Environmental Footprints and Eco-design of Products and Processes

Miguel Angel Gardetti
Subramanian Senthilkannan Muthu
Editors

Handbook of Sustainable Luxury Textiles and Fashion

Volume 1

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Contents

Introduction

Coco Chanel once defined luxury as "*(…) a necessity that begins when necessity ends*" (Coco Chanel quoted in Okonkwo [15]). In this same line Heine [9] defines luxury as something desirable and more than a necessity. However luxury has been a sign of prosperity, power and social status since ancient times [11]. Already in Robert H. Frank [3] stated in his book 'Luxury Fever—Weighing the Cost of Excess' the need to minimise the culture of "excess" to restore the true values of life. And this is in line with the World Commission on Environment and Development [19] report, Our Common Future, also known as the Brundtland Report, which defines sustainable development as the development model that allows us to meet present needs, without compromising the ability of future generations to meet their own needs. Luxury—according to Kleanthous [12]—is becoming less exclusive and less wasteful and more about helping people to express their deepest values. So, sustainable luxury would not only be the vehicle for more respect for the environment and social development, but it will also be synonym of culture, art and innovation of different nationalities, maintaining the legacy of local craftsmanship [5].

Godart and Seong [8] show us that the relationship between luxury and fashion is quite an ambiguous one, because fashion does not fully belong to the luxury world as it once did up until the turn of the nineteenth century, but overlaps with luxury in its most expensive and exclusive segments. Luxury fashion is a recurrent change at its highest level, and it is distinguished from other luxury segments by its constant pressure to change. In other words, we can say that when we talk about fashion we are referring to clothes and accessories, while the term luxury means status, elegance and sophistication given by a brand, quality, price, originality and creative content.

Sustainable fashion is an approach to the fashion system intended to minimise negative environmental impacts, and, in turn, maximise positive impacts (benefits) for workers and their families all along the value chain, hence playing a decisive role in poverty reduction. For this reason, Kate Fletcher [2] in the preface of the book wrote, *For me the fostering of alternatives to the status quo in fashion and* *textiles is essential if we are to deeply engage with the process of sustainability…* So, our challenge is to adjust sustainability paradigms and develop new ones that would fit the nature of the luxury textile and fashion industry, one of the sectors called "core luxury sectors" within the luxury framework.

Luxury depends on cultural, economic or regional contexts. This transforms luxury into an ambiguous concept [14] and shows for some researchers such as, Scheibel [17], the absurd aspect of this industry. Christopher L. Berry in his work "The idea of Luxury" from 1994 [1]—one of the most interesting and comprehensive pieces on the concept of luxury particularly its intellectual history—establishes that luxury has changed throughout time and that it reflects social norms and aspirations.

True elements of (authentic) luxury rely on the search for beauty, refinement, innovation, purity, the well-made, what remains, the essence of things, the ultimate best [7]. However this luxury has given way to the *new luxury* through its democratisation (massification?) that occurred when family and artisanal luxury companies sagged against the large conglomerates which had a strong focus on economic aspects. It means that the image—*neither reputation nor legitimacy*—was the way, and marketing was the function [6].

The relationship between luxury, textiles and fashion is quite an ambiguous one, as textiles and fashion does not fully belong to the luxury world, but overlaps with luxury in its most expensive and exclusive segments [8]. According to Kapferer [10] both luxury and fashion share the common need for social differentiation, but they differ in two major aspects: first, whereas luxury is timeless, fashion is ephemeral, and whereas luxury is for self-reward, fashion is not. Thus, luxury fashion seems to be a contradiction in terms: as luxury, it is supposed to last, although as fashion it is supposed to change frequently. However, since the essence of fashion is change, luxury fashion gives exclusive access to enforced change. Luxury fashion is recurrent change at its highest level, and it is distinguished from other luxury segments by its constant pressure for change. This is shared by Pinkhasov and Nair [16] who add that in a celebrity-driven culture, fashion has come to dominate the image and attitude of luxury.

