladies coat, ladies linen thongs and underwear/briefs (85 % linen, 12 % nylon, 3 % spandex), women's linen socks (85 % linen,15 % nylon), etc. all show that there a good fashion market exists internationally.

Pineapple leaf fibre (PALF) is another unexplored natural fibre extracted from the green pineapple plant leaf, which is normally considered an agricultural product (Banik et al. 2011). Pineapple leaf fibre also has immense potential for use as a fibre source in the arena of sustainable fashion textiles (Debnath 2016). This fibre is very strong, lustrous, and creamy in colour. It found during a review (Anonymous 2015a) that pineapple leaf fibre is considered to be more delicate in texture than any other vegetal fibre. One kilo of leaves may provide ≤15 to 18 pieces of white, creamy, and lustrous silk-like fibre approximately 60 cm long, and it easily retains dyes. These leaf fibres are scraped by means of a broken plate or coconut shell, and a fast scraper can extract fibre from >500 leaves/day, after which the fibres are washed and dried in the open air. Then they are waxed to remove tangles, and the fibres are knotted and bound into yarns for the next process of weaving it the yarn to fabric. Pineapple fabrics are mainly used for creating Barong Tagalog and other formal wear. It is also used for other products where a lightweight but stiff and sheer fabric is needed. It is sometimes combined with silk or polyester to create a textile fabric. The end fabric is lightweight, easy to care for, and has an elegant appearance similar to that of linen. Pineapple silk is considered the “queen” of Philippine fabrics and is considered the fabric of choice of the Philippine elite. In the Philippines, PALF-based fabric is also popularly known as *pina fabric*. Different fashion products (both apparel and nonapparel) are available in the market made up of PALF. Figure 4 shows Filipino shirts that are national dress, worn by everyone from the Filipino president to brides and grooms, made from piña, a type of fabric made from pineapple fabric (Anonymous 2015b). Because the pineapple leaf fibre is lustrous, the cloth made out of this fabric is very lustrous even after it is dyed, and thus garments become even more eye-catching (Fig. 5).

Although pineapple fabrics were first created in the Philippines, the pineapple plant actually originated in South America around the region of Paraguay. In the 16th century, Spaniards invaded the Northern Philippines and planted pineapple plants, which they had discovered can grow successfully in their hot and moist island tropical climate. As far as the global market is concerned, Anonymous (2015d) is one of the commercial sellers of different types of pineapple leaf fibre based fabric globally. As far as blended pineapple leaf fibre material is concerned, Ghosh and Sinha (1977) is a pioneer in textile product development from PALF fibre. In their study, they used a special technique to spin pineapple in jute-spinning machinery. They found that fine pineapple leaf fibre could be spun into in yarns of 70- to 170-tex linear densities, which are prerequisite for fashion textiles. However,

Fig. 4 Fashion shirt made from pineapple leaf fibre used during wedding in the Philippines (Anonymous 2015b)

Fig. 5 Pineapple fabrics and their lustrous eye-catching luxury and beauty as made by couture designers (Anonymous 2015c)

in admixture with jute, 10–15 % pineapple fibre will improve the performance of jute-blended yarn, and fine jute/pineapple blend yarn can be produced. These fine pineapple and pineapple/jute blend yarns, plain and twill woven cloth, have been developed for sustainable fashion fabric development. Furthermore, these lightweight fashion fabrics are used to design fashion bags, curtains, furnishing fabrics, etc. Finally, the authors concluded that for sustainable fashion textiles, pineapple leaf fibre or jute/pineapple leaf fibre blend products have huge potential. Along the same line of research, Ghosh et al. (1982) carried out the processing of pineapple leaf fibre in a cotton-spinning system. Before processing in the cotton-spinning system, they studied and compared the physical and mechanical properties of cotton, jute, and pineapple leaf fibres. It was observed in their study that the 100 % pineapple leaf fibre is not at all possible to spin into yarn in cotton-spinning machinery. Hence, they tried to process PALF of different proportions (50, 33, 20 %) with cotton. From this study they optimized a blend of pineapple and cotton (50:50). Although the spinning performance is poor in cotton/pineapple blended fibre, a huge amount of cotton can be saved, and thereby value-added green products can be made out of this blended yarn. In the same area of blending pineapple leaf fibre evidence exists to study the performance of blended pineapple leaf fibre/acrylic fibre in jute-spinning systems (Ghosh et al. 1987; Dey et al. 2009). These authors studied the fibre properties of pineapple leaf fibre and acrylic fibres and compared their similarities and dissimilarities. Five different blends of pineapple leaf fibre and acrylic fibre have been tried, viz., 87:13; 67:33; 50:50; 33:67, and 13:87. From all of these blends, fine yarns of 84 tex were spun in a wet-spinning process where the rove was passed through a temperature bath (80–100° C) before spinning. They also spun the same yarns through a dry-spinning process. Finally, they compared the dry- and wet-spinning process and found that in wet spinning the breaking stress was reduced but the breaking strain was improved by 6 times. The optimum blend composition found from their studies is 67:33 pineapple/acrylic blend yarn (Basu and Roy 2008). The wet-spinning performance is much superior to that of the dry spinning method. Finally, the authors also concluded that there is ample scope for the development of green fancy apparel products out of these pineapple/acrylic blended yarns (Dey et al. 2009; Basu et al. 2006). In their papers, Ghosh and Dey (1988), Ghosh and Sinha (1977) showed different prospects and possibilities of pineapple leaf fibre based textiles for fashion apparel. Their study also confirms the types of fashion apparel/outerwear applications and fashion shopping bags, table cloths, etc. That can be made from PALF-based material.

Dogan et al. (2008) reported that the stem and fibre of stinging nettle are used to prepare traditional handicrafts in several Balkan countries. This nettle fibrous material in Bulgaria, locally known as *Kopriva*, is used for the sustainable development of cloth, sack, cord, and net manufacturing applications. In Romania, nettle is known as *Urzica*, and it is used as a substitute for cotton in fishing net and paper making. It is known as *Kopriva* in Serbia, where nettle fibre is considered to be one of the major textile fibres used in the spinning industry to produce textile products. Overall, there is a wide range of possible handicraft products (doormats, flower vases, wall hangings, door chains, carpets, hand bags, table mats, beach umbrellas, lamp shades, etc.) that can be made out of nettle either from fibre or yarn, fabric, or combination of these. All of these products have huge profit margin due to their high cost-to-benefit ratio. Most of the handicraft products fall under the category of fashion items. Similarly, Dunsmore (2006), in her findings, explained how different handicraft products are made out of nettle fibres and hand-spun yarn from Nepal. This study also elaborates on the sustainable rural livelihood earned through the cultivation of nettle to handicraft development of nettle products. This handicraft-making from nettle fibrous material by rural hill people created an alternative source of income during the lean period of agricultural activities. Economic development to the nettle-processing community of Nepal has been created through proper marketing strategy and exporting fashion textiles and handicraft products to Europe and America (Dunsmore 1998). Bacci et al. (2010) also reported that for sustainable handicraft products made from nettle, it is essential to use enzymatic retting to obtain the best quality fibre. Deokota and Chhetri (2009) reported in their research that handloomed products and handicrafts are sold side-by-side to promote nettle-based products in Nepal. These include coarse hand-woven cloths, sacks, bags, fishnets, and *namlo* (head straps to carry load), which are sold in the local market or in some cases are bartered for food or other necessary items in some rural communities. They have also demonstrated various sustainable fashion products made out of nettle and its blends such as hats, jacket, room decorations, and various handicraft products. Many of such products are available in the international market. An internationally known company, Swicofil (Anonymous 2015e), has used the juice of the nettle stem, and leaves have been used to produce a permanent green dye, whereas a yellow dye can be obtained form boiling the roots of nettle plant and used for dyeing fashion clothes. Both of the colours have been used extensively in Russia for fashion garments. Furthermore, an Italian fashion company, Savage Designs, introduced an environment friendly alternative to contemporary textiles and dyes. A light nettle jacket (Fig. 6) made of 70 % hand-spun and -woven wild nettle blended with 30 % organic cotton, unisex wild nettle pants (Fig. 7a, b), black-colored wild nettle jeans (Fig. 8), and a fashion ladies dress and shawl (Fig. 9a, b, respectively) are some of the commercial products made of nettle that are available in the global market.

Similar to nettle, ramie is also another bast fibre extracted from the bark of the ramie plant. Literature (Anonymous 2015f) reveals that ramie is also known as China grass, grass linen, rhea, and grass cloth. It is said that ramie fibers are one of the oldest natural vegetable fibers and have been used for thousands of years for fabric and clothing including ancient Egyptian mummy wraps and shrouds. The fiber is white, lustrous, and fine like silk. However, it is somewhat stiff and brittle, which is great for coarser products such as twine, rope, wallpaper, and nets. Ramie is often used as a substitute for cotton. When spun wet, it produces a high-luster softer yarn. Dry spinning results in a harsher, hairier yarn. The versatility of ramie fiber allows it to be made into fine yarn for all types of garments ranging from dresses and suits to sportswear and jeans. Fabrics made of 100 % long and fine ramie fibers are lightweight and silky. The fibers are uneven, which gives ramie fabric a similar appearance to linen. To produce fabrics with various improved characteristics, ramie is often blended with other fibers such as cotton. By doing so, the creation of fabrics from fine linens to coarse canvas gives ramie fibers almost unlimited potential. By blending with wool, the fabric is lighter, and shrinking is

Fig. 6 Coloured jacket made out of nettle fibre

Fig. 7 **a**, **b** Self-designed fashionable nettle unisex pants

minimized. Cotton blends result in increased strength, color, and luster, whereas rayon blends result in a higher wet strength. Ramie is also commonly used as a substitute for flax/linen and can also be blended with silk fibers. Ramie/China grass fibers are commonly used in blends for sewing threads, fashion sweaters, fancy clothing, and linens. Due to the fashion industry becoming more and more eco-conscious, the popularity of ramie will continue to rise. Interest in ramie is being rekindled, and it is appearing more often in the fiber content of clothing and textiles. Because of the trend toward natural fibers, expect to see ramie become even more popular. Ramie fabric is used for apparel including suits, skirts, jackets, dresses, shirts, blouses, pants, and handkerchiefs. It is also commonly used in home-fashion articles such as draperies, upholstery, linens, and thread (Anonymous 2015f). Industrial uses of ramie include parachute fabrics, fire hoses, and canvas. High-quality paper goods, such as bank notes and cigarette papers, are produced from the short fibers. Research findings show the processing technology of cotton/ramie blends (Anonymous 2002a, b) on short-staple spinning system (cotton spinning). Because both of the fibres are of natural plant origin, the final products are environmental friendly. Different fashion items, such as *Lisingphee*, fancy ramie/cotton woven towels, fancy designed fabrics, etc., are some of the novel fashion products developed form cotton/ramie blended yarns. However, less effort has been documented in the sustainability of the product. The main problem associated with ramie fibre is its gum content. Ramie fibre usually contains as high

Fig. 8 Blue-coloured ladies jeans

as 30 % gum. Two processes are normally used to extract the removal of gum of the fibre: One is chemical (alkaline treatment), and the other is microbial/enzymatic process. Although the microbiol process is more sustainable, it is associated with greater cost and is a time-consuming process. China is popular for the development of eco-friendly sustainable ramie-based textile products for fashion products. Different international repute companies (Joanna Hope linen blend trousers) are marketing ramie/linen *Kurti* for women's fashion wear.

Banana fibre is another unexplored natural fibre used in the fashion industry for sustainable product development. These fibres are extracted from the pseudo-stem of the banana plant. The fibres are bleached and blended with jute fibre aiming for a diversified, value-added fashionable product (Debnath and Das 2012). The authors focused on different fashion products made from banana-based textiles. Sinha (1974a, b) is pioneer in making the effort to blend banana-based fibre for different product development. This work elaborates the use of white jute, tossa jute, and kenaf, which were blended at different proportions for the development of different sustainable products. Anonymous (2012a) reported conventional hydrogen

Fig. 9 **a** Women's fashion gown made from nettle. **b** Women's fashion shawl made from nettle

peroxide bleaching, which is used to bleach the fibre, alter which further dyeing is carried out. Trials have been performed on jute/banana fibre in different blend ratios (100:0, 75:25, 50:50, 25:75, and 0:100), and the properties of the yarn were compared. Due to the coarseness and brittleness of the banana fibre, 100 % banana fibre shows poor results when spun. Furthermore, Anonymous (2012b) disclosed further that bleached and dyed jute-banana fibre blended yarns can be used to develop ornamental fibre using a jacquard attachment on a handloom. The decorated fabrics are used for the development of fashion jackets and other garments. Hence, there is immense potential to design and develop green banana fibre based textiles (Basu et al. 2006; Basu and Roy 2008). Apart from these, in commercial market, a banana fibre cardigan by People Tree (Fig. 10), hand-crafted in Nepal using banana fibres with an open gauge finish, features a deep V neckline, raglan-style long sleeves, twin pockets at the hips, and a single button fastening at the front (Anonymous 2015i). In Denmark, pants designed with a logline fit (Fig. 11) are made from silky banana fibre based material. They are available online in Denmark from Edwin Milano Baker. Apart from these fashion garments, sarees (Fig. 12) made from silk/banana fibre blend material are also available in the global market (Anonymous 2015k). Banana fibre also found importance in the fashion footwear industry (Fig. 13), wherein every component of the fashion footwear can be made different parts of the banana plant. Overall, there is an immense scope for using banana fibre in the fashion industry for sustainable development. This remuneration is due to extra utilization, and hence income, from the unused part of

Fig. 10 Fashion banana-fibre cardigan for women (Anonymous 2015i)

Fig. 11 Logline-fit pants made from banana fibre (Anonymous 2015i)

Fig. 12 Banana/silk blend fashion saree (Anonymous 2015k)

Fig. 13 Banana-fibre fashion footwear (Anonymous 2015k)

the banana plant after the banana crops are harvested. Nowadays, there exist some online marketing industries that deal with banana fibre based fashion textiles globally (Anonymous 2015j, l).

Sisal in one of the unexplored fibres extracted from the leaf of the sisal plant. Brazil is a pioneer in cultivating this fibre for rope twine, paper, cloth, wall coverings, dartboards, etc., as well as for different fashion applications (Anonymous 2015m). The literature also reveals that different commercial manufacturers worldwide are involved in producing sisal-based fashion products (Anonymous 2015g, h, m, n). A Thailand manufacturer/exporter/wholesaler of natural handmade handbags based in Bangkok provides sustainable and trendy sisal ladies' handbags, shopping bags, cosmetic bags and cases, gift bags, promotional gifts, shoulder bags, hats, handmade baskets, etc., and other various products at very attractive prices. Apart from the green-fashion area of sisal fibres, this fibre is also blended with wool and nylon for manufacturing fashion carpets and rugs (Anonymous 2015n). One of the important fashion as well as utility product made from sisal is sisal-based body scrubber. Basu et al. (2012) highlighted different prospects including fashion aspects of Indian-variety sisal. Anonymous (2004) developed an innovative processing technology of sisal/jute blends for the production of body scrubbers that have potential to replace the existing shoddy nylon scrubber. Overall, there is huge potential to develop sustainable fashion product from sisal.

Coconut/coir fibre is extracted from the outer shell of the coconut fruit. White and brown coconut fibres are the two main types of fibre available. White fibres are extracted from the green (tender) coconut, and brown fibres are extracted from mature coconut; the latter takes 3–6 months of retting in brackish water (Bhattacharya and Basu 2009). There are evidences about the processing of coconut (coir) fibre (*Cocos nucifera*) in small-scale jute-spinning systems (Anonymous 2002b). Anonymous (2006a, b) developed different types of lightweight handbags of fancy designs that go nicely with fashion garments. Further, Anonymous (2012c) reported that jute (60 % plus 40 % coconut) can be blended further for the development of value-added jute/coconut fibre blend yarn. The blended yarn is further used for the development of ornamental woven fabric can be used for fashionable ladies slippers, decorative handbags, etc. Furthermore, work has been performed to soften the coir fibre for better flexibility, and attempt have been made to develop dyed jute/coconut fibre blend yarn. It has also been documented that ornaments such as fashion necklaces (Fig. 14) have been designed by artists in Papara, Tahiti, and French Polynesia wherein the hybridization of coconut fiber, coconut shell, and black pearl is used for the development of fashion items (Anonymous 2015o). Furthermore, fashion footwear (Fig. 15) also uses sustainable coconut fibre.

Fig. 14 Fashion necklace made from the hybridization of coconut fiber, coconut shell, and black pearl

Fig. 15 Unisex fashion footwear made from coconut fibre

3 Sustainable Fashion Industry—*Fashion Fibres, Fibres for Fashion Products, Product Diversification, Technology Gap, Economics in Using Known Natural Fibres in Fashion Industry, Problem Associated with the Fashion Industry*

Apart from cotton, silk, and wool, many other known plant fibres, such as jute, banana, sisal, flax, ramie, coir, etc., have immense potential in sustainable fashion-product development. Most of these fibres plants do not need specialized attention during the production of the fibre (coir, jute, nettle, banana, pineapple, etc.). Because of this, many of these fibres have been used together for several centuries before much development was made in science and technology. The main advantages of these natural fibres are that they come from plant sources and the process of producing them, from production to fibre extraction, is sustainable (Debnath 2015a). With advances in fibre technology, many synthetic/artificial fibres have been developed and used for past 60 decades. However, in the last 15–20 years, special attention has been given to using lesser quantities of synthetic fibre, and more emphasis has been placed on the use of natural fibres in different areas of fibre application. With this, the production of natural fibre obtained special attention, and application of these fibres in different textile fields, including fashion, also increased. Due to the scarcity of agricultural land and urbanization in limited areas, greater amounts of fibre are being produced (for example 85–90 lakh bales/year of raw jute were produced during 1990–1995, and there was an increase in he production of 115–120 lakh bales/year during 2010–2013. However, along with this improved productivity, more importance is being placed on the sustainability of production systems.

In cottage and small-scale industries, fashion products are being produced directly from raw plant fibres without much use of chemicals and machinery. Some fancy items are also being produced in decentralized sectors. However, large industries, including composite plants, are used to producing fashion products in huge quantities. Many common products can be made from unexplored plant fibres such as sacks, both for packaging, agricultural applications (Debnath 2014a), etc. However, there will be huge value addition if we switch to the production of diversified fashion and lifestyle items from conventional products. Many of the industries processing natural fibres worldwide are now concentrating on value addition in product design. For instance, jewelry made from jute fibres/coconut/sisal fibres require a lower quantity (a few grams) of such fibres, and the value gain in final fashion products made of such fibre is a few hundred times. Hence, product diversification from conventional products is order of the day for sustainable development in the fashion industry.

In many cases, these natural plant fibres require tedious processes, including human drudgery, to extract the fibres from the plant component (Basu and Dutta 2014), and different chemicals and energy consuming processes (Debnath 2014c) are being used to convert those fibrous materials into yarn, fabric, and, finally, fashion products. These processes are compensated by extra profit when marketing those fashion items. With time, people are becoming aware about environmentally friendly/green chemicals and processes. Hence, more effort should be given, and in-depth research should be performed, to using more environmentally friendly chemical processing (Basu and Dutta 2014). It is also essential to use energy in an economical mode to form an overall sustainable process. For instance, in the jute industry, jute-batching oil is used to process the jute fibre during spinning. This oil is extracted during the petroleum-refining process and has been found to pose carcinogenic effects to human health. A substitute hydrocarbon-free oil has been developed, which is from vegetable origin and can be used to address this problem (Basu et al. 2009). However, this green-processing oil technology is somewhat less cost-effective and in some cases leads to technical problems during processing. Because some fashion products come into direct contact with the skin during their use, the eco-friendliness of the product—as well as the processes of its development—plays an important role.

Natural plant fibres have various advantages as reported by Anonymous (2015f). For instance, ramie fibre is highly absorbent, has a natural ability to resist stains, has a lustrous appearance, is strong and durable, is naturally resistant to bacteria, molds, and mildew, has low elasticity so it does not shrink easily, can withstand higher water temperatures, has good dimensional stability, is resistant to light, rot, and insect attack, dyes easily, and the fiber can be bleached plus it absorbs heat and releases moisture making it comfortable to wear in warm weather, etc. The clothing and textile fashion industry recognizes ramie as a premium product because it is one of the strongest natural fibers. Ramie fibre can be up to 8 times stronger than cotton and has the quality of being even stronger when it is wet. Ramie is a member of the nettle family, so it is well suited to growing in tropical climates. This hardy perennial can be harvested up to six times a year with a useful crop life of 6–20 years, and it produces premium long vegetable fibers. It is a highly sustainable fiber source, which makes it a wonderful eco-friendly alternative to synthetic fibers. High yields of biomass are often produced, but ramie is susceptible to pests and disease. Fiber extraction is an expensive process, which leads to a higher price for ramie fibers (Anonymous 2015f). Unlike ramie, jute is also a highly sustainable fibre crop. It absorbs huge amount of carbon dioxide and makes the environment clean and pollution free (Bhattacharya 2013). Many of the unexplored fibre crops are also sustainable due to multiple use of the plant components such as coconut plant apart from the fruit, coir fibre, pineapple fruit and fibre from its leaf, banana fruit and fibre from the plant, linseed oil from the plant and fiber from the plant stem, etc. However, emphasis must be put on the extraction process to get a better economic return due to difficulties in fibre extraction (Basu and Dutta 2014; Bhattacharya and Basu 2009).

4 Conclusions and Future Prospects

Natural fibres are the ultimate resource for future fashion industries. Due to scarcities of natural reserve resources, synthetic fibre production will decline in near future. Optimum use of energy will produce a good amount of natural fibres, which as yet remain unexplored. Greater application of eco-friendly processing technology and product diversification will sustain the fashion industry. It can also be concluded from this chapter that there are many fashion/utility materials based on natural plant fibres (not explored much) that have immense potential with proper marketing, advertising, and appropriate technologies to convert those fibres into yarn and, finally, fashion products. Minimum use of man-made chemicals and maximum use of natural chemicals (natural dye) will lead to green process and a sustainable fashion industry. Finally, each and every fibre has unique properties, and thus blending them with different natural fibres or blending them with a minimum quantity of synthetic fibre will also provide diversified end uses as far as sustainable fashion is concerned.

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Sustainable Biopolymer Fibers—Production, Properties and Applications

Karthik Thangavelu and Krishna Bala Subramani

Abstract The ultimatum for renewable raw materials is growing steadily as the drive for a green economy and a sustainable future accelerates. Escalating environmental problems and changing attitudes of consumers have made petroleum-based manufactured products more expensive and less desirable in the present world. Biopolymers, which are biological or biologically derived polymers, are a petroleum-free source of fibers for the textile industry and have a significant positive impact by reducing the dependence on fossil fuels as well as the carbon foot print and may even offer cost and durability benefits compared with synthetic textiles. This chapter deals with the less investigated and emerging biopolymer fibers, which will have huge impact on sustainable luxury fashion in the future. Bio-fibers from animal protein (spider silk, hag fish slime), regenerated cellulose (seaweed), and regenerated protein (milk fiber) as well as biopolymers synthesized from bio-derived monomers (PLA, PTT) are discussed in depth. The raw materials for production/extraction of fibers and their properties, applications, and ecological impacts are discussed.

Keywords Sustainability · Luxury · Biopolymer · Spider silk · Hagfish slime · Seaweed · Milk fiber · PLA · PTT

1 Introduction

The terms “sustainability” and “luxury” were one considered oxymorons, but a paradigm shift is taking place as luxury brands are embracing sustainability, and new concept of sustainable luxury and fashion is emerging. During the past decade,

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S.S. Muthu and M.A. Gardetti (eds.), *Sustainable Fibres for Fashion Industry*,
Environmental Footprints and Eco-design of Products and Processes,
DOI 10.1007/978-981-10-0522-0_5

sustainability has been developing in all industries, and luxury textiles and the fashion industry are no exception.

According to the UN World Commission on Environment and Development, also known as Brundtland Report, sustainability is defined as “meeting the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland and Khalid 1987). It is also defined by the UK Forum for the Future, 2006 as “A dynamic process which enables all people to realize their potential and improve their quality of life in ways which simultaneously protect and enhance the Earth’s life support system.” In simple words, sustainability is development for environmental, economic, and social well-being for today and tomorrow. It is based on two concepts: the concept of needs and the idea of limitations on the environment’s ability to meet present and future needs. Sustainable development implies the minimization of adverse impacts on the quality of air, water, and other natural elements so as to sustain the ecosystem’s overall integrity. In contrast to sustainability, luxury is defined as something that a consumer “wants” rather than “needs,” and it varies depending on cultural, economic, or regional basis (Joy et al. 2012). Although these concepts of “sustainability” and “luxury” contradict one another, in recent times customers who have concerns about both environment and his or her quality of life are looking for luxury textiles with sustainability, i.e., “sustainable luxury.”

The clothing/textile industry involves heterogeneous processes covering a wide range of activities: obtaining raw materials, production of yarn and fabrics, finishing and processing, and transformation of fabric into garments (Gardetti and Torres 2013a, b). Procurement of raw material is first or critical step for making sustainable textiles. Raw materials that are used extensively in textiles include plant fibers such as cotton, animal fibers such as wool and silk, and synthetic fibers such as polyester, aramid, acrylic, nylon, spandex, and carbon. These raw materials create a significant impact on the environment with the excessive use of pesticides and consumption of water in case of plant fibers and with treatments such as scouring in case of animal fibers as well as due to relying on nonrenewable resources for the manufacturing of synthetic fibers. Thus, there is a strong need of raw materials that are sustainable.

The recent idea of “seasonal new collection” in the apparel industry encourages consumers to purchase more clothes. An increase in buying fashion apparels raises the rate of textile consumption. Consequently, more textile waste will be created. The fashion carbon footprint of today dispels that myth as sustainable fashion designs increase in popularity and fashion styles move in the direction of eco-friendly apparel. The clothing-manufacturing process involves the design of garments, making patterns and samples, cutting the fabric and sewing the garments, and finishing and packaging the garments for distribution. Environmental sustainability issues differ throughout the manufacturing process. For example, smaller manufacturers might depend on a number of sewers at different locations, often home-based workers. This can increase fuel consumption and greenhouse gas (GHG) emissions because products must be transported from one location to another for each process rather than being processed in a factory. In some cases, the product might be sent in batches to different sewers who are spread across a large area. Thus, the apparel industry has sustainability issues throughout the supply chain.

In today's world, fashion is not limited to the aesthetic look of the garment; the functional features of the garment also play an important role. Furthermore, due to an increase in consumers' expectations, designers and manufacturers are also focusing on new dimensions of fashion by using unconventional fibres. Specialty hairs presently have vital spectra in the ever-changing fashion world. Utilization and application of specialty hair is the emerging trend, and it is growing slowly yet steadily. It is no secret that the world's softest garment fibre comes from a docile and adorable animal called the angora rabbit, and this fibre has huge commercial value. These fibres possess excellent thermal characteristics and hence provide the necessary comfort in cold-weather clothing. Textile materials nowadays are used in various sectors, especially based on the luxury requirement. The home furnishing sector is one the major markets where luxury textile materials have been used widely. Some of the natural luxury fiber used to make fabric includes silk, hemp, wool, horse hair, cashmere, mohair, and camel hair. Unconventional natural fibres, such as soy protein fibres, pine fibre, and lotus stem fibres, are emerging in the sustainable fashion market due to their inherent properties.

Rubelli, Ralph Lauren, and Etro textiles are the world's leading top three luxury home-textile producers. Most of these products from these companies are still completely hand-made on traditional looms the way it was done hundreds of years ago. The next important potential sector is luxury-brand automotives upholsteries. High-end car manufacturers, such as Mercedes, Lamborghini, Jaguar, and Rolls-Royce., use textile fiber based upholstery fabric that either meet functional requirements, such as sound and thermal insulation, or provide decorative aspects.

These limitations in currently available natural and synthetic fibres lead to the development of biopolymers/biodegradable polymers/green polymers, which are either (1) polymers occurring in living organisms with a specific biological function, or (2) plastic materials that are made from renewable resources or polymers that disintegrate by micro-organisms, or (3) polymers that promote environmental sustainability during their life cycle. Biopolymers offer a significant positive impact by reducing the dependence on fossil fuels and reducing carbon dioxide emissions.

Bio-polymers as a raw material present great development scope because they combine both technical potentialities and sustainability. Biopolymers are polymeric materials derived from raw materials for biological provenance. Some of these polymers can be produced directly by biological systems, such as polysaccharides, protein etc., or by indirectly using biological systems such as polylactic acid, poly (trimethylene terephthalate) (Averous and Pollet 2012). Biopolymers are different from biodegradable and green polymers. Biodegradable polymers are ones that break down into smaller fragments due to the action of bacteria and other microorganisms. Green polymers, on the other hand, are those produced using green (or sustainable) chemistry, a term that appeared in the 1990s. According to the International Union of Pure and Applied Chemistry (IUPAC) definition, green chemistry relates to the “design of chemical products and processes that reduce or eliminate the use or generation of substances hazardous to humans, animals, plants, and the environment.”

This chapter aims to provide detailed insight into emerging biopolymer fibers, which will have huge impact on sustainable textiles in the future. It elaborates the classification of biopolymers produced (1) from natural resources such as polysaccharides, (2) from animal protein, namely, spider silk and hagfish slime, (3) from regenerated cellulosic and protein fibres, and (3) synthesized from bio-derived resources, namely, PLA, PTT, etc. The raw materials, the production/extraction of fibers from the raw material, and the properties of the fibers are discussed in detail.

2 Environmental Impact of Current Natural/Synthetic Polymers and Need for Alternative Material

A comprehensive analysis of the impact of important natural and synthetic fibres and an environmental benchmark of fibres are shown in Table 1.

Cotton, the most used natural fiber when grown by conventional means, requires enormous amount of pesticides and water and needs large quantities of chemicals for processing and dyeing. Regenerated cellulosic fibres such as rayon and viscose are made of cellulose from trees, but they require chemical processing to be useful as polymers. Other synthetic fibers, such as polyester, nylon, acrylics, etc., rely on nonrenewable petroleum sources for their production. Thus, there is a major impact of such polymers on environmental in terms of depletion of fossil fuels, increase in landfills, dumping of waste in ocean, increased emission of CO_2, pollution caused by toxic emissions, recycling plastic might cause negative balance in ecosystems, and, more importantly, increased global warming. From an economic point of view, a dwindling oil supply is likely to boost oil prices, skyrocketing energy costs, etc. prevails. Thus in recent years, we have been experiencing the need for renewable polymers, and there has been a major thrust toward the development of bio-based materials. There is paradigm shift from petro-chemistry to green chemistry. The concept of green chemistry was developed in the 1960s, and it was implemented in the 1990s. The green concept focuses on minimizing the environmental impact of manufacturing processes through the careful management of feedstocks, energy, waste, and products (Slater et al. 2002; Mulhaupt 2013; Anastas and Warner 2000).

Table 1 Environmental impacts of important natural and synthetic textile fibres

Textile Fibre	Nonpolluting to obtain, process, and fabricate?	Made from renewable resources?	Fully biodegradable?	Reusable/recyclable?
Cotton	No	Yes	Yes	Yes
	Fertilizers, herbicides, pesticides, dyes, and finishing chemicals used can pollute air, water, and soil	Cotton comes from cotton plants, which are renewable		However, it is difficult to recycle cotton from postconsumer products
Wool	No	Yes	Yes	Yes
	Runoff contamination, chemicals used for cleaning, dyeing, and finishing can cause pollution	Wool comes from sheep, which are renewable		Wool can been recycled
Rayon	No	No	Yes	Yes
	Harsh chemicals used to process wood pulp, as well as dyes and finishing chemicals, can cause pollution	Wood pulp used for rayon comes from mature forest		Rayon fibers have not been recycled
Tencel®	No	Yes	Yes	Yes
	Chemicals used for dyeing and finishing can cause pollution	Trees used for Tencel® are replanted		Tencel® has not been recycled
Polyester	No	No	No	Yes
	Chemicals used for dyeing and finishing can pollute air and water	Petroleum sources are not renewable		100 % polyester has been recycled
Nylon	No	No	No	Yes
	Chemicals used for dyeing and finishing can pollute air and water	Petroleum sources are not renewable		100 % nylon has been recycled

Source Karthik and Gopalakrishnan (2013)

3 Biopolymers

Bio- based polymers are materials that are derived from renewable resources (Babu et al. 2013; Mohanty et al. 2002). The first generations of biopolymers are polymers derived from agricultural feedstocks such as corn, potatoes, and other carbohydrate sources. However, in recent years the focus is shifted from food-based resources due to significant breakthroughs in biotechnology. Biopolymers can be produced by bacterial fermentation processes by synthesizing the building blocks from renewable resources including lingo-cellulosic biomass, fatty acids, and organic waste (Averous and Pollet 2012; Vroman and Tighzert 2009). Biopolymers thus can be classified according to chemical composition, method of synthesis, method of processing, etc. (Shen et al. 2009) and can be categorized as follows (Fig. 1):

1. Polymers extracted directly from natural sources such as cellulose, starch, lignins, proteins and lipids.
2. Polymers produced from bio-based monomers obtained by fermentation/ conventional chemistry followed by polymerization. Some of examples include polylactic acid, polybutylene succinate, and polyethylene.
3. Polymers produced by micro-organisms or genetically transformed by bacteria, for example, polyhydroxyalkanoates.

The following section deals with the class of each biopolymer and some of the fibers under each category.

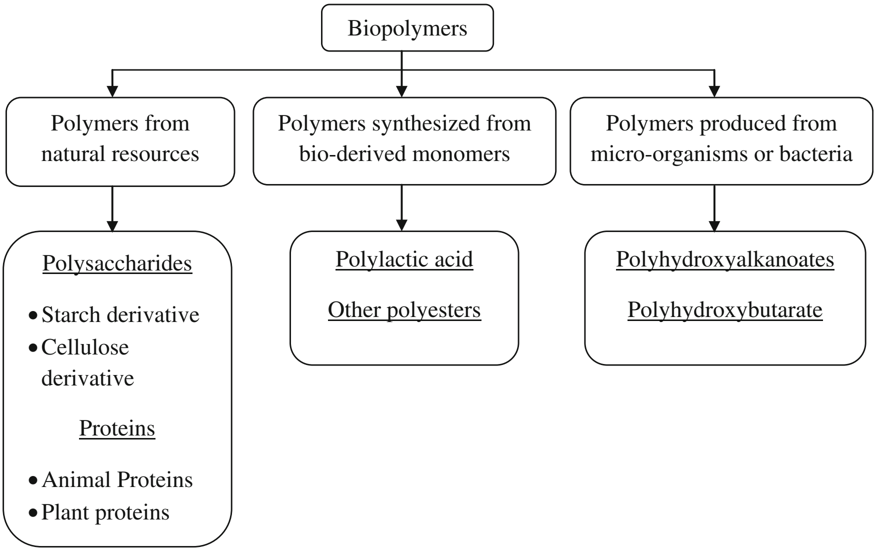


Fig. 1 Classification of biopolymers

3.1 Biopolymers from Natural Resources: Polysaccharides

Polysaccharides are the most abundant macromolecules, and complex carbohydrates form the structural elements of plants and animals (Averous and Pollet 2012; Vroman and Tighzert 2009). Various polysaccharides from which biopolymers can be synthesized are as follows:

- Starch: extracted from wheat, corn, potatoes
- Chitin and Chitosan: Crystalline microfibrils forming structural components in exoskeleton of arthropods or in the cell walls of fungi and yeasts.
- Pectin.