Sustainable development is a problematic expression on which meaning few people agree. Each person can take the term and "reinvent" it considering his/her own needs. This is a concept that continuously leads us to change objectives and priorities since it is an open process and as such, it cannot be reached definitely. The essential objective of this development model is to raise the quality of life by long-term maximisation of the productive potential of ecosystems with the appropriate and relevant technologies [4].

Some authors, such as Walker [18] and Koefoed and Skov [13], have studied the contradictions between fashion and sustainability. But, beyond these contradictions, fashion should not necessarily come into conflict with sustainable principles. Indeed, fashion plays a role in the promotion and achievement of sustainability, and it may even be a key to more sustainable ways of living. According to Godart and Seong [8] luxury can offer a unique opportunity for creating sustainable business environments due to its two core features that set it apart from other market segments or industries. First, luxury is (often times) based on unique skills. This allows luxury to provide high-quality and rewarding business conditions. And, second, luxury is characterised by its peculiar relation with time, for its value is inscribed in the long-term. This allows luxury to offer a sustainable business model for resource management and high-quality product development, just to name a few relevant elements of sustainable luxury.

If luxury is becoming less exclusive and less wasteful and more about helping people to express their deepest values [12]. So, sustainable luxury is the return to the ancestral essence of luxury, to the thoughtful purchase, to the artisan manufacture, to the beauty of materials in its broadest sense, and to the respect for social and environmental issues.

We decided to bring out the details pertaining to sustainable luxury in textiles and fashion sector and hence this idea of handbook has come out. Handbook of Sustainable luxury in Textiles and Fashion is coming out in two volumes. This is the *first volume* and it has been divided into three important parts, which are presented below:

Part I—*Use of Materials*
Part II—*Sustainable Production Processes*
Part III—*Sustainability and Business Management*

Eight chapters are presented in this book to deal with these three parts. Each part is dealt with informative chapters earmarked to dissect every minute information and present to the readers with all the sufficient information. The first part, *Use of Materials*, has four chapters. The first chapter on Lotus fibre and sustainable luxury deals with the lotus fibre and its applications in sustainable luxury field. Narrating the entire history of lotus fibre and its processing details, this chapter presents exclusive information on how this bountiful fibre can be utilized in sustainable luxury sector.

The second chapter in this part deals with the flax fibre and presents discussions on how flax can contribute to sustainable luxury sector. Presenting the details of a collaborative project on flax (ProjectFlax), this chapter enumerates the delivery of novel applications in sustainable materials for human and environmental wellbeing produced premium products from an unexpected plant source.

The next chapter is assigned to investigate the potential of Great potential of nettle in sustainable luxury area of fashion and textiles sector. In this chapter, the first part details the properties, production and applications of nettle fibre in sustainable textiles.

The last chapter in this part is an overview chapter on "Sustainable Luxury Natural Fibers—Production, Properties, and Prospects". This chapter presents comprehensive details on conventional and unconventional sustainable luxury fibers and their applications in textiles and fashion sector.

The second part of the book is earmarked to deal with the *Sustainable Production Process*, and this important aspect is disseminated with the aid of three chapters. The fifth chapter in this book (first one for this part) deals with the "Sustainable Processing of Luxury Textiles". This chapter presents informative aspects pertaining to various areas such as fibers used in luxury textiles and their processing aspects, importance of sustainability in luxury textile processing and assessment of environmental impacts of luxury textile processing along with discussions on future trends in sustainable processing of luxury textiles.

The sixth chapter in this book—"Sustainability in Luxury Textile Applications: A Contradiction or a New Business Opportunity?" includes discussions pertaining to re-use and recycling of high valuable fibre materials like polyamide and carbon used in luxury applications along with two interesting case studies.

The seventh chapter in this book—"Specialty Chemical Finishes for Sustainable Luxurious Textiles" details presents a glimpse on numerous specialty chemical finishes and their applications on sustainable luxury segment of textiles and fashion sector.

The third part of the book is planning to cover *Sustainability and Business Management* and for this part one chapter is included in this book to deal with. This chapter on deals with an overview of luxury apparel industry and its sustainability practices. Also, this chapter analyses sustainable practices of nine global luxury brands with the aid of a case study approach.