3.2 Biopolymers from Natural Source: Animal Protein

Proteins are polypeptide-based polymers formed by condensation polymerization of amino acids. Collagens, casein, fibroin, and keratin are the important animal proteins. Proteins play a critical role as building blocks of many complex hierarchical biological material scales. In this section, two promising protein-based bio-polymers are discussed: spider silk, which has been investigated by researchers for a long time, and hagfish slime.

3.2.1 Spider Silk

Spider silk is a natural protein fiber and has better mechanical properties than silkworm silk. This is mainly due to the fact that silkworm uses the silk for protection during metamorphosis, where spiders use their silk to catch the prey (Hardy et al. 2008). Spider silk has been recognized as a fiber with a unique combination of high strength and rupture elongation. In the 1950s, spider silk, specifically dragline silk, attracted the focus of material scientists owing to its outstanding mechanical properties, which can outperform any natural or synthetic fibers.

Of particular interest are silks from spiders that produce orb webs, which are used to catch aerial prey. The silk in these webs must be capable of capturing and holding the spider's flying prey, which requires the interplay of various silks with different properties. Female orb-weaving spiders can produce up to seven different silks with a range of properties. The golden orb spider and its spinneret are shown in Fig. 2. Spider silk proteins are synthesized from specialized abdominal glands that function as "bio-factories" to produce large quantities of silk fibroins, which are spun into silk with different properties, compositions, and morphologies.

Fig. 2 Golden orb silk spider species and the spinneret of spider silk (*source* http://www.chm.bris.ac.uk)

Types of Spider Silk

The many unique characteristics of spider silk can be attributed to the different types of spider silk. The variety of the silk comes from the ability of the spider to produce different qualities of silks for different uses in their biological environment. The common silks produced in most arachnids include major ampullate silk, capture spiral silk, tubuliform silk, aciniform silk, and minor ammuplate silk.

Most researched spider silk is dragline silk (major ampullate silk) from *Nephila clavipes*. The species has major gland ampulla making the silk and three pairs of spinnerets called "anterior laterals," "posterior laterals," and "posterior medians," respectively. Dragline silk has a skin core like structure where the skin is weak and the core is made of twin filaments that are stuck together and have a circular cross-section. Silk is made of fibroin proteins (spidorin I and II) that feature a repeated amino-acid sequence forming stiff crystalline structures in a more elastic matrix (Heim et al. 2009; Kubik 2002; Singha et al. 2012). However, due to the extensive time it takes to produce mass amounts of this precious silk, recent science has developed alternative methods to harvesting artificial spider silk and other silk-like high-performance materials.

Production of Spider Silk

The spiders have different glands to produce the different types of silk mentioned previously. Spiders produce silk by a process called "pultrusion." Unlike extrusion, in which fibre is squeezed out of a reservoir, the spider pulls the finished thread directly from the silk-making gland. Large-scale production of spider silk is difficult, which is hindering the use of spider silk in many applications. Farming spider silk is very difficult because they do not produce a lot of silk. Also, they are predatory in nature and will readily resort to cannibalism in the absence of other prey. Spider webs cannot be reeled as a single fiber like fibroin from the cocoon of the silkworm. Spider silk production is still in the very early stages, and it may be decades before it can be used in actual applications (Singha et al. 2012; Heim 2009). However, many research groups are focusing on the development of a technique for the mass production of spider silk (Heim 2009; Hisa et al. 2011). The efforts to reproduce spider silk have resulted in many innovative methods and materials, ranging from genetic modification to recycled silk to stem cells, with many success and limitations (Kang 2014; Xia et al. 2010).

Traditional Methods

Spiders are highly territorial and aggressive creatures; hence, it is not possible to raise spiders together in the same environment. In order to collect silk directly from spiders, they would have to be captured from the wild and housed individually. *Nephila clavipes*, a golden orb-weaving spider, has been studied extensively by numerous groups worldwide because it is a larger spider, which makes routine operations and handling a little bit easier.

Artificial Biosynthesis

As outlined previously, direct extraction of silk from spiders is not feasible for commercial production. Researchers have developed methods to artificially produce the liquid silk precursor using other organisms. Some of these methods are discussed below.

1. Chimeric Silkworms

Silkworms do not exhibit the territorialism and cannibalism seen with spiders, and hence they can be cultivated in mass. Normally, postproduction spinning technologies have to be used, such as extrusion, to convert the liquid monomers into silk fibers; however, these techniques are not yet reliable or effective. One requirement of this production method is that silkworms still produce endogenous silk proteins; thus, the resulting product is actually a combination of both silkworm and spider silk fibers. On the other hand, the composite fibers have been shown to be tougher than the parental silkworm fibers and as tough as the native dragline silk fibers.

2. Transgenic goats

Mammal cells have also been used as a host to produce spider silk monomers. Research in this field was first performed by *Nexia Biotechnologies*, who took genes from spider dragline silk, flanked these with regulatory sequences, and then inserted them into goat mammary gland cells, which are responsible for milk production in female goats. As a result, the spider silk proteins are produced only in the milk of lactating goats.

3. Metabolically engineered *Escherichia coli*

Using *E. coli* as an expression system to produce spider silk proteins of similar molecular weight and mechanical properties as native spider silk has been reported. The vector used was a plasmid, and it contained regulatory sequences to promote the transcription of the gene, a His-tag, to aid in the purification of the protein as

Table 2 Developers of synthetic spider silk at various stages of progress

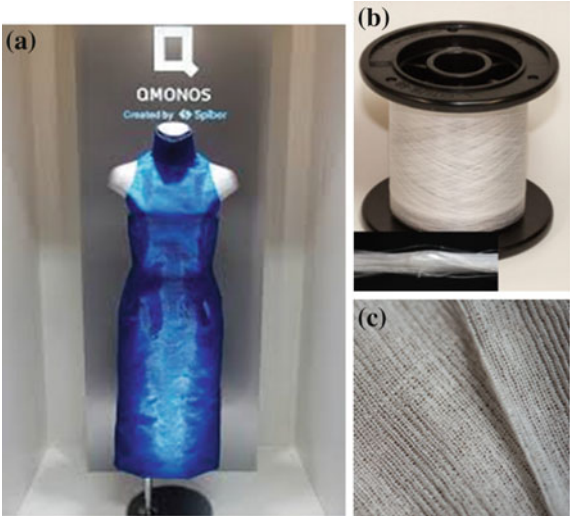
Organization/company	Technology	Application
AMsilk	Recombinant spider using *E. coli*	Hydrophilic, biocompatible, and bacterial spider silk can be key component in a variety of medical products including fibers, implant coatings, functional cosmetics, wound care, skin barriers, and surgical products
Araknitek	*E. coli*, transgenic alfalfa, goat, silkworm	Films—Fabric liners Sprays—Fabric strengthening and protection, sealants, medical coatings Liquids—gels, cosmetics Fibers—sports equipments, raw fabric inputs, ropes Fabrics—consumer, industrial, military clothing, tissue replacement, parachutes, and sails
Korea Advanced Institute of Science & Technology	*E. coli*	Fiber stronger than Kevlar
Kraig Labs	Transgenic silkworm	Hybrid spider/silkworm fiber for textiles
Qmonos® Spiber	*E. coli*	Fibers developed, apart from being used in clothing, can be used in sports, space exploration, and auto-industry and for a new line of accessories

well as the spider silk gene sequence. This specific spider silk gene sequence resulted in proteins, which are high in glycine. Several companies are making efforts to make artificial spider silk, as illustrated in Table 2, and well as products of which they are made (Fig. 3) (Scott 2014).

Properties of Spider Silk

Spider silks are considered to be superior to synthetic fibers such as polyamide or polyester with its combination of mechanical properties of high strength, high elasticity and low modulus. It is also five times stronger than steel on a weight-by-weight basis and twice the stretching ability of nylon. Spider silk is finer than human hair, more resilient than any synthetic fiber, and completely biodegradable. It has a strength of 1.74 GPa (three times tougher than aramid or industrial fibers) at a breaking elongation of >26 %. It has good waterproof characteristics and can absorb three times the impact force without breaking. Another fascinating characteristic of spider silk is its ability to super-contract: It can contract to <60 % of its original length when wet. In nature, this characteristic property allows the reorientation of hydrogen bonds between spider silk protein molecules during the uptake of water, thereby plasticizing the thread and changing its

Fig. 3 Synthetic spider silk from various research groups: **a** Electric blue dress from Qmonos® Spiber displayed at the Roopongi Hills complex, Tokyo, **b** Biosteel®, AMsilk and **c** knitting trials on Monster Silk®



mechanical properties. Interestingly, the super-contraction of spider silk takes place at ambient temperatures, whereas induction of the same process in man-made fibers generally requires elevated temperatures. Furthermore, spider silk also has a torsional shape memory, which allows the spider dragline thread, after being twisted, to oscillate only slightly and by this means to totally recover its initial form. This unique property allows spiders to rapidly descend using dragline silk as a lifeline in case of danger. Table 3 illustrates compares the tensile properties of spider silk with those of other high-performance fibers (Kubik 2002; Heim et al. 2009; Hisa et al. 2011).

Although dragline spider silk can be thought of as a new “super-substance,” its behaviors begin to change at different temperatures. At very low temperatures, it was found that dragline silk had an increase of strength showing that is more energy absorbent than synthetic polymer fibres. The strength decreased, however, with an increase of temperature to >60 °C. There are two main temperatures where the protein begins to breakdown: The first, 198 °C, is attributed to breakdown of the crystal phase of the protein into a liquid, whereas the second, 309 °C, is attributed to the partial recrystallization of the silk.

3.2.2 Applications of Spider Silk

If the production of spider silk ever becomes industrially viable, it could replace Kevlar and can be used in diverse range of applications such as the following:

- Bullet-proof clothing,
- Wear-resistant lightweight clothing,
- Ropes, nets, seat belts, parachutes,

Table 3 Comparison of tensile properties of spider silk with those other high-performance fibers

High-performance fibers	Density (g/cm^3)	Tenacity (GPa)	Extensibility (%)	Toughness (MJ/m^3)
Nylon 6,6	1.1	0.95	18	80
Kevlar 49	1.4	3.6	3	50
Dragline of A. diadematus	1.3	1.1	27	160
Wool	1.3	0.2	50	60
PLA	1.24	0.7	22	90
Carbon fiber	1.8	4	1.3	25
High-tensile steel	7.8	1.5	1	6

Source Kubik (2002). With permission

- Rust-free panels on motor vehicles or boats,
- Biodegradable bottles,
- Bandages, surgical threads, and
- Artificial tendons or ligaments, supports for weak blood vessels.

The mechanical properties of spider silk also suggest a potential for many applications such as thin sutures for eye or nerve surgery, plasters and other wound covers, textiles for parachutes, protective clothing, etc. Research on better understanding spider silk better and applying it for diverse applications is still in progress (Singha et al. 2012; Gole and Kumar 2012).

3.2.3 Hagfish Slime Fibers

One of the world's creepiest creatures may be the source of new kinds of petroleum-free plastics and super-strong fabrics. These are hagfish, ancient snake-like creatures that live on the bottom of the ocean. Hagfish are known for their ability to produce large volume of slime as a defensive mechanism when they are provoked or stressed. They do not have jaws, so they have evolved their own way to protect themselves from predators such sharks (Fig. 4).

Hagfish produce a mucus-like, viscous substance from their body when startled. This slime is composed of mucins and seawater held together by long protein threads. The slime reacts with water and clogs the gills of the predator fish, an effective and unique defense mechanism. The slime is produced at an astonishing speed at rate of approximately clogging 20 liters of water in a bucket in minutes (McKittrick et al. 2012). They have numerous glands located on either side of their abdomen (Fig. 5a), and these glands contract to expel the crude slime, which rapidly hydrates to final a polymer concentration of approximately 0.004 %. This enables the hagfish to leave a large bundle of slime, and it is reinforced with a thread that starts off as a miniature bundle of slime (Fig. 5b, c) containing one continuous fiber (15 cm long); these fibers unravel upon expulsion.

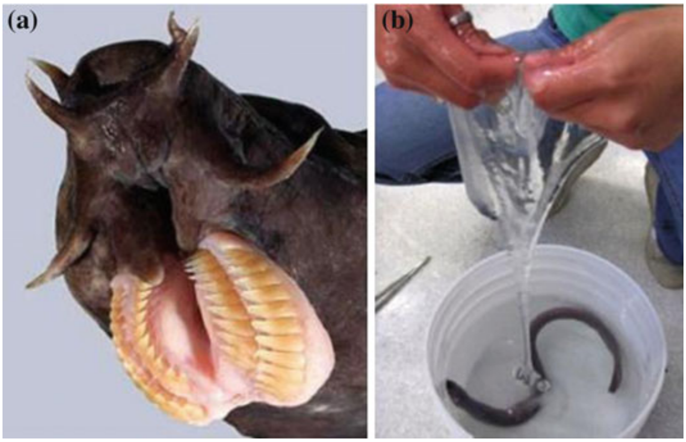


Fig. 4 Hagfish and its slime. **a** Photograph of the tongue of a broadgilled hagfish with keratin teeth. Photography by Carl Struthers © Museum of New Zealand Te Papa Tongarewa. **b** Slime produced by hagfish (http://www.people.fas.harvard.edu/lim/research.htm)

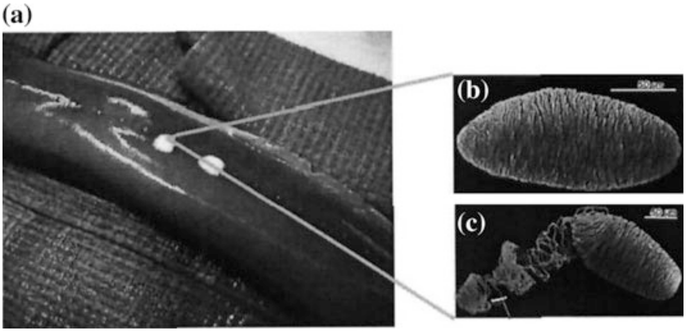


Fig. 5 Hag fish abdomen with slime and its structure (Fudge et al. 2003. With permission)

Extraction of Slime

Slime can be extracted either in the presence of water or by electrical stimulation in the absence of water. Hagfish is stimulated in sea water by agitation or local pressure. The voluminous slime thus produced contains a loosely tangled mass of fibers that is several centimeters long. This mass contracts spontaneously, and the resulting compact mat of fibers contains strands that can be drawn out several feet in length with variable thickness. The strands are soft and elastic when wet and strong and flexible when dry. The yield of fiber is approximately 0.25 g from a liter of slime.

To avoid the presence of water, the secretion was obtained undiluted by stimulating the animals outside of water. The hagfish was anesthetized with ether,

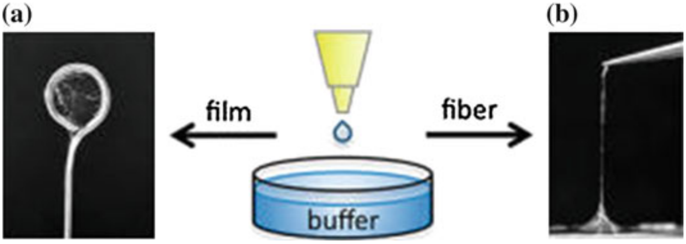


Fig. 6 Formation of fiber/film from hagfish slime: **a** Transfer of film membrane of regenerated thread protein off of the aqueous surface onto a metal ring. **b** Drawing up a fiber by picking up the films with forceps. Film and fiber were made using 5 % protein dope on 100 mM $MgCl_2$/20 mM HEPES, pH 7.5 buffer (Negishi et al. 2012. With permission)

suspended vertically, and wiped clean. On local electrical stimulation, the slime glands discharged white drops of secretion. The latter contained no extended fibers, but there were fibers in tightly rolled coils of uniform elliptical shape approximately 0.11 mm in length and 0.06 mm in width. Several dozens of these coils were discharged simultaneously from a single duct as could be observed with a microscope. When the secretion was diluted with either sea water or distilled water and slightly agitated, the coils unrolled to produce extended fibers (Ferry 1941).

Using solubilized hagfish slime thread proteins, castings of thin, free-standing films were formed onto aqueous electrolyte buffers, which were subsequently drawn into fibres. The single-thread intermediate filament protein was extracted and then purified. Then, before spinning, a protein dope solution was prepared (Negishi et al. 2012). Fibers were initially spun using a wet-spinning technique as shown in Fig. 6.

Structure of Hagfish Slime

The slime threads have an α-keratin like intermediate filament (IF) structure, and thread bundles are aligned, are 1–3 μm in diameter, and are several centimeters long. The formation of these bundle of fibers is unique, as shown in Fig. 7, and consists of the following steps: Individual α-helices form coiled-coil dimers (A) that self-assemble into sub-filaments, which in turn form complete IF (B) 10 nm in diameter, which align to form one continuous macroscopic fiber (C). This process occurs entirely within a single gland thread cell (GTC) and does not stop until the entire cell is completely filled with this newly formed fiber. On ejection out of the glands, the individual GTCs lose their thin membranous coating (D and E) (Ferry 1941; Negishi et al. 2012; Fudge et al. 2005).

The slime contains tens of thousands of 1- to 3-μm diameter threads composed of proteins from the “intermediate filaments” family of proteins (IFs). IFs are ubiquitous 10-nm cytoskeletal elements that are found in most metazoan cells, and

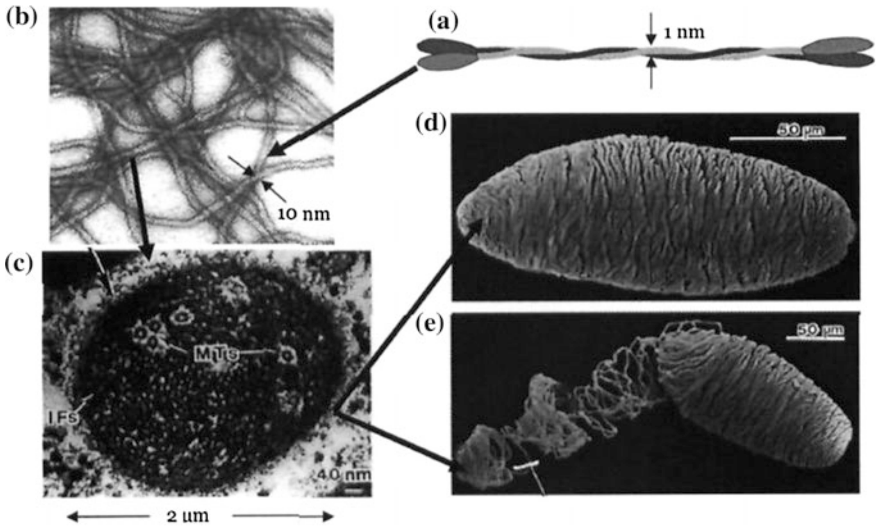


Fig. 7 Helical structure of slime threads (Fudge et al. 2003. With permission)

they also make up the fibrous component in mammalian α-keratins. Hagfish slime threads that are stretched in water and dried have excellent material properties. These draw-transformed slime threads resemble dragline spider silks in some aspects of their super molecular structure; both materials possess β-sheet crystallites, which are believed to be the source of strength in spider silk. IF proteins have the ability to self-assemble into networks of high aspect ratio filaments (i.e., 10 nm diameter, >103 nm in length) in aqueous solutions, which raises the possibility that fibers could be spun from IF gels.

Properties of Slime Threads

Slime threads and constituents intermediate filaments possess a number of attractive properties that make them promising protein fibers along with spider silk. Threads that have been stretched in water and dried have excellent material properties. These threads resemble dragline spider silk in the super molecular structure aspects (Fudge et al. 2010).

To understand the tensile properties of hagfish slime threads, properties of wool, which is also a keratin fiber, are used for comparison. Figure 8 shows a comparison between tensile stress strain curves for wet wool and for hagfish slime thread, and Table 4 provides a comparison of mechanical properties of hagfish slime with those of spider silk and wool. The mechanical response of dry slime and wet slime are different from each other with Young's Modulus of dry slime being 7.7 Mpa, which is higher that of wet slime and similar to other keratin fibers. This can be attributed

Fig. 8 Tensile properties of wool and hagfish fibres (McKittrick et al. 2012. With permission)

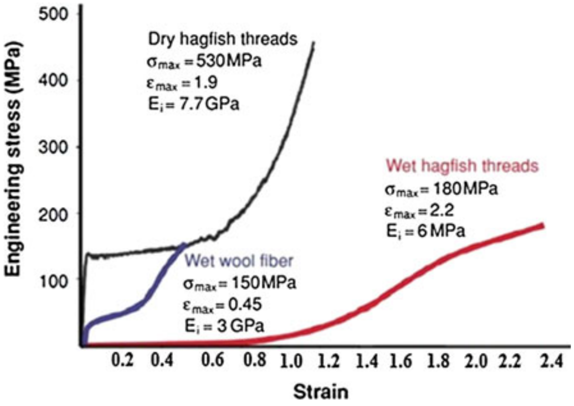


Table 4 Comparison of mechanical properties of hagfish slime, wool, and spider silk

Material	Initial modulus (E_{int})	Breaking strength (σ_{max})	Extensibility (E_{max})	Toughness (MN/m^3)
Spider dragline silk	10	1.2	0.3	160
Wet wool	0.5	0.2	0.5	60
Dry wool	4	0.25	0.3	60
Wet hagfish fibre	0.005	0.2	2.5	130

Fudge et al. (2003). With permission

to dependence on the degree of hydration. When compared with wet wool, it is found that the initial slope is a magnitude lower, but the maximum failure strain is four times higher (McKittrick et al. 2012). From the table and figure, it can be observed that the very low initial modulus, the impressive increase in the slope of the curve due to strain hardening, and the amazing extensibility of this fiber give the fiber a toughness easily comparable with that of spider dragline silk, −130 MJ/m^3.

Applications of Hagfish Slime

Many researchers are working on the analysis and production of hagfish slime, and it will not be long that the fibers will available in useful form. When stretched in water and dried, hagfish slime resembles silk, and soon it will be released as synthetic fibers, like nylon and polyester, in many applications. Researchers indicate that hagfish slime threads will be a candidate for the production of high-performance eco-friendly clothing, and will be a fashion fiber for the future. It also might be used for stockings or breathable athletic wear or even bullet-proof vests and other ballistic protection (McKittrick et al. 2012).

3.3 Regenerated Fibers

Regenerated fibers are sometimes known as man-made fibers. These fibers have been created artificially by using the building blocks provided by nature (e.g., proteins or cellulose) as opposed to fibers made entirely by nature. They can be categorized as fibers regenerated from cellulose and fibers regenerated from proteins. In recent years, bio-fibers from both of these categories—regenerated cellulosic and regenerated protein—are gaining importance given the increasing environmental concerns.

3.3.1 Bio-fibers from Regenerated Cellulosic Fiber

Rayon, the first regenerated cellulosic fiber, became popular owing to a shortage of natural fibers, large availability of renewable forest resources, and relatively low prices. However, the development of cheaper synthetic fibers, environmental concerns owing to the use of carbon disulphide in manufacture, and the depletion of forest resources led to the fall of the first generation of regenerated cellulosic fibers. However, in recent years, an environmentally friendly lyocell process, based on *N*-methylmorpholine-*N*-oxide monohydrate solvent system, has been developed for the manufacturing of regenerated cellulosic fiber (Chavan and Patra 2004). Among the regenerated cellulosic fiber, “seaweed fiber” mainly refers to the number of fibers that come from the sea such as seaweed, sargassum, kelp, and other algae. The extract-obtained alginate has been widely considered and researched for raw materials as a textile fiber material due to its biodegradability, health benefits, etc.

SeaCell® Fiber

SeaCell® fiber is a third-generation regenerated cellulosic fiber. Zimmer AG has succeeded, after intensive research, in developing SeaCell fiber,® a bio-fiber made of renewable resources. SeaCell® fiber is produced using an innovative lyocell technique in which seaweed containing vitamins, minerals, and trace elements is added to the cellulosic pulp before the spinning process. SeaCell® fibers can be known as the “wellness fiber with power of the sea” because it brings the power of nature back to people in an ecological, environmental friendly and contemporary way (Jackowski et al. 2004; Zikeli 2006; Hipler and Wiegand 2011).

Manufacture of SeaCell® fiber

SeaCell® fiber is manufactured using the environmental friendly lyocell process with seaweed and cellulose as illustrated in Fig. 9. Seaweed, mainly from the family of brown, red, green, and blue algae, and particularly the brown algae *Ascophyllum nodosum* and/or the red alga *Lithothamnium calcareum*, is used for the manufacture of sea cell fibers. Coarse crushed seaweed material is processed to fine seaweed

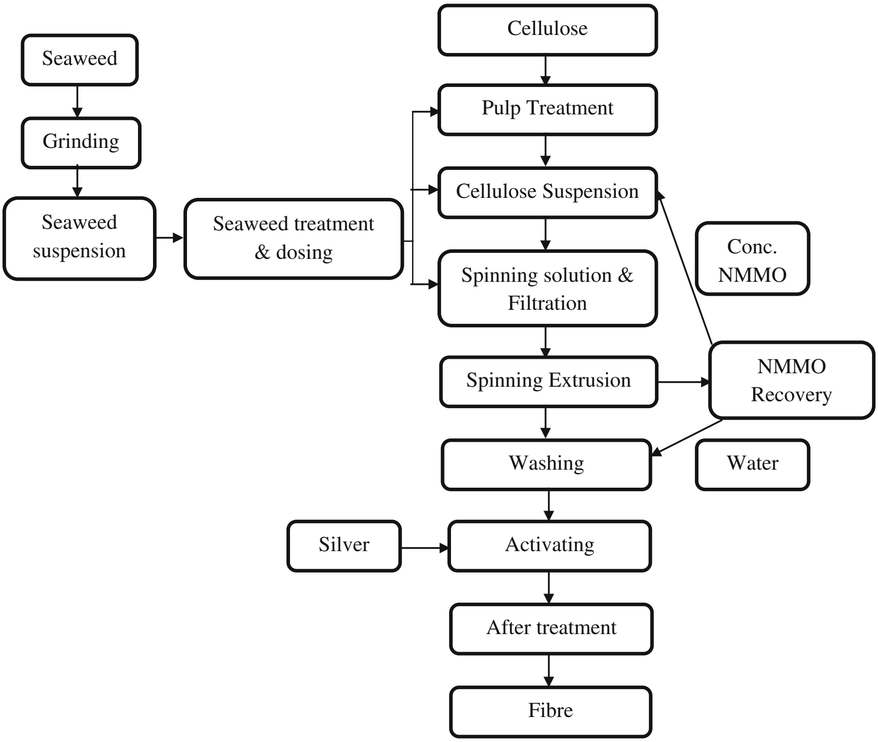


Fig. 9 Manufacturing process of SeaCell® active fibers (Zikeli 2006)

powder by specialized milling technology. The seaweed/algae are added either as a powder form or as a suspension in one of the processing steps preceding the spinning of the cellulose solution. In the lyocell process, the cellulose is dissolved directly without the formation of derivatives because the solvent used is the non-toxic aqueous solvent *N*-methylmorpholine-*N*-oxide. The spinning solution is processed in a combined dry-/wet-spinning process to form fibers and shaped cellulosic materials. During the spinning process, the solvent used in the spinning solution is washed out and is almost completely recovered.

SeaCell® fiber production can be either SeaCell® Pure, which is cellulosic fiber containing seaweed, or SeaCell® Active, which is cellulosic fiber containing seaweed and enriched with silver. One peculiarity with SeaCell® fiber is its capacity to bind and absorb substances, such as bactericidal metals, e.g., silver, zinc, and copper. This constitutes an important advantage compared with any other antibacterial fibers in the market (Zikeli 2006; Hipler and Wiegand 2011).

Properties of SeaCell® fibers

SeaCell® fibers can be produced as both staple fibers and filament. It has high tenacity and elongation properties (Table 5), which remain unchanged during the

Table 5 Tenacity and elongation properties of SeaCell® fibers (Zikeli 2006)

Properties	Lyocell	SeaCell® pure	SeaCell® active
Count, dtex	1.3	1.4	1.4
Tenacity, cond, cN/tex	36.5	35.9	34.4
Tenacity, wet, cN/tex	31.4	31.1	2.8
Elongation cond, %	12.1	11.9	9.3
Elongation, wet, %	15.3	13.4	14.2

production of SeaCell® Active fibers. Cellulosic characteristics of fiber make it feel soft, and textile made with SeaCell® fiber is impressive for imparting such a soft feel to skin. The skin-care properties of textile made of SeaCell® Active fibers are a distinguishing factor compared with other cellulosic fibers because SeaCell® fiber consists of health-promoting nutrients such as magnesium, calcium, potassium, phosphorus, trace elements (mainly iron and iodine), amino acids, and vitamins B, A, and E.

SeaCell® Active uses silver as a safe active substance without the need for organic compounds, thus providing an antibacterial effect without impairing its skin compatibility. Apart from these properties, it was found that the wear comfort, skin compatibility, antimicrobial properties, and other physical properties remain unchanged even after frequent washing.

Applications of* SeaCell® *fibers

SeaCell® fiber can be used in fabrics and nonwoven material at 100 % content or as blends and still retain its antimicrobial effects. These properties enable it to be used in a wide range of applications (Zikeli 2006). Some of the applications include the following

- Workwear: Gloves
- Sportswear: Socks, Yoga attire
- Underwear and Lingerie
- Home textiles: Furnishings, Bedding, Filters, Blankets
- Non-woven materials and Technical applications: Wipes, filters, and masks
- Household and Hygiene applications: baby clothings, towels, etc.

3.3.2 Bio-fibers from Regenerated Protein Fiber

Regenerated fibers from protein are called “azlons,” and sources of protein include soy, corn, peanuts, and even milk. Azlon is produced by dissolving proteins such as casein from milk, soy protein, or zein from corn in dilute alkali and forcing the solutions through a spinneret into an acid formaldehyde coagulation bath. These fibers resemble natural protein fibers, but they suffer from low dry and wet strength and sensitivity to alkalis (Brooks 2009).

Milk Protein Fibers

Milk protein is a new innovative fiber that was developed to compete with wool; it is a regenerated protein fiber made of casein from milk through bioengineering. Milk fibers were first introduced in 1930 in Italy and America to compete with wool fibers and products. Even though milk fibers, otherwise termed "casein fibers," lack some desirable properties of wool, it was a means to replace wool fibers at lower cost. Casien fibers cannot be distinguished from wool fibers by chemical or burning tests because their chemical composition is very similar, but they can be identified by a microscope because they lack scales, which are characteristic of wool. Some of successful brands that developed milk protein fibers are Aralac (America), Lanital (Belgium, France), Merinova (Italy), and Fibrolane (Britain [www.swicofil.com]).

Production of Milk fibers

The various processes involved in production of milk fibres are shown in Fig. 10 (Kiron 2013; Saluja 2010).

1. Extraction of raw materials—To extract casein protein, milk is first dewatered and skimmed and casein obtained by the acid treatment of skimmed milk. The casein coagulates as a curd, which is washed and dried and then ground to a fine powder. It can be obtained from skim, evaporated, or condensed milk. From 35 l of skimmed milk, approximately 1 kg of casein protein can be extracted.
2. Polymerization (mixing, filtration, deaeration)—Protein-spinning fluid suitable for wet-spinning process is manufactured by means of a new bioengineered technique. Casein is blended to minimize the effects of variation in quality and then dissolved in sodium hydroxide. The solution is allowed to ripen until it reaches a suitable viscosity and is then filtered and deaerated.
3. Spinning—Wet-spinning technique is used by extruding the spinning solution through spinnerets into a coagulation bath consisting of 2 parts sulphuric acid, 5 parts formaldehyde, 20 parts glucose, and 100 parts water. The jet of solution coagulates into filaments similar to the coagulation of viscose filaments. As the filaments emerge from the spinnerets, liquid polymer is converted to a rubbery state, and it further solidifies. The endless filaments formed are stretched to

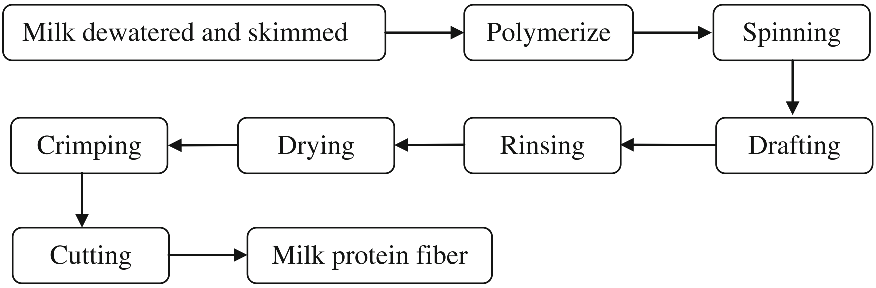


Fig. 10 Production of milk protein fiber

some degree during coagulation. The coagulated casein filament is very soft, weak, and can readily break. Hence, further processing is required so that the filaments can be successfully used in textile applications.
4. Crimping, cutting to staple fibers—After spinning, long staple filaments are crimped and cut into staple fibers.
5. Hardening—Water can penetrate in fibers, thus readily pushing apart long casein molecules and hence softening and swelling the filament. This makes them of little use as a textile fiber. Many methods of increasing the water resistance of casein have been developed to enable the long molecules to hold together in the presence of water. One such process is hardening to minimize the softening effects of water.
6. Washing, drying, and baling—After hardening, the fibers are washed, dried, and packed into bales.

Properties of Milk fibers

Milk protein fibers are silk-like, soft, glossy, lustrous, luxurious, and smooth to the skin. They are hygroscopic in nature adding to their comfortability. They are very easy to dye and can be dyed under normal temperatures. Because they contain amino acid, milk proteins have antibacterial and antifungal characteristics. Milk fibers have a tenacity of 2.8 cN/tex, but when they are dry this falls to 2.4–2.6 cN/tex on wetting with elongation of approximately 60–70 %. Milk protein fibers generally soften on heating, particularly when wet. Fibers become brittle and yellow on prolonged heating. Milk fibers are stable to acids of moderate strength under normal conditions but sensitive to alkali. Milk protein fibers have excellent properties such as a silk-like "hand," soft and elegant luster, wear resistance, stain resistance, moisture permeability, skin-affinity characteristics, etc.

Applications of milk protein fibers

1. Pure milk protein fibers - The major uses of milk fibers are as follows:
    - Intimate garments
    - Children's garments
    - T-shirts
    - Sweaters
    - Women's garments
    - Sportswear
    - Uniforms
    - Bedding
    - Eye masks, etc.
2. Blends with other fibers:

Silk protein fiber can be blended with other fibers such as cashmere, silk, spun silk, cotton, wool, ramie, and other fibers to make fabrics with features of milk protein fibers.

- Blends for cool type—Milk fiber blends with silk, bamboo fibers, natural silk, and cashmere
- Blends for thermal protection—Milk fiber blends with mercerized wool and cashmere
- Blends for top-grade intimate garments—Milk fiber blends with cotton and cashmere
- Blends for health care and beauty—Milk fiber blends with cotton
- Blends for home textiles—Milk fiber blends with cotton and silk.

3.4 Biopolymers Synthesized from Bio-derived Monomers

Bio-based polyester is derived from natural resources using biotechnology. It includes polylactic acid (PLA) and poly (trimethylene terephthalate) (PTT).