We would like to take this fantastic opportunity to thank all the contributors of the chapters presented in this book for their intensive efforts in bringing out this first volume of this handbook so successfully with enriched technical content in their chapters. We are very much confident that this handbook will certainly become as an important reference for the researchers and students, industrialists, sustainability professionals working in the textiles and fashion sector.

Miguel Angel Gardetti
Subramanian Senthilkannan Muthu

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Part I
Use of Materials

The Lotus Flower Fiber and Sustainable Luxury

Miguel Angel Gardetti and Subramanian Senthilkannan Muthu

Abstract The lotus flower—of great religious and cultural significance- is adored for its characteristic of rising above the muddy water, indicating how one can rise above defilements of life. Apart from motivation for life, the plant also provides fibers which are used for making a rare kind of cloth matching with the flawless virtues of silk. Extracting fibers from the lotus stems have been in practice since 1910. Later during the 90's designers of Japan setup workshops to create a foreign market for their fabric. But due to low demand in Japan, the lotus fiber fabric remained a rare and handmade textile. The lotus plants are pure by virtue, and they radiate this purity through their fibers. The fabrics are 100 % organic, and hence they are environmentally friendly. The entire process of fiber extraction, spinning it into yarn and making the fabric is completely handmade making the process time-consuming. This also limits the quantity of the fabric produced. Stems of the lotus plants are collected, cut, snapped, and twisted to expose their fibers. These are thin and white filaments around 20–30 in number, which are rolled into a single thread. Around 20–25 women are needed to extract fibers this way for one weaver to work with. Fibers extracted from the stem are spun into yarn. The extracted fibers are placed in the skeins on a bamboo spinning frame preparing them for warping. Yarns are made by placing the fibers on a bamboo spinning frame and transferring the thread into winders for warping. With much care, not to get tangles, threads up to 40 m long are made. These threads are then taken from the warping posts, and are coiled into huge plastic bags. Yarns for the weft are wound into bamboo bobbins. Yarns are woven in manual looms. Excess

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warp is stored and later released during the course of weaving. During the weaving process, threads are frequently moistened with water, as the lotus fibers need to be kept cool. The fibers are very delicate and should be woven within 24 h of being extracted so as to prevent their deterioration. The fabric looks like a blend of linen and silk, and has wrinkle resistant and breathable properties given by the molecular makeup of the lotus plant. Based on the experience of the Italian luxury brand Loro Piana, but mainly in the Somatoa, a company founded by Awen Delaval in Cambodia, this chapter examines the potential of this fiber in the (sustainable) luxury sector.

Keywords Lotus flower · Sustainable luxury · Loro piana · Samatoa

1 Introduction

Sustainable development is a problematic expression, on which few people agree what it means. Each person can take the term and "reinvent" it considering his/her own needs. It is a concept that continuously leads us to change objectives and priorities since it is an open process and as such, it cannot be reached definitely. However, one of the most widely accepted definitions of sustainable development—though diffuse and non-operating—is the one proposed by the World Commission on Environment and Development [37] report—Our Common Future—also known as the Brundtland Report, which defines sustainable development as the development model that allows to meet the present needs, without compromising the ability of future generations to meet their own needs. The essential objective of this development model is to raise the quality of life by long-term maximization of the productive potential of ecosystems, through the appropriate technologies for this purpose [12].

Some authors—Frankel [10] and Elkington [7]—define sustainability as the balance between three elements: economy, environment and social equity.

The textile industry across the globe is constantly striving for an innovated supply chain to gain sustainable development in the entire sector. It is high time to reduce the size of the environmental footprints made by this sector. This includes the development of sustainable and eco-friendly raw materials, less energy intensive and minimum polluting process sequences and technologies and so on and so forth. Obviously the role of raw materials in making an eco-friendly product is highly inevitable and occupies an important proportion compared to other elements in the entire life cycle of a textile product. Additionally, employing an eco-friendly raw material can complement the other life cycle phases in terms of reducing their impact; and it helps in terms of obtaining a reduced environmental footprint out of a textile product.

There is an urgent need to manufacture a textile product which stems from renewable resources such as plants/trees (bast and leaf fibers), produced by ecologically sound manufacturing processes, transported and used with minimum environmental burdens and finally ending its life smoothly without any additional environmental burdens (recyclable and biodegradable at the end of life). The textiles produced with fibers originating from plant resources will satisfy most of the above mentioned needs, although the manufacturing sequences/processes may not be with guaranteed lower footprints, since it highly depends on how the fiber is going to be converted to a final product.

Against this background, textiles made with bast and leaf fibers are gaining huge importance from the sustainability perspective, and there are various plant resources used to create textiles out of them. One of the plant textiles is the lotus fiber fabrics or textiles. The sacred lotus, named as queen of water plants has a sentimental value for the Hindus and Buddhists. The lotus is affirmed as a celestial fiber for the Hindus and Buddhists. Fibers extracted from this auspicious flower are used for textile fabrics intended for various applications. The fabric surface made out of the lotus fiber fabric is seen to be uneven with small lumps, and it can be used for garments or developed as various home utensils [9, 33]. Fabrics made out of the lotus fiber could be an alternative to waterproof synthetics [8].

The lotus flower has a philosophical sense of touch to human lives, i.e., how a human being can rise above the defilements of life, as the lotus flower does by rising just above the grimy and muddy water. It is an admirable characteristic of this flower that one has to learn and practice in daily life. Besides, as stated earlier, the fibers from the plant can be used to produce a fabric with the flawless virtues of a silk fabric. One of the eco-friendly elements that comes into play in terms of manufacturing is that the fibers extracted from the lotus flowers are spun by hand and woven within 24 h to produce a fabric similar to that of silk [9].

This chapter explores the details of the Lotus flower fiber and its processing. It begins by describing the fiber's historical and religious aspects and, ends with this fiber's potential in the luxury sector, and particularly, in the sustainable luxury sector based on two experiences: Loro Piana's (Italy) and Samatoa's (Cambodia).

2 The Lotus Flower: Historical and Religious Aspects

The lotus (Nelumbo nucifera) also called as Indian lotus, sacred lotus, bean of India is one of the two species of aquatic plants in the Nelumbonaceae family and it belongs to the Proteales order and Nelumbo Genus. It is native to Asia and Queensland, Australia, generally cultivated in water gardens. This is an aquatic perennial, at times mistaken for water-lily; however, it has an entirely different structure altogether. It is the national flower of India and Vietnam [26, 36].

The lotus flower has played a major role in the history of many parts of the world, such as Egypt, Thailand, and China.

2.1 Ancient Egypt

The lotus flower has a pretty long history that dates back to Egyptians times, when it had a very important religious value. The lotus is the symbol of resurrection, purity, serenity and peace. Throughout the ancient Egypt history, the lotus has been pictured in various works of art. The lotus is seen everywhere in ancient Egyptian tombs and temples, often held in the hands of gods and royalty. The lotus plant is flower and fruit at the same time, which makes it very special as it would emerge as pure white from the depths of the muddy swamp and grow above the water. The lotus flower was part of the Ancient Egyptian creation story. It portrays the meaning of creation and rebirth (incarnation), since at nightfall it closes and goes underneath the water, and at dawn it climbs up above the water and reopens. It is a symbol of rebirth and eternal life, which is the main theme of Egyptian religion. According to the creation story, Ra, the Sun God, was created from amidst chaos and first emerged from the petals of the lotus flower. When Ra returned to the lotus flower each night, its petals enfolded him once again. The lotus was also used in their math, helping them to count. One lotus would act as 1000 and two lotus as 2000 and so on and so forth [26, 27].