3.4.1 Polylactic Acid (PLA)

Polylactic acid (PLA) is the first melt-processable synthetic fiber produced from renewable resources, which combines ecological advantages with excellent performance in textiles. It is aliphatic polyester based on lactic acid ($C_3H_6O_3$) and is produced from the fermentation of agricultural resources. PLA requires 20–50 % fewer fossil resources and has the potential to reduce atmospheric CO_2 levels. It is an interesting polymer combining advantages of both natural and synthetic fibers and has wide range of applications (Avinc and Khoddami 2009; Farrington et al. 2005). Currently, Nature Works LLC USA is a major supplier of PLA fibers under the brand name Ingeo®, and others PLA fibers include Lactron® (Kanebo Gohsen Ltd), Ecodear® (Toray Industries), Terramac® (Unitika), Plastarch® (Kuraray), etc. (Hongu et al. 2005).

Ingeo® PLA Fibers

In 1988, Cargill Incorporated began an investigation into lactic acid and collaborated with The Dow Chemical Company to form Cargill Dow LLC in 1997 to develop and bring PLA technology and products to full commercialization. The trade name of PLA polymer is Nature Works® PLA and for PLA fibers is Ingeo® fibers (Gruber and O'Brien 2005; Vink et al. 2004; Gupta et al. 2007; Avinc and Khoddami 2009).

Lactic acid is the starting material for the PLA-production process. The monomer lactic acid is hydroxyl carboxylic acid, which can be extracted from corn starch through converting starch to fermentable sugars (dextrose) by enzymatic hydrolysis followed by bacterial fermentation. PLA from lactic acid monomer can be produced by two routes: (1) polycondensation of lactic acid under high vacuum and high temperature; and (2) ring-opening polymerization of a cyclic dimer of lactic acid (Avinc and Khoddami 2009; Farrington et al. 2005; Vink et al. 2004; Gruber and O'Brien 2005). Route 1 involves the removal of water by condensation and the use of solvent under high vacuum and temperature. In this technique, it is difficult to obtain high molecular weight PLA due to water formation during the reaction. Route 2 produces a high molecular weight polymer, which is based on removing water under milder conditions without solvent to produce cyclic intermediate dimer referred to as "lactide."

Cargill Dow LLC developed a patented, low-continuous process for the production of lactic acid based polymers. The process starts with a continuous condensation reaction of lactic acid to produce low molecular weight PLA pre-polymer. Pre-polymer is converted into a mixture of lactide stereoisomers using tin catalysts to enhance the rate of intramolecular cyclization reaction. Finally, PLA polymer is produced using ring-opening lactide polymerization, thus eliminating the use of solvents. After the polymerization is complete, any remaining monomer is removed under vacuum and recycled to be used as a raw material (Farringto et al. 2005; Vink et al. 2004).

Spinning of PLA fibers

Transformation of PLA into textile structures is complicated and depends on structural changes in the polymer that occur during processing. Extrusion of polymer into mono-/multi-filaments can be achieved by melt spinning, dry spinning, wet spinning, or dry jet wet spinning. Distinct features of each of these processes are reflected in the fiber properties. Due to its thermoplastic nature, melt spinning is widely used to extrude into fibers. It has many advantages compared with wet spinning, e.g., it is a solvent-free process and hence there are economic and ecological advantages. However, melt spinning is not always possible because the polymer sometimes degrades while melting. In the case of dry spinning, solvents are removed by thermal evaporation, whereas in wet spinning the coagulation of polymer is carried out in another fluid that is compatible with the spinning solution (Gupta et al. 2007).

Properties of Ingeo® PLA fibers

As a melt-processable fiber from a vegetable source, PLA has characteristics similar to many other synthetic fibers. PLA has high mechanical strength, compostability, and biocompatibility with properties mainly a cross between those of polyamide and those of PET. Properties of PLA fibers compared with other natural and synthetic fibers are listed in Table 6 (Vink et al. 2004; Farrington et al. 2005; Durgan 2001).

The tenacity of PLA is similar to that of PET and higher than that of natural fibers. PLA is highly resistant to degradation by ultraviolet exposure. PLA can achieve good degree of crimp and good retention level through processing. It has advantages with respect to smoke generation and flammability because it has both a higher limiting oxygen index and lower smoke generation than PET. PLA exhibits good moisture management and comfort properties. The lower contact angle compared with that of PET leads to improved wicking with water. Unlike other synthetic fibers, PLA does not absorb light in the visible region of spectrum, and

Table 6 Properties of PLA fibers compared with those of other fibers

Properties	PLA fiber (Ingeo®)	PET	Nylon	Cotton
Specific gravity	1.25	1.39	1.14	1.52
Tg (°C)	55–60	70–80	50–90	–
Tm (°C)	130–175	255	215	–
Tenacity (g/d)	2.0–6.0	2.4–7.0	5.5	4
Moisture regain (%)	0.4–0.6	0.2–0.4	4.1	7.5
Elastic recovery (5 % strain)	93	65	89	52
Heat of combustion (MJ/kg)	19	25-30	3.1	17
Flammability	Low smoke	High smoke	Medium smoke	Burns
LOI (%)	26-35	20–22	20–24	16–17
UV resistance	Excellent	Fair	Poor	Fair-poor
Refractive Index	1.35–1.45	1.54	1.52	1.53
Contact angle (ϕ)	76	82	70	–

Source Natureworks LLC, Ingeo®

this leads to very low strength loss compared with synthetic fibers on exposure to UV light. On the contrary, they have some disadvantages too. PLA exhibits higher sensitivity to alkali and causes strength loss. PLA has a surface cohesion, which gives the fibers a property known as “scroop,” which influences resilience and causes problem in applications by resisting recovery after deformation.

Applications of Ingeo® PLA fibers

The ease of melt processing has led to the production of PLA fibers, which are increasingly being accepted in a wide variety of textiles from dresses to sportswear, furnishings to drapes. Due to its natural flame retardancy and good moisture management, PLA fibers are well suited to fabrics from fashion to furnishings. They can be applied as fiberfill for products such as pillows, duvets, and comforters due to their superior loft characteristics compared with conventional synthetics. In term of nonwoven products, they can be used in health and hygiene products.

Lactron®—PLA Fibers

Kanebo, Inc. introduced a PLA fiber under the trade name Lactron® fiber at the February 1998 Nagano Winter Olympics under the theme of “Fashion for the Earth.” Kanebo exhibited several garments from PLA or PLA/natural fiber blends (Hongu et al. 2005; Farrington et al. 2005). Lactron® is made of PLA fibers in turn made from lactic acid obtained through the fermentation of cornstarch. Lactron® has the highest melting point of any biodegradable fiber ever developed, so it can be processed into multifilament, monofilament, staple fibers or spun-bonded fabrics suitable for any type of textile applications. The characteristics of Lactron® include the following:

- Fiber strength is as great as that of nylon and polyester making it suitable for spinning
- Young's Modulus is between as that of nylon and polyester
- Has a soft touch, good water diffusion, is sweat-absorbable and dries quickly
- Low refractive index and mild gloss
- Dyeable by disperse dyes at 98 °C, ambient pressure
- Melting point is 175 °C, higher than any other biodegradable polymers
- Anti-bacterial, weak acid, and retains humidity.

Lactron® has fiber properties and processbility comparable with those of conventional polyester and nylon. Considering the biodegradability of fibers, which is important for achieving sustainability, it has been determined that Lactron® fibers completely degradable. The weight of fibers decreases within a few years in soil followed by reduction in strength and, ultimately, decomposition of the fibers.

Because Lactron® fibers can be processed in various shapes, such as filament, staple, monofilament, spun bond, and flat yarn-spinning fiber, they can be developed in various goods from noncloth applications, such as agricultural textiles, fishing goods, and construction textiles, to apparel goods. They can be blended with wool to achieve lightness, form stability, be crease resistant, be fashionable, etc., and blended with cotton/rayon to achieve moisture/sweat absorbing characteristics, quick-drying effects, silky luster, etc. The main merit of using "corn fiber" or "PLA fiber" in applications is that it can solve the problem of dumping while retaining the advantages of conventional mixtures of synthetic and natural fibers (Hongu et al. 2005; Farrington et al. 2005).

3.4.2 Poly (Trimethylene Terephthalate)

Polyester and polypropylene terephthalate (PET) are dominant synthetic fibers in apparel, home furnishings and many other industrial applications. As an engineering thermoplastic, poly(trimethylene terephthalate) (PTT) has a very desirable property set combining the rigidity, strength, and heat resistance of PET and with good processability of polybutylene terephthalate (PBT). In terms of fiber, they have the good resiliency and wearability of nylon as well as the dyeability, static resistance, and chemical resistance of PET (Hongu et al. 2005; Houck et al. 2001).

PTT, which was synthesized in 1941 and has good physical and chemical properties as well as many potential applications, has not been commercialized due to the high cost of raw material (1,3-propanediol (PDO)). DuPont pioneered a way to produce PDO from corn sugar using a patented fermentation process, and PDO thus produced is termed "Bio-PDO™." DuPont introduced their PTT, also known as 3GT, under the trade name Sorona® and targeted its applications to textiles, carpets, industrial fibers, and engineering plastics. Sorona® is corn-based fiber made from 1,3-propanediol (PDO) and a petrochemical-based monomer (Kurian 2005; Wolf et al. 2005).

Production of PTT

The production of PTT consists of two steps: (1) production of Bio-PDO™ and (2) production of PTT from Bio-PDO™.

Production of Bio-PDO™

In 2004, DuPont formed a joint venture with Tate & Lyle, a major producer of corn-products with expertise in fermentation processes, to produce Bio-PDO.™ The fermentation process consists of two steps: (1) yeast ferments glucose to glycerol and (2) microbes ferment glycerol to PDO. DuPont developed a patented process in collaboration with Genencor that consists of the metabolisation of glucose derived from wet-milled corn by genetically engineered microorganism *E. coli* (Fig. 11). After the organism ingests glucose, it produces PDO, which is separated by filtration and concentrated by evaporation followed with purification by distillation.

Production of PTT from Bio-PDO™

PTT can be produced either by transesterification of dimethyl terephthalate (DMT) with PDO or by esterification route starting with purified terephthalic acid (PTA) and PDO as shown in Fig. 12. Polymerization is continuous process similar to that of PET, and in the first stage of polymerization, low molecular weight polyester is produced in the presence of an excess of PDO with water or methanol removed. This is followed by polycondensation, and chain growth occurs by the removal of PDO and the remaining water/methanol. Both monomers should be pure because chain termination can occur at any time. In the final step, the highly viscous molten polymer is blended with additives in a static mixer and then palletized.

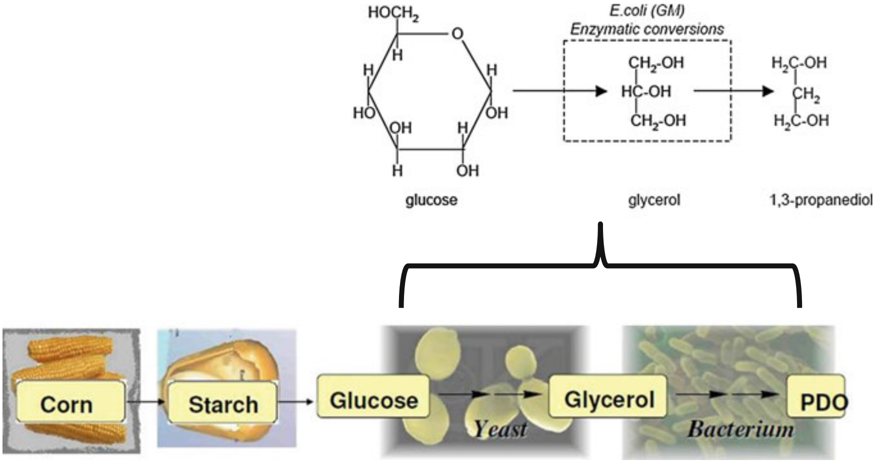


Fig. 11 Production of Bio-PDO™ by the fermentation route (*source* Kurian 2005)

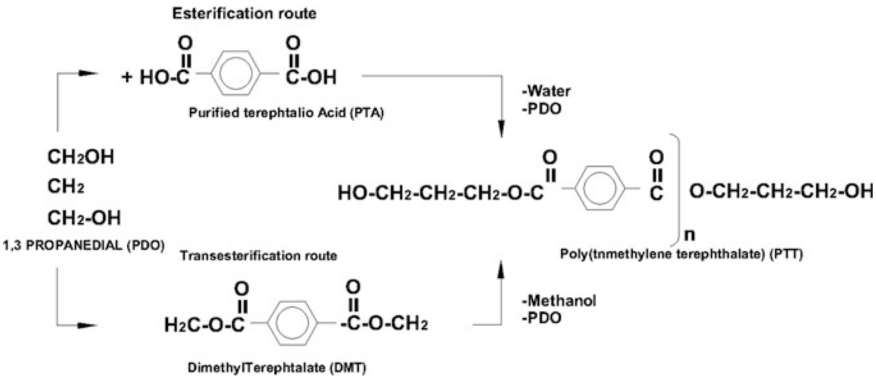


Fig. 12 Formation of PTT from Bio-PDO™ (*source* Kurian 2005)

Properties of PTT Fibers

PTT combines several advantages of other fibers such as the strength, stiffness, toughness and heat resistance of PET; the processing parameters, such as low melt and mould temperatures, rapid crystallization, and faster cycle time, of PBT; and the good resilience and wearability of nylon. The tenacity of Sorona® (PTT) fibre is as high as that of nylon, but it is softer and 2–3 times stretchier than nylon. The unique tensile properties of fibers are derived from a semi-crystalline molecular structure featuring a "kink." When the molecule undergoes stress, strain deformation occurs first in its crystalline regions; as the stress is released, the crystalline structure locks in, thus allowing complete recovery to its initial shape. Due to moderate glass-transition temperature, PTT fibers are dyeable with common disperse dyes without a dye carrier, thus saving energy compared with dyeing PET fibers. It also exhibits uniform dye uptake and with selected dyes, its color-fastness is comparable with that of nylon. It has excellent UV resistance, chlorine resistance, and low static-charge generation (Kurian 2005; Wolf et al. 2005; Shen 2009).

Applications of PTT Fibers

Sorona® fibers can be used for various applications such as apparel, outdoor/sport goods, floor coverings, and carpet fibers. Significant advantages of Sorona® fibers for apparel are softness and natural hand, printability, and easy dyeability. In addition, resistance to chlorine and UV add value in outdoor/sport markets. The fibers can be blended with other natural fibers such as cotton, wool, etc., or synthetic fibers such as PET, acrylics, etc., for enhanced softness, stretch recovery, and other functional attributes. These fibers can be made in a variety of colors and styles, with good dye uniformity, and can be better candidate for floor coverings. It also offers superior bulk, resilience, texture retention, stain resistance, easy dryability and softer feel. These fibers are also capable of recycling like polyester fibers (Kurian 2005).

3.5 Polyhydroxyalkanoates

Polyhydroxyalkanoates represent family of intracellular biopolymers synthesized by bacteria as intracellular carbon- and energy-storage granules. They are mainly produced from renewable resources by fermentation. A wide variety of prokaryotic organisms accumulate PHA from 30 to 80 % of their cellular dry weight. Depending on the carbon substrates and the metabolism of the microorganisms, different monomers, and thus copolymers, could be obtained. They are suitable for various applications such as short-term packaging, are biocompatible in contact with living tissues, and can be used for biomedical applications. Worldwide, >24 companies are engaged in the production and applications of polyhydroxyalkanoates; however, compared with PLA its production is lower.

PHA polymers are synthesized in the bodies of bacteria fed glucose in a fermentation plant. In the late 1980s, ICI Zeneca commercialized PHAs under the trade name Biopol. However, their high cost, small difference between their melting and thermal degradation temperatures, and low impact resistance prevented large commercial applications. However, in recent years many companies have been producing PHA polymers, and their development looks promising (Volova 2004; Wolf et al. 2005).

4 Conclusions and Recommendations for Going Forward

The term “luxury” is a buzzword in the high-end fashion industry. Luxury comes from a textile material, not from of a designer or a brand. The term comes from the quality of the material as well as the sustainable/eco-friendly manufacturing process. Hence, the products often have a high price range. In order to fulfill the requirements of the ever-changing market, designers always look for new colours, fabrics, styles, etc., to offer designs to the market. In today’s world, fashion is not limited to the aesthetic look of a garment; it is also related to its functional features. Furthermore, due to a increase in customers’ expectations, designers as well as manufacturers are also focusing on this new dimensions of fashion by using unconventional fibres. Environmental and social impacts of the fashion industry are growing, but there are many ways that we can reduce negative environmental impact as well as increase positive environmental and social benefits through the informed choices of materials and intelligent design. The search continues for the ideal natural fibre (where the entire process all begins), i.e., a fiber that is organically cultivated with zero or minimal artificial assistance, ethically manufactured, sustainable, processed without chemical aid, has reusable by-products, and is completely biodegradable.

Hence, companies are more focused on these kinds of sustainable fibers. This ultimately reduces the carbon foot print and improves the sustainable nature of the product. The designers and fabric manufacturers who focus on this sector have huge potential to use conventional and unconventional fibers. This chapter provides insight to the available details of various luxury fibers. The impending scope of application for these fibers are also heartening researchers and manufactures alike in the era of co-compatible sustainability and luxury.

Synthetic fibers have shown tremendous growth since the 1950s, and they are the raw materials for most fashion clothing. However, in recent years increasing oil prices, depletion of oil feedstocks, growing concerns over the environment, increasing greenhouse gases, and global warming have led to the development of materials from natural renewable resources. Three principal ways by which these biopolymers are synthesized are using biomass (polysaccharides, proteins, etc.), using bio-based monomers (polylactic acid), and generated by microorganisms or modified bacteria (polyhydroxyalkanoates). This chapter highlighted some of the polymers in each category such as spider silk, hagfish slime threads (synthesized from animal protein), sea cell fibers (regenerated cellulosic fibers), milk fibers (regenerated protein fibers), and PLA and PTT fibers (from corn).