2.2 Thailand

The lotus flower plays a significant role in the life of Thai people. The lotus is the most common flower of Thailand, which can be easily seen in ponds, swamps, small canals, roadside ditches, even in jars and on top of pillars in most of the temples. The lotus flower—actually five kinds of it—can be found in Thai literature. The lotus flower has a very rich symbolism, which has adorned Thai literature since ancient times. Many Brahman goddesses have lotus blooms in their hands and this can be seen in paintings. There are three names in Thai for lotus and water lilies, which are Bua, Pathum and Ubon. These names are popularly used in Thai culture to name people, monasteries, provinces, districts and villages because of their favorable connotations. The Lord Buddha compares man to four states of the lotus. Thai Buddhists always use the lotus in paying homage to the image of the Buddha [27].

2.3 China

There is a long connection between the Chinese and the lotus. Chinese are regarded as gentle people, who keep themselves clean, alive and healthy in a dirty environment. Essentially the lotus flower represents the creative power and purity amid adverse surroundings. It is also a symbol of the seventh month, summer. In China, there are many poems about the lotus flower, often describing how they come out of the dirty mud under the water and yet retain their pureness, freshness and beauty [27].

2.4 Religious Aspects of the Lotus Flower

The lotus flower is considered to be a powerful religious symbol in many cultures, such as Asian, Egyptian, and Indian ones. From prehistoric times, the lotus has been considered as a divine symbol in Hindu tradition. It is often used as an illustration of the divine beauty and its unfolding petals imply the development of the soul. The Hindu deities are often depicted with the lotus flowers as their seats, and the meditating yogis traditionally sit in the lotus posture (Padmāsana) [2, 23]. This can be seen from many paintings/art works. Based on the ancient Hindu tradition, a lotus flower is also considered as a symbol among the earliest Buddhist symbols. It represents an enlightened being, Buddha or Bodhisattva, rising above the muddy waters of the world; and the Buddha is often depicted sitting on a giant lotus blossom [2, 19, 36]. Buddhists believe that the Lord Buddha himself was born on a lotus leaf and many legends tell that when Buddha was born, he walked seven steps in ten directions and with each step a lotus flower appeared. The lotus is thus one of the eight auspicious symbols associated with the eight-fold path to enlightenment, and symbolizes faithfulness [23].

The lotus has different colors and in Buddhism, each color has a different meaning, which is explained below:

White Lotus (Skt. pundarika; Tib. pad ma dkar po): it represents purity of total mind and spiritual perfection. The white lotus flower is also regarded as one of the four noble truths.

Red Lotus (Skt. kamala; Tib: pad ma chu skyes): This portrays the original nature and it is also a symbol of purity (more closely, purity of the heart). It is regarded as a symbol of passion, love and compassion, which are obviously the qualities of the heart. It is the flower of Avalokiteshvara, the bodhisattva of compassion.

Blue Lotus (Skt. utpala; Tib. ut pa la): The blue lotus is a symbol of victory, victory over the senses. It signifies knowledge and wisdom. It is the preferred flower of Manjushri, the bodhisattva of wisdom.

Pink Lotus (Skt. padma; Tib. pad ma dmar po): This is the Supreme lotus. It is generally meant for the highest deity. The pink lotus stands for Lord Buddha itself, so it automatically stands for Lord Buddha's teachings too [4, 30].

3 The Lotus Flower Fiber: Aspects and Processing of the Fiber

The lotus fiber fabrics are finding great application in the textile sector, especially in the luxury sector. The lotus fiber fabrics can be best described as in-between silk and linen; the lotus flower fabric is naturally stain resistant, waterproof, and soft to the touch. This breathable, wrinkle-free fabric was once used to make robes for high-ranking Buddhist monks [8]. This section describes the properties of the lotus fiber and processing details of the lotus fiber to produce a textile fabric.

3.1 Properties of the Lotus Fibers

With the purpose of contemplating the fundamental physical properties of the lotus fiber and of providing the theoretical basis for developing the lotus fiber fabric, a study was conducted in 2008. This study reported the tested fundamental physical properties of the lotus fiber, such as density, linear density and moisture regain. As per the results of this study, the density of lotus fiber varies between 1.184 g/cm ~3, much less than cotton, ramie and wool fibers, but similar to silk and acrylic. The linear density of lotus fiber is 1.55 dtex, finer than ramie and silk fibers, and similar to cotton and cotton type chemical fibers. The moisture regain of the lotus fiber is 12.32 %, larger than cotton and silk, and less than of wool and viscose, but similar to ramie fiber. Further, this study also indicated that the lotus fiber is very fine and beneficial to the resultant yarn strength and yarn evenness. It can be used to spin high count yarns. It was also reported that the lotus fiber has very good absorbent quality [35].