Biobased polymers offer significant a positive impact on the environment by reducing dependence of fossil fuels, reduced carbon dioxide emissions etc. Also, biobased polymers have increased attention from customers due to increased awareness about the environment. A large number of companies are involved in producing these biopolymers. In addition, R&D works focusing on the development of technologies to make biopolymers are contributing to their growth. However, there are many challenges that must be addressed for the commercialization of these biopolymers such as relatively high cost of production, relevant technologies to produce biopolymers, lower performance of biobased materials, and management of raw materials. It can be concluded that it will not be long that these biopolymers will overcome these challenges and will be substituted for synthetic fibers for various applications from commodity to high-tech markets. Still building large-scale plants can be difficult due to the lack of experience in new technologies and the estimation of supply/demand balance.

To make these technologies economically viable, it is essential to develop logistics for biomass feed-stocks, novel production routes with high yields, new microbial enzymes, and effective downstream-processing techniques for the recovery of biobased products. The current biobased industry is focusing on the production of biopolymers from existing monomers and polymers.

Of late, several research works have been carried out toward the manufacturing of biobased polymers that have higher performance and value. For example, Nature Works LLC has introduced new grades of PLA with higher thermal and mechanical properties. New PLA-tri block copolymers have been reported to behave like thermoplastic elastomer. Many developments are currently underway to develop various polyamides, polyesters, polyhydroxyaloknates, etc., with high differentiation in their final properties for use in automotive, electronics, and biomedical applications.

For biobased polymers such as PLA and PHA, additives have been developed to enhance their performance by blending them with other polymers. However, the additive market for biobased polymers is still very small, which makes it difficult to justify major development efforts according to some key additive supplier companies. Various nano-reinforcements currently being developed include carbon nanotubes, graphene, nanoclays, 2-D layered materials, and cellulose nanowhiskers. Combining these nanofillers with biobased polymers could enhance a large number of physical properties—including barrier properties, flame resistance, thermal stability, solvent uptake, and rate of biodegradability—relative to unmodified polymer resin.

Even though new biobased polymers are produced on an industrial scale, there are still several factors that must be determined for their long-term viability. It is expected that there will be feedstock competition as the global demand for food and energy increases over time. Currently, renewable feedstocks used for manufacturing biobased monomers and polymers often compete with requirements for food-based products. The expansion of first-generation biobased fuel production will place unsustainable demands on biomass resources and this is as much a threat to the sustainability of biochemical and biopolymer production as it is to food production. Several initiatives are underway to use cellulose-based feedstocks for the production of usable sugars for biofuels, biochemicals, and biopolymers.

Biobased polymers could replace conventional polymers in the near future. Currently, biobased polymers are usually found in several applications from goods to hi-tech applications due to developments in biotechnologies and public awareness. Nevertheless, regardless of these developments, there are still some drawbacks that prevent the wider commercialization of biobased polymers in many applications. This is mainly due to performance and price when compared with their conventional counterparts, which remains a significant challenge for biobased polymers.

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Case Study of Renewable Bacteria Cellulose Fiber and Biopolymer Composites in Sustainable Design Practices

Y.A. Lee

Abstract This case study challenged researchers and practitioners to rethink what constitutes sustainable consumer products in a world of increasingly stressed natural resources by exploring innovative ways to develop renewable biocomposite materials, e.g., leather-like nonwoven fabrics, that can be used for apparel and footwear products. Scientific research was conducted to identify cultivation and treatment methods that produce cellulose fiber mats, formed by bacteria and yeast in fermenting tea, with sufficient strength for use in apparel. Wearable products made of the green-tea based cellulose fiber mats can be an alternate future in which we move to a cradle-to-cradle (C2C) system instead of relying on materials derived from unsustainable sources. The outcome of this innovative and sustainable design effort is presented by creating aesthetically pleasing, biodegradable apparel prototypes and providing a promising future for this nonwoven material as an alternate future suitable for the apparel and footwear industries. A consumer survey was conducted of users' perceptions and acceptance of using apparel products made of this material, and the results of the survey are discussed.

Keywords Apparel · Bacteria cellulose fiber · Biodegradable · Renewable · Sustainable

1 Introduction: Key Issues on Sustainable Design Practices

Historically, the textile and apparel industries have been major contributors to environmental pollution through contaminated wastewater used in production processes, especially with chemically intensive processes including dyeing, fin-

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S.S. Muthu and M.A. Gardetti (eds.), *Sustainable Fibres for Fashion Industry*,
Environmental Footprints and Eco-design of Products and Processes,
DOI 10.1007/978-981-10-0522-0_6

ishing, slashing, and other operations. Textile waste from apparel production is a major contributor to landfills. Scraps of textile waste (after cutting garments) often do not degrade (compost) if placed in landfills because of their synthetic contents (US Environmental Protection Agency 1996, 2015, n.d.). Other sources of environmental contamination result from the large quantities of pesticides, herbicides, defoliants, and fertilizers used to produce fiber crops such as cotton. Marquardt (2001) stated that an estimated 81 million pounds of pesticide were applied annually to upland cotton in the US. In the apparel industry, the many stages of production, from raw materials to finished products, are often handled as separate processes and include disconnected operations with little consideration to the total product waste. Additionally, producers along the production pipeline have given little attention to postconsumer product disposal.

Gam et al. (2009) studied a comprehensive model to evaluate the environmental impact of apparel at all stages, which was built on the cradle-to-cradle (C2C) model for sustainable design developed by McDonough and Braungart (2002). Contrary to the traditional linear model, whereby products, even if recycled, eventually become part of a landfill, the C2C model proposes that materials for products should be incorporated into a continuous cycle of reuse or regeneration. Thus, a circular model, rather than a linear model, is used. With this model, all aspects of a product (materials and processes) are evaluated in relation to being sustainable.

C2C is a design framework that incorporates several ideas to help with sustainable product design including safe material use, continuous recovery and reuse of materials, clean water, renewable energy, and social equity (MBDC LLC 2012; McDonough et al. 2003). According to the C2C framework, the idea of "waste" is eliminated, and thus products are designed so that they become either biological or technical nutrients for something new at the end of their lifecycle "To eliminate the concept of waste means to design things—products, packaging, and systems—from the very beginning on the understanding that waste does not exist" (McDonough and Braungart 2002, p. 104). McDonough and Braungart (2002) suggest that products can be composed of either biodegradable materials, which will become food for biological cycles, or of technical materials, which will continue to circulate as valuable industrial nutrients. Instead of the traditional linear "cradle-to-grave" product design and development models, C2C offers a closed-loop cycle of flow of materials, products, and processes (Gam et al. 2009). Biological nutrients are biodegradable materials or products that are consumed by microorganisms on entering the biological cycles, thereby enriching and supporting the ecosystem (McDonough and Braungart 2002). Technical nutrients are materials or products designed to return to the industrial technical cycles, thereby eliminating useless and hazardous waste, saving money and resources, and eradicating need for extracting new raw materials (McDonough and Braungart 2002). The C2C model fits well with the purpose of the case study that will be introduced in this chapter: Evaluate bacterial cellulose as a potential environmentally friendly biodegradable material for apparel production.

2 Bacteria Cellulose Fiber and Its Effectiveness

Sustainable apparel can be seen as a contradictory concept because the apparel industry, which heavily reliant on the concept of fashion, is guided by constant change and replacement of old styles with new ones (Farley and Hill 2015). Although this presents unique challenges to apparel designers and product developers, it has not stopped the industry from making considerable efforts toward sustainable apparel and environmentally responsible practices. For example, Patagonia has introduced innovative approaches in an attempt to make production and consumption processes sustainable. Other companies, such as Nike and Timberland, have taken steps toward sustainability. However, there have not been many efforts in introducing novel sustainable fiber and materials to apparel production beyond organic or natural fibers.

Natural fibers (i.e., fiber produced by plants and animals), such as hemp and cotton, are generally associated with being environmentally friendly; however, in many cases this is a wrong assumption. Chen and Burns (2006) state “Fiber content alone may not be an accurate indicator of the full environmental cost of producing textile product” (p. 149). Although natural fibers are produced from naturally occurring sources and are not dependent on nonrenewable sources, the cultivation of these crops is laden with heavy environmental impact (e.g., heavy pesticide and herbicide use). Although organic fibers are cultivated pesticide-free, the amount of water used for irrigation and resources used for processing these fibers account for high environmental damage. Maintenance of garments made of natural fibers is also associated with high environmental cost.

An alternative natural fiber source that has received some attention in the apparel industry is bacterial cellulose (BC), also referred to as “bacterial nanocellulose” or “microbial cellulose” in the scientific literature. Bacterial cellulose (BC), an emerging nanomaterial, is a natural, nontoxic, biocompatible, and stable hydrogel with unique properties produced by several species of bacteria (Gama et al. 2013). Compared with wood- and plant-based cellulose, cellulose produced by bacteria “form a three-dimensional network that provides unique mechanical properties” and is pure and free from “plant components such as hemicelluloses and lignin” (Gama et al. 2013, p. ix).

Among various BC forms synthesized by different species of bacteria, a unique BC variety can be “easily and effectively synthesized from kombucha” (Zhu et al. 2014), a popular health drink. Kombucha is a lightly acidic beverage that is derived through the fermentation of sweetened tea using a symbiotic colony of bacteria and yeast (SCOBY). Simultaneous to the fermentation process, a translucent and gel-like cellulose membrane is produced at the air/liquid interface of the fermenting tea (Zhu et al. 2014). This flat cellulose membrane, when removed and dried, resembles a leather-like material that could be used as a sustainable material for apparel applications. Although BC has been studied for multiple applications, from biomedical tissue engineering through wound dressing to foods and cosmetics

(Gama et al. 2013), research on its use for apparel applications has received little attention so far.

Bacterial cellulose (BC) is a biopolymer that can be produced by several species of bacteria, the most important of which is *Gluconacetobacter xylinus* (*G. xylinus*), which was identified in 1886 (Gama et al. 2013). Cellulose produced by bacteria has a molecular formula and morphology similar to that of plant cellulose; however, BC is pure and does not require additional processing to get rid of impurities such as lignin, pectin, and hemicellulose (Lin et al. 2013; Gama et al. 2013). *G. xylinus* can be found in nature on places such as rotting fruits or other places that have fixed sources or carbon such as sugars or alcohol, and it is able to make use of various sugars and other compounds for synthesizing cellulose (Saxena and Brown 2013). Being strictly an aerobe, it is usually found on the air medium interface, and its presence can be easily recognized if it produces a cellulose film (Saxena and Brown 2013).

Bacterial cellulose (BC) can be produced through static (stationary) or agitated (shaking) culture-cultivation methods. In agitated cultivation, small BC particles or pellets are produced that have lower degree of polymerization, crystallinity, and mechanical strength compared with the mat-like cellulose produced in static fermentation (Shah et al. 2013; Saxena and Brown 2013). In static cultivation, the cellulose is formed on the surface (i.e., the air liquid interface) of the culture medium in a stationary container. In this case, a cellulose membrane or pellicle is produced on the entire culture medium surface conforming to the form of the container (Shah et al. 2013). During the static-cultivation process, “the glucose chains produced inside the bacterial body extrude out through tiny pores present on their cell envelope,” which then combine and form microfibrils, which in turn aggregate to form cellulose ribbons (Shah et al. 2013). This nanofiber ribbons later forms a highly porous web network structure referred to as a pellicle, membrane, sheet, mat, film, etc.

In static cultivation, as the fermentation time increases as does the thickness of the nanofiber membrane also increases, which grows downward until “the cells entrapped in the membrane become inactive or die due to oxygen deficit” (Shah et al. 2013, p. 1587). Bacterial cellulose can be shaped into three-dimensional structures during cellulose synthesis using various molds and porogens that allow producing cellulose with desirable geometries (Gatenholm et al. 2013).

Various bacterial-cellulose (BC) composites have been synthesized by incorporating a variety of materials, ranging from organic polymers to inorganic nanoparticles, where the BC served as a support matrix or a reinforcing material (Shah et al. 2013). The BC-composite synthesis is mainly done via the in situ addition of reinforcement material into the BC culture media or the ex situ addition of reinforcement materials into the fiber BC structure (Shah et al. 2013). Composites allow modification and enhancement of BC properties to be used in various applications such as in biomedical fields (e.g., wound dressing, burn treatments, tissue engineering), electrical devices, conductive material, sensors, foods, packaging, and cosmetics. Research on BC has recently also focused on increasing the hydrophobicity of the material for improving its barrier properties while maintaining its mechanical properties and stability (Silva et al. 2013).

A major direction in bacterial cellulose (BC) research has been the improvement of cellulose production (Shah et al. 2013). Another direction is the identification of alternative and more economical raw sources for BC production, which include low-cost agricultural products and industrial or agricultural wastes such as waste from beer fermentation broth, various fruit juices, molasses, rice bark, wheat straw, and cotton textile waste (Hong et al. 2012; Shah et al. 2013).

The bacterial cellulose (BC)–production process could be a sustainable process because the growth medium can be reused to grow new cellulose fiber mats. Moreover, a sustainable C2C closed-loop production could be set up where the cellulose would be used for apparel production, and the liquid media could be bottled and sold as the kombucha health drink. Produced with common natural ingredients, BC and the apparel made with it could be a biological nutrient as described by McDonough and Braungart (2002). When not needed anymore, they can be composted by users or may become fertilizers for farmers, thus re-entering the biological cycle instead of going to the "grave." As McDonough and Braungart (2002) state, after customers are finished using a product that is designed to be biological nutrient, they can "throw it onto the soil or compost heap without feeling bad—even, perhaps, with a kind of relish" (p. 109).

It is important to further investigate BC as a potential environmentally friendly, sustainable material, specifically, assess its performance, durability, and other characteristics that are relevant to wearing apparel. Using biobased environmentally-friendly materials can help reduce the apparel industry's dependence on nonrenewable sources and solve environmental problems associated with apparel production and consumption (Cao et al. 2014). It is equally important to investigate consumer evaluation and acceptance of apparel made of this bacteria cellulose material. Research has shown that consumers are progressively aware and concerned about the global environmental and social sustainability problems (Gam and Banning 2011; Gleim et al. 2013). However, purchasing sustainable products has not been growing according to expectations due to lack of acceptance and popularization of sustainable products (Gleim et al. 2013; Moon et al. 2013).

3 Case Study on Developing Renewable Bacteria Cellulose Fiber and Biopolymer Composites for Sustainable Design Practices

This case study takes a step toward sustainability in the apparel industry by investigating a potential biomaterial for apparel use. Bacteria cellulose (BC) has been studied and utilized in many other fields as a valuable material, however, studies are lacking in the apparel field. New environmentally friendly renewable materials, such as BC, could help reduce the industry's dependence on nonrenewable material sources and alleviate its tremendous contribution to environmental degradation. It is important to examine the suitability of BC as a novel environmentally friendly material for apparel products.

In recent years, the textiles and apparel industries have made progress in the reduction of toxic wastes due to environmental regulations. However, innovative methods that look beyond traditional textile natural fibers, such as cotton, flax, silk, wool, and other animal hair fibers, have largely been ignored. One option explored by Lee (2011), as reported in the popular press (Llanos 2012), is the use of cellulose fibers grown by bacteria and yeast in fermented tea. The cellulose fibers form a mat-like layer that floats on top of the fermenting tea. Lee found that the cellulose fiber mat could be removed and used as a nonwoven textile after the moisture evaporated. The resulting nonwoven had an appearance and texture similar to those of leather.

However, one major problem was reported, the cellulose mat easily regained moisture from the atmosphere or the human body, which resulted in a softening of the mat and loss of tensile strength. The reduction in tensile strength could be sufficient as to allow a garment to fall off the wearer. Lee’s work has focused on using the cellulose fiber mat for one-of-a-kind fashion apparel that can be produced by sewing and/or molding into shape. Little scientific research has been conducted to identify a cultivation method or treatment methods that yield a cellulose fiber mat formed by bacteria and yeast in fermenting tea that has reduced moisture absorption and increased tensile strength.

The cultivation process used to produce the cellulose fiber mat formed by bacteria and yeast in fermenting tea is an option that has the potential to yield a cellulose textile that could have little or no waste and that could be produced without fertilizers, irrigation, or farm equipment needed for the production of other cellulose fibers such as cotton. The tea medium can be reused after a layer of the fiber mat is harvested, and if disposed of as waste, it is nontoxic to the environment. As a cellulose fiber, the mat is biodegradable and compostable. It will not contribute to landfill issues.

As previously stated, the cellulose fiber mat readily absorbs moisture and looses tensile strength. To be a viable fiber source, a method of modifying the cellulose mat to reduce moisture absorption and increase tensile strength must be found. This is a *challenge* because of the limitations of chemical compatibility with the cellulose molecule and the necessity to have all aspects of the product and processes be sustainable. Historically, a textile with weak tensile strength would be bonded to another substance with glue, which would render the textile incapable of being either biodegradable or recyclable. Recent developments with sustainable biopolymers have the potential to be combined with the cellulose fibers to produce composite textiles with the cellulose fiber mats. To meet the *technical challenge* of combining the cellulose fibers grown in mats with sustainable biopolymers, *innovative and inventive* research was employed.

The aim of this study was to identify a method of growing and combining cellulose fibers grown from bacteria and yeast in fermented tea with sustainable biopolymers obtained from agricultural plant products, such as corn or soy, to reduce moisture regain and to increase the strength of the cellulose fiber. New products developed from the composites would have good tensile strength and relatively low moisture regain, which are the key parameters for regular daily wear. Figure 1, developed by the author, illustrates the flow chart of the proposed approach for the study. Emphasis was given to materials and processes that would be consistent with the benefits of people, prosperity, and the planet, which include a cleaner community environment, reduction in energy use, reduction of fiber-processing and fabric-production costs, reduction of material waste, and development of a textile that has potential for a large-scale production beyond an experimental prototype.

The first stage of the study involved various experiments to identify the optimal protocol for consistent growth of cellulose fiber mats. Such a protocol was achieved using the following combination of ingredients in a 16 × 12 × 8-in. plastic container at a room temperature of 27–30 °C, 3760 ml distilled water, 9 organic green tea bags, 540 g granulated cane sugar, and 632 ml white vinegar. Approximately 100 g of commercial organic SCOBY were added to the tea mixture to start the growing process of the cellulose fiber mats (see Table 1).

Cellulose fiber mats started visibly forming on the surface of mixture within 1 week and were harvested after 4 weeks of growth. The mats then went through the purification process, by washing and boiling in deionized water, to get rid of sugar and other impurities. The mats were air-dried at room temperature on a fiberglass screen wire on a flat surface. Several cellulose fiber mats were air-dried without the purification process to allow comparison with the purified samples. *The comparison results prove that the purification process significantly improves the material's hand and properties.* Both unpurified and purified samples had a leather-like appearance and texture; however, the purified mats were flexible, dry, and pleasant to touch, whereas the unpurified mats were flexible but very sticky to touch. The properties of these mats were tested in the various stages in terms of reducing moisture regain and increasing tensile strength.

The next step of this study involved the development of cellulose/biopolymer composites (stage 2 in Fig. 1). The goal of this stage was to identify biopolymers compatible with the cellulose mats grown and to successfully develop composite mats with enhanced properties. Uncoated and biopolymer coated samples, unpurified cellulose film mat subjected to dip-coating by polylactic acid, PLA (solution of PLA in chloroform), and an aqueous caster oil based polyurethane dispersions (PUDs) with approximately 30-nm particle size were examined using scanning electron microscopy (SEM) for imaging the surface and the cross-sectional microstructure. Sample imaging was performed using a Quanta 250 Field Emission instrument. Samples were examined under high-vacuum as well as variable-pressure mode depending on the sample moisture content as required. All samples were mounted on 1″ stubs and coated with a 5-nm layer of iridium to increase conductivity and prevent any charging during the imaging process. Figure 2a–f summarizes the morphological study for raw, unpurified cellulose film mat subjected to dip-coating by polylactic acid (PLA) and an aqueous caster oil based PUD. Images were captured at 10 kV for different

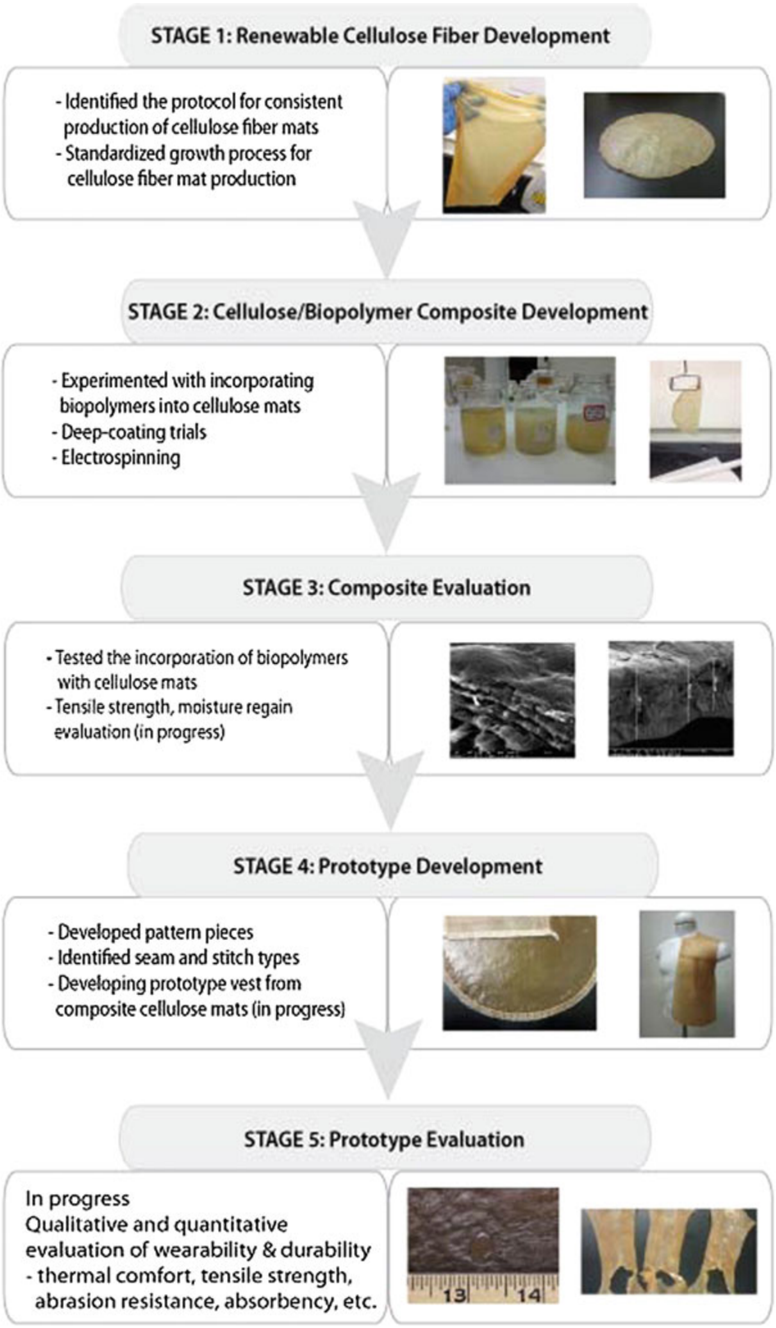

Fig. 1 Development process of sustainable vest using renewable bacteria cellulose fiber mats. *Source* Flow chart developed by the author, Young-A Lee, March 16, 2014

Table 1 Standard formula and procedure to grow consistent cellulose-fiber mats

Standard formula	Standard procedures
• Distilled water: 3760 ml • Organic green tea: 9 tea bags • Granulated cane sugar: 540 g • White vinegar (5 % acidity): 632 ml • Organic starter SCOBY: approximately 100 g	1. Set room temperature at 27–30 °C 2. Immerse tea bags in about 300 ml boiled hot distilled water so they are covered. Let stand for 10 min to brew. Discard the tea bags 3. Add the tea brew, the rest of the water, and the other ingredients in the desired container (it is easier to dissolve the sugar in the hot tea first) 4. Add the SCOBY 5. Cover the top of the container with a clean paper towel or muslin, and secure with clips 6. Let stand under static conditions for approximately 4 weeks at room temperature

Source Table developed by the author, Young-A Lee, March 16, 2014

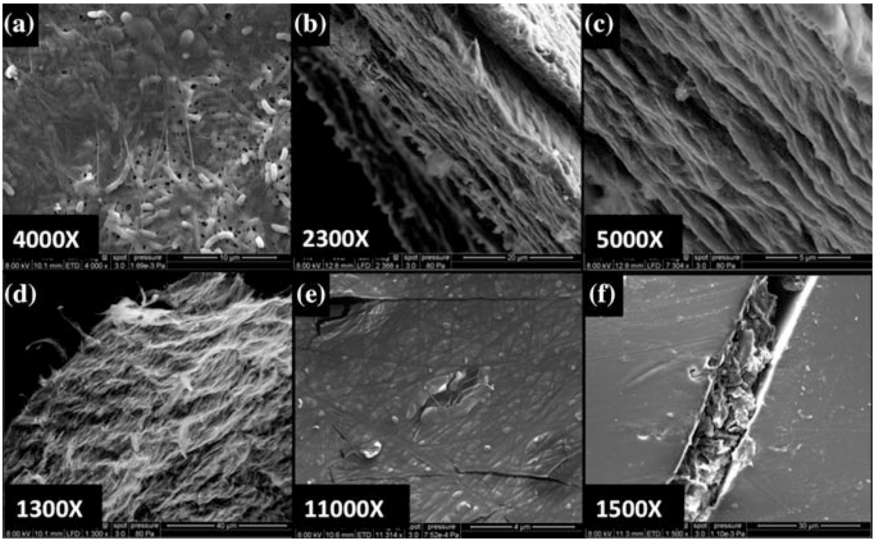

Fig. 2 SEM images of unwashed cellulose sample. **a** Surface. **b–c** Cross-section. **d** Cross-section of PU-coated sample. **e** PLA-coated cellulose. **f** PU-coated cellulose. *Source* Image by the author, Young-A Lee, March 16, 2014

magnifications. A considerable level of charging and sample "burning" was observed. As can be seen from images (a–c), the presence of a dense network of fibers, as might be expected [ref: Book Chapter-Bacterial cellulose by Bielecki et al. (2005)], was not observed.

Fibrous bundles on the surface were seen at higher magnifications, and multiple layers were observed in the samples mounted for cross-sectional imaging. A large amount of clumps and bundled networks can be distinguished. Our understanding at this stage estimates that such a morphology is due to the presence of unused or excess sugars from growth processing.

As can be seen in Fig. 2e, the PLA coating is observed as a smooth, nonporous covering, whereas the PU coating in Fig. 2f shows a similar smooth coat with no pores. Because the objective of coating the cellulose fibers with biopolymers is to make them water-resistant but allow for a ventilated surface at the same time, the dip-coating method was probably not the best method to make our cellulose films as required.

The next approach was to subject the SCOBY-grown cellulose fiber mats to multiple washing, boiling, and rinsing with deionized water by using a basic medium (pH 8–10) and allow for air drying after neutralization (pH 5–7). SEM images were collected for these samples subject to similar conditions of sample coating with iridium and examination at 10 kV, and they are summarized in Fig. 3a–f. The purified samples without any polymer coating were air dried on a wire mesh and have an embedded pattern as seen in Fig. 3a–c. Magnified images of the surface in Fig. 3b, c, however, do not conclusively show the presence of a dense fibrous network as would have been expected. This can be an issue due to the drying process, which may cause coagulation in some form and result in a nonobservable fibrous network. However, the cross-section of the purified samples provides a very interesting viewpoint. As can be seen in Fig. 3d–f, *the cellulose film comprises multiple layers approximately* 1-µm *thick with a network of fibers on the surface of each layer as anticipated*. This was a very encouraging result, and it is attributed to the thorough purification of the samples, which extracts any excess

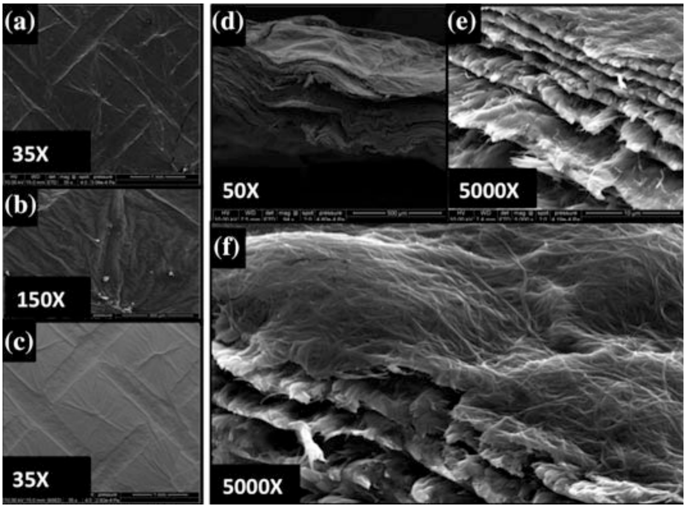

Fig. 3 SEM images for bicarbonate purified cellulose samples. **a**–**c** Sample surface at low magnification and in Se and BSE modes. **d** Low-magnification image of cross-sectional mounted sample. **e** Cross-section showing multiple layers. **f** Fibrous network on surface layer of washed cellulose sample. *Source* Image by the author, Young-A Lee, March 16, 2014

sugar or bacterial depositions on the cellulose. The fibers are approximately 100–150 nm in width, and they are present in each layer of the film.

Electrospinning was considered as a more controlled way of depositing the biopolymer coating on cellulose films. Samples were coated with aqueous caster oil-based PUD because the PLA did not provide a sufficiently adherent layer on the cellulose. SEM imaging for the surface and cross-sectional morphology of electro-spinning PU-coated samples can be seen in Fig. 4a–d. As observed in Fig. 4c, the PU-coated samples showed an almost uniform spread of nanospheres with diameters between 50 and 100 nm. A few very large PU spheres were also observed (see Fig. 4b), and could be due to the anomalous deposition of PU droplets onto the surface during the initial steps of the electro-spinning process.

Tensile testing was also performed to examine the properties of the composites developed from the cellulose fiber mats and biopolymers. Tensile properties of the cellulose fiber mats were determined using load cells of varying magnitudes (10 N, 100 N) on an Instron universal testing machine (model 4502). Tensile test results discussed here are based on the test conditions using a 100-N load cell and a strain rate of 3 mm/min. All samples were tested at least five times to obtain reliable data. Testing results included here are the summary of average values that were determined experimentally. Uncoated and nonpurified samples at the early stages of this study showed some strength compared with the PU or PLA dip-coated samples (see Figs. 5 and 6).

In an effort to estimate the strength with more accuracy, tensile tests on the purified samples for uncoated and PU-coated samples were performed using a

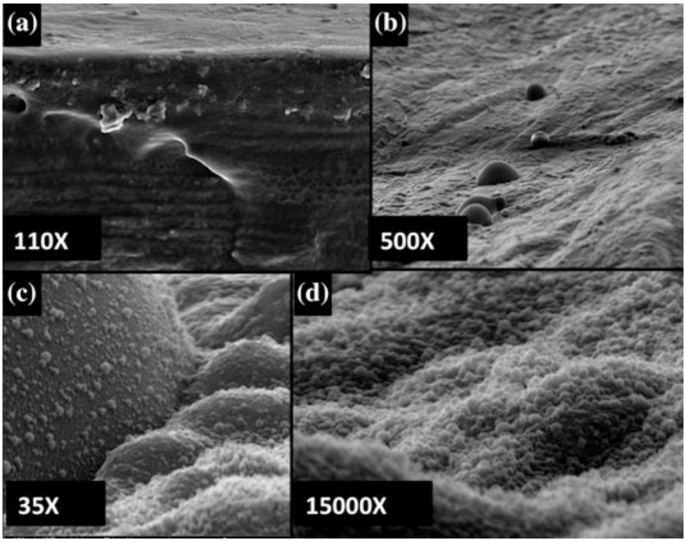

Fig. 4 SEM Images for PU-coated cellulose by electro-spinning method. **a** Low magnification showing a fine layer of PU coating on multilayered cellulose film. **b**–**d** Various magnifications of PU coating on the cellulose. *Source* Image by the author, Young-A Lee, March 16, 2014

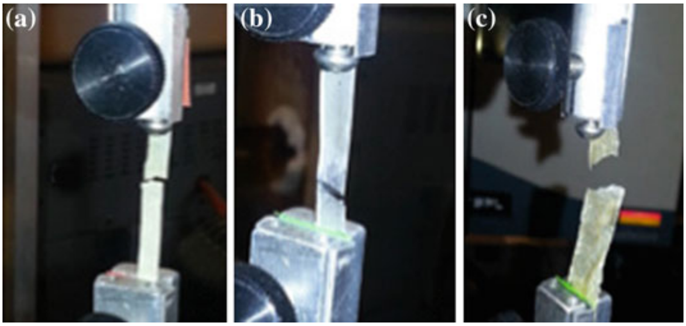

Fig. 5 Preliminary samples for uncoated **a** PU-dip coated, **b** PLA-dip coated, and **c** cellulose fiber mats. *Source* Image by the author, Young-A Lee, March 16, 2014

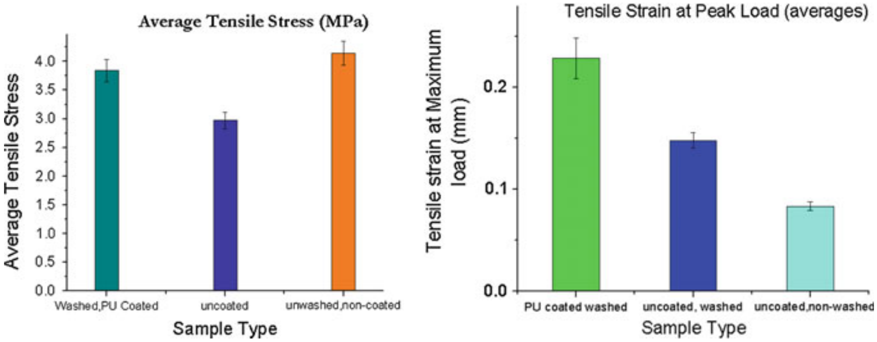

Fig. 6 Tensile test results on the purified samples for uncoated and PU-coated samples. *Source* Figure developed by the author, Young-A Lee, March 16, 2014

100-N load cell and an extension rate of 3.00 mm/min. A summary of the results is shown in the graphs below (see Fig. 6).

Tensile test results lead to the following conclusions: (1) The average tensile strength of unpurified, noncoated samples is higher than the purified samples, which could be attributed to the fact that the presence of excess sugars in the layers provide a reinforcement effect to the cellulose matrix that would be able to withstand a higher applied stress; and (2) the average tensile strength of the PU-coated samples is comparably higher than that of the uncoated, purified fiber mats. This indicates that the PU-coating provides some additional strength. The difference not being very high could be an indication of (a) the nonuniformity of the PU coating; and (b) the necessity of improving the nature of the coating (fibrous networks as opposed to fine nanospheres layer). *The trend in the tensile stress at maximum or peak load shows that the PU-coated cellulose fiber mat is much stronger than the unpurified, noncoated version*. This result proves that *the processing of the fiber mat after its growth plays a very important role in dictating the resulting* *mechanical properties*. The purified and PU-coated samples were found to have a maximum extension of approximately 1 mm and an average extension of 0.2 mm from the stress-strain data.

To test water regains of the cellulose fiber mats, a simple version of Hu et al.'s (2005) fabric moisture-management test was implemented with the following three samples: unpurified, purified thin, and purified thick. No significant difference was found among all three samples regarding the diameters of the water drop before and after the test. This may be due to our samples having a great ability to absorb the water, which results in the solidification of the water drop. In addition, the film-like, nonwoven surface of the sample may also restrict the spread of the water because of the surface tension of the water drop. Further testing is needed to reduce the water absorbency of this material.

In short, the case study includes characterization of the developed composites (e.g., morphology, strength, moisture regain) as well as sustainable prototype development and its evaluation. This case study provided proof of concept that products developed using cellulose-based biocomposite materials can provide significant environmental and economic benefits. Successive experiments in part of this study revealed the broad capabilities of biopolymer composite materials to be used to develop various types of products by considering different end users. The cultivation process used to produce the cellulose fiber mat formed by bacteria and yeast in fermenting tea is an option that has the potential to yield a cellulose textile that could have little or no waste and is produced without fertilizers, irrigation, or farm equipment needed for the production of other cellulose fibers such as cotton. The tea medium can be reused after a layer of the fiber mat is harvested, and if disposed of as waste, it is nontoxic to the environment. As a cellulose fiber, the mat is biodegradable and compostable. It will not contribute to landfill issues. The study also provided an initial start to make connections among the source of raw materials, the processing needed to transform the fibers into a new textile composite suitable for apparel, the impact of products and processes on the environment, and the potential for the process and the product being adapted to larger-scale production.

From this study, the following matters were raised and discussed, which lead to the recommendations for future study. Standardization of the growing process of cellulose fiber mats is needed through controlling liquid temperature, liquid flow, and pH level. The growth process of cellulose fiber mats could include nonheated gentle-pressure compression for making samples with uniform thickness. This step will help in obtaining dependable, replicate tensile testing and dynamic mechanical analysis (DMA) testing results. The purified samples are assured to be capable of withstanding >100-N applied load because they did not always break as was expected in this test. It is estimated that the use of a load cell of higher value (2–5 kN) should provide more accurate estimates of the mechanical strength of the material. The PU coating on the cellulose fiber mats was observed as large deposition of approximately 100-nm spheres on its surface for a layer having thickness of the same order. It is estimated that concentrating the PU solution used in the coating to a more viscous form will provide a mesh-like coating that can substantially increase the strength of the material.

Because alkaline washing causes the material to turn a rich, deep brown color, we expect that there is also scope for adding dyes as suitable coloring to this material for appropriate uses. In the case of using the material as a water-repellant vest, suitable chemical dyes that interact well (hydrogen bonding) with PU coating on the surface may help in making the product more commercially marketable. The mats are highly dependent on temperature. Under cold-weather conditions (e.g., −10 °C), the mats were easily broken. It is recommended to improve the smell and the tensile strength in cold conditions. For this study, all cellulose-based mat samples (unpurified, purified, PU coated, PLA coated) were air dried. It is recommended to try the freeze-drying method for further exploration. During the prototype-development process, the purified mats broke when stitching two pieces together; on the other hand, the unpurified ones were a bit sticky. Further exploration is needed for the best way to assemble pieces together (e.g., sewing, bonding, melting) for large-scale production in future.

4 Case Study of User Acceptance of Apparel Products Made of BC Material

Research has identified several barriers that prevent the acceptance of sustainable goods and apparel by consumers including lack of expertise about the effects of sustainable products on the environment, difficulty in finding sustainable products, high prices, and negative perceptions of sustainable apparel as being nonfashionable and unattractive (Moon et al. 2013; Gleim et al. 2013). It is essential to assess consumers' acceptance and evaluation of sustainable products in the product-design and -development stage to ensure that consumer preferences and needs are being considered so that the product is successful when introduced to the market.

Although bacterial cellulose (BC) has been proposed as a potential eco-friendly material for apparel production, there is no research exploring consumer acceptance and evaluation of this material when used in apparel. Therefore, the aim of this study was to explore consumers' perceptions and expectation toward the use of this newly developed, cellulose-based sustainable nonwoven fabric in apparel or other product development. Specific research objectives were to (1) examine consumers' level of understanding on the general terms, sustainable or green fabric/material; (2) explore study participants' thoughts on the newly developed sustainable fabric and their general attitudes toward environmental issues; and (3) investigate study participants' expectations and perceptions toward the use of sustainable fabrics in apparel design as well as the use of sustainable apparel made of the newly developed BC material.

An online survey methodology, including both open- and closed-ended questions, was used to collect consumer data. A convenience sample of undergraduate and graduate students age ≥18 years was obtained from US Midwestern universities and used for data analysis. Prospective student participants received an invitation email including the study description, consent elements, and a link to a short Web-based questionnaire that would take approximately 20–25 min to complete.

Participants were asked questions to (1) evaluate their level of understanding about sustainable fabric/material, (2) obtain their thoughts on the newly developed sustainable fabric/material by way of visual inspection (see Figs. 7 and 8), (3) collect their general attitudes toward environmental issues as well as their expectations and perception toward the use of this sustainable nonwoven fabric/material as well as apparel made of this sustainable fabric, and (4) obtain their demographic information. The closed-ended questions, except for the demographic information items, were measured using a seven-point Likert-type scale. Before initiating data collection, the pretest of this online survey was completed to check the clarity of the question wordings. After completing the data collection, the quantitative data were analyzed using SPSS 21 software to perform basic descriptive statistics, correlations among variables, and others. The qualitative data from open-ended questions were analyzed using content analysis approach.

A total of 97 responses were received from the college students, and among those 86 usable data were obtained and used for data analyses. The sample consisted of 71 female students and 15 male students. Participants' ages ranged from 19 to 42 years with a mean of 20 years. The majority of respondents ranged from age 19 to 22 years. Most were white/European-American (62 %) followed by Asian (22 %), Latino or Hispanic American (11 %), and other ethnicities (5 %). The college status of respondents was 47 % seniors followed by 27 % juniors, 17 % graduate students, 6 % sophomores, and 3 % other. Most study respondents were affiliated with the College of Human Sciences (80 %) followed by Engineering (8 %), Liberal Arts and Sciences (6 %), Business (3 %), Agriculture and Life Sciences (2 %), and Design (1 %).

Participants were asked to write down the materials or fabrics that first come to mind when visually examining the images shown in Fig. 7. The majority of participants thought the vest was made of leather, rawhide, paper, or plastic. They commented that the texture of the vest was "stiff, like leather." They were also

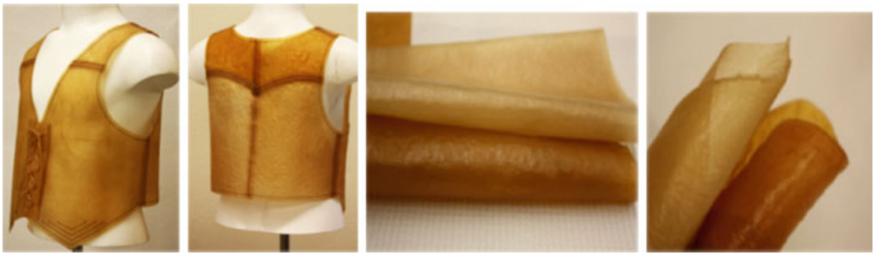

Fig. 7 Visual images of new bacteria cellulose nonwoven material and vest prototype. *Source* Image by the author, Young-A Lee, April 15, 2015

Fig. 8 Process of developing new bacteria cellulose nonwoven material and vest prototype. *Source* Image by the author, Young-A Lee, April 15, 2015

asked to indicate their response to each adjective (e.g., soft vs. hard) that best describes their thoughts about the texture of the material (see Table 2).

The participants viewed the texture of the BC material as likely thin ($M = 5.09$), stiff ($M = 4.64$), hard ($M = 4.55$), slick ($M = 4.48$), and harsh ($M = 4.29$). Participants were also asked to respond on the material's color intensity, uniformity of color, uniformity of surface, transparency, gloss, and purity. As shown in Table 3, the participants viewed the surface of the BC material toward smooth surface ($M = 4.43$), pure ($M = 4.12$), shiny ($M = 3.85$), even-colored ($M = 3.84$), and slightly opaque ($M = 3.69$).

The results indicate that by visual inspection, the participants determined the material to be thin and lightweight, the texture hard and stiff, the surface smooth, and the color light and even. According to open-ended questions, most participants were concerned about the color and the texture of the BC material. They suggested having more color variations and a solution of discomfort because of hard and stiff texture. The results lead to future research on the sensory test of this newly developed BC material so users could inspect the material physically (e.g., visual, odor, tactile). The participants generally thought that using this material is an interesting idea and that it is good to use it because it is sustainable; however, they expressed their concern about this BC material in terms of its visual appeal, color variation, wearer comfort, durability, and care.

After participants evaluated the BC material by visual inspection, their perception and attitude toward the BC material, and whether they would purchase

Table 2 Visual inspection of the texture of bacteria cellulose material

Texture characteristics	Mean	SD
Soft to hard	4.55	1.81
Silky to harsh	4.29	1.61
Firm to stretchy	3.07	1.74
Floppy to stiff	4.63	1.74
Crisp to limp	3.12	1.74
Rough to smooth	4.60	1.69
Thick to thin	5.09	1.70
Scratchy to slick	4.48	1.63
Tight to loose	4.18	1.62
Light to heavy	2.82	1.64
Dead to springy	3.22	1.43
Cool to warm	3.46	1.68

Note Items were measured using a seven-point Likert-type scale ranging from "adjective located on left (1)" to "adjective located on right (7)"

Source Table developed by the author, Young-A Lee, April 15, 2015

Table 3 Visual inspection of the surface characteristics of bacteria cellulose material

Surface characteristics	Mean	SD
Light to dark	3.03	1.81
Uneven to even	3.84	1.61
Bumpy to smooth	4.43	1.74
Sheer to opaque	3.69	1.74
Dull to shiny	3.85	1.74
Blurry to pure	4.12	1.69

Note Items were measured using a seven-point Likert-type scale ranging from "adjective located on left (1)" to "adjective located on right (7)"

Source Table developed by the author, Young-A Lee, April 15, 2015

products made of this material when it is available, were measured. Overall, study participants had a positive attitude toward the BC material ($M = 4.46$) based on the rating scale from poor (1) to excellent (7); however, their response to the anticipated acceptance of this material to general consumers were just slightly over medium ($M = 3.89$) using the rating scale from not at all (1) to extremely acceptable (7). Participants had a positive perception toward the BC material developed for the study, especially considering the material as very unique ($M = 6.25$) and interesting ($M = 6.14$). They also thought that this material is usable, durable, and desirable (see Table 4), but their willingness to purchase the products made of this BC material was in the medium range ($M = 3.63$).

In general, participants had positive perception and attitude toward the BC material. Specifically, participants thought the material is unique and that the idea to

Table 4 Consumer perception on bacteria cellulose material

Perceptions of material	Mean	SD
Usable	4.78	1.46
Durable	4.35	1.47
Unique	6.25	0.92
Interesting	6.14	0.97
Desirable	4.11	1.70
Comfortable	3.94	1.66

Note Items were measured using a seven-point Likert-type scale ranging from "strongly disagree (1)" to "strongly agree (7)"
Source Table developed by the author, Young-A Lee, April 15, 2015

use this renewable sustainable material for apparel products is interesting. According to the theory of planned behavior, a positive perception leads to positive attitude, which then leads to a behavioral intention. However, this study shows a medium acceptance rate for the BC material developed. The possible reason could be that without physical inspection, participants have doubts about the actual texture of the material. In the open-ended questions, they expressed their concern about the durability and comfort of the material. This suggests future study that involves physical inspection. In addition, the improvement of the BC material in terms of durability, comfort, and care should be taken into account for further research.

This study also investigated participants' general perceptions about sustainable materials and products made of those materials as a means of understanding the current sustainable product market. Most participants perceived "sustainable" as eco/environmentally friendly and "sustainable products" as green products that are environmentally friendly and made of organic and reusable materials. In specific to the apparel industry, participants thought that sustainable apparel products are usually made of organic, natural, or recycled materials. The study also examined participants' expectations (a consumer's mental impression of a stimulus object) and perceptions (a form of consumer hypothesis) about (1) currently available sustainable materials and products made of them; and (2) products made of the newly developed biodegradable BC material.

Participants had high expectations and perceptions toward products made of sustainable materials in general. There was a significant gap between their perceptions and expectations. Their perception did not match with their expectation, indicating that the current products made of sustainable materials need further improvement. On the other hand, there was no significant gap between their perception and expectation on the products made of the BC material indicating that the products made of the BC material meet participants' expectation of such material. Participants' expectations and perceptions were significantly higher for the products made of sustainable materials currently available in the market than for the products made of the BC materials developed for the study, indicating as a newly developed material, the participants do not anticipate that this BC material could function in market available sustainable products yet.

The results indicate that as a newly developed material, and only visually, not manually, inspected by the participants in this study, the BC material was perceived to be good as a sustainable material that slightly but not significantly exceeded participants' expectation. The result indicates that the BC material has the potential to gain consumers in the future. Although participants did not perceive the BC material as good as currently available other sustainable materials, they showed great interest in this BC material, thus providing potential use of the material in shoes, packaging bags, or curtains. Further study should be done to explore more of the potential of this BC material for the variety of products beyond apparel.

Among the study participants, 39.7 % considered switching from their favorite brands or stores to other brands that sell environmentally friendly products, and 11.1 % of them would not switch the choice of their brands. Approximately a half of them (49.2 %) were not sure about this matter, indicating that consumers' acceptance of environmentally friendly products is still immature; thus, the market for the products made of these materials still needs growth. Approximately 30 % of the participants were willing to pay a 5 % price premium to buy green products, and 27 % would be willing to pay more than a 10 % price premium of the products indicating that more than half of the consumers would be willing to pay more for green products because of their sustainability practices. This result encourages researchers to developing new sustainable materials to gain the market and save the planet. Novel, sustainable materials, such as bacterial cellulose, could be the ones to expanding the market, but consumer awareness of this type of material should come first.

Participants also shared their ideas on other alternate products that would be good to make from this BC material. Most participants thought it is a good idea to use this material as packaging material such as a grocery bag. Some also thought it is a good material to make other apparel products like shoes or hats as well as home decorations like curtains. Figure 9 presents a few alternate shoe products made of

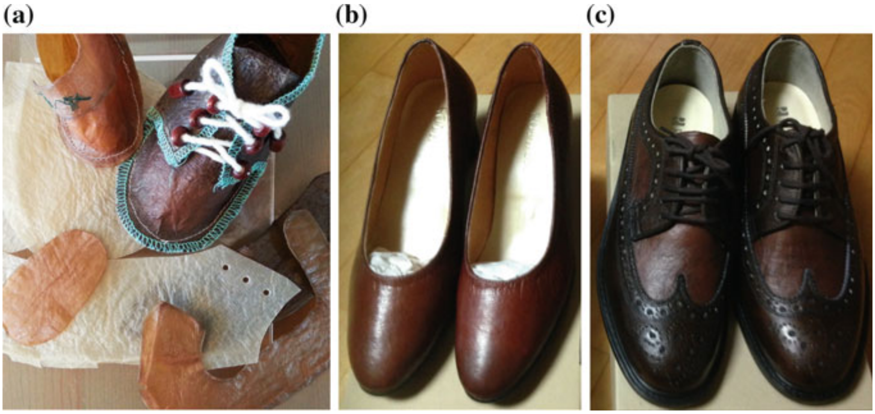

Fig. 9 Shoe prototypes made of renewable bacteria cellulose nonwoven material. **a** Baby shoes. **b** Women's shoes. **c** Men's shoes. *Source* Image by the author, Young-A Lee, August 19, 2015

this BC material as a leather replacement. These prototypes were designed and developed by this case study research team and are currently in the product property evaluation stage.

5 Summary and Future Trends

How do we design, develop, produce, and consume materials and products in sustainable ways and still participate with fashion? We must embrace the wide range of complexities of sustainability that fashion can address. The materials and processes will be consistent with the benefits of people, prosperity, and the planet including a cleaner community environment, reduction of energy use, reduction of fiber processing and fabric production costs, reduction of material waste, and development of a textile that has potential for larger-scale production beyond an experimental prototype. In our current society, it is crucial to continuously note how fashion professionals, and we as consumers, can integrate and sustain environmental protection, economic prosperity, and social benefits in rural communities as well as the apparel and textiles industries. Through demonstrated benefits to people, prosperity, and the planet, the case study presented in this chapter will be expanded in future years across scales in larger regions.

In summary, the following addresses how the case study in this chapter relates to different dimensions of sustainability (i.e., people, prosperity, and the planet). As a global industry, the development of a sustainable textile and apparel production process has a huge potential for improving the living conditions for individuals and factory workers. The potential exist for a new and sustainable textile production system to provide jobs in a sector where none exist at the present time. Safer materials, as well as the sustainable production of apparel and its related products, will benefit many people on many different levels. With the proposed textiles (e.g., bacteria cellulose biocomposite material), apparel and its related products are sustainable and are created from fibers that have a history of consumer acceptance.

The potential for a new and sustainable textile production system to provide jobs in a sector where none exist at present will result in improved economics for workers. The reduction in waste will result in the use of fewer resources related to postproduction waste and the reduction of economic strain on communities. By developing a textile that will not require the additional steps of making fiber into yarn and yarn into fabric, fewer resources will be used. This will provide the potential for increased profits for the manufacturer and reduced costs for the consumer. This will result in improved economic circumstances for manufacturers and consumers. A detailed cost-benefit analysis will be useful for future study.

Reduced use of resources, such as water, and the reduction of effluents resulting from traditional processing will improve community environments. Postproduction wastes will be compostable, thereby reducing landfill waste. Postconsumer waste of apparel and its related products created with this bacteria cellulose fabric will be compostable given the design within the context of a C2C model.

Acknowledgments This work was supported by US Environmental Protection Agency (USEPA) [grant number SU835524 and SU83573301]. Its contents are solely the responsibility of the grantee and do not necessarily represent the official views of the US EPA. The author thanks Drs. Cheryl Farr, Samy Madboudy, Zhiyou Wen, Chunhui Xiang—as well as graduate assistants Armine Ghalachyan, Rui Li, Changhyun Nam, and Gauri Ramasubrmanian—for assistance in moving forward this project.

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