Another study conducted in 2011 reported the structural characteristics and physical properties of the lotus fibers obtained from Nelumbo nucifera petioles [28]. As shown in this study, the lotus fiber is a natural cellulose fiber isolated from the lotus petiole and botanically. The fiber is the thickened secondary wall in xylem tracheary elements. The fine structure and properties of the lotus fibers were researched with the aid of transmission electron microscopy (TEM), confocal laser scanning microscopy (CLSM), atomic force microscopy (AFM), X-ray diffraction (XRD), among others, to obtain essential information for their preparation and processing. The results of this study stated that the lotus fibers displayed a rough surface topography and an internal structure different from common plant fibers. The percent crystallinity and preferred orientation of crystallites in the lotus fibers are 48 and 84 %, respectively, as per this study. Considering the average breaking tenacity and Young's modulus, the lotus fibers are similar to cotton. The elongation of the lotus fibers is only about 2.6 % while their moisture regain is as high as 12.3 % [27].

A recent study conducted in 2012 further reported on the other properties of the lotus fiber. This third study was conducted to study the chemical components, morphological structure, aggregation structure and mechanical properties of the lotus fiber with the aid of chemical quantitative analysis, scanning electron microscope, infrared spectra, X-ray diffraction analysis, among others. Based on the results of this study, the lotus fiber consists of cellulose, hemicellulose, fat waxy, lignin, ash, pectin, hydrotrope, and amino acids; being cellulose is the main ingredient. The lotus fiber that shows a ribbon spiral revolving structure vertically has clearly imperceptible cross striation, and it is a bundle fiber composed of many monofils. The cross-section of lotus monofil is circular or similar to a circular shape. The lotus fiber is a typical cellulose structure with 48 % crystallinity and 60 % orientation, as shown in this third study, which is slightly different from the previous one, mentioned further above. The density, fineness and moisture regain of the lotus fiber are 1.1848 g/cm^3, 1.55 dtex, 12.32 %, respectively. The lotus fiber has high strength and low stretch with an initial modulus of 146.81 cN/dtex, its breaking strength is 3.44 cN/dtex and the breaking elongation is 2.75 % [3].

3.2 Processing of the Lotus Fibers[1]

The lotus plant blossoms in warm tropical climate and it is able to withstand even below freezing temperatures when it is quiescent. At least, 5–6 h of sunlight a day for a minimum of 3–4 weeks with an air temperature of 80 degrees Fahrenheit and a water temperature in the 40 and 50 s above is the minimum need for a lotus flower to blossom. The flower and its leaves rise on 61 cm to 1.9 m long stems above the water surface from 15 to 46 cm long nodes. To obtain stems of optimum length, the harvesting must take place in the rainy season from June to November when, for example, a lake water level is at the highest point [11]. Just one week prior to the lotus flower harvesting period, popped rice is scattered on the water and offerings are made to placate the spirits of the locality in order to seek their permission and ensure a good harvest. During the day of harvesting, the gatherers propitiate their patroness. Prayers are also offered to the Buddha for a bountiful harvest [31].

When it comes to the processing of lotus fiber fabrics, it is laborious and tedious. Lotus fiber fabrics are prepared by a handmade artisan process that requires time and thoughtfulness as it takes approximately 32,000 lotus stems to make just 1.09 yards of fabric, and approximately 120,000 for a garment [8].

The lotus leaf stems are usually gathered by younger women in the morning time to begin the process. Following the removal of the nubbly prickets with a coconut husk, the stems are then placed beside a young woman seated at a low table. A shallow knife cut is made around a bunch of 5–6 stems which are quickly snapped off and twisted to reveal some 20–30 fine white filaments that are drawn and rolled into a single thread which is coiled onto the plate seen on the left. It takes approximately 15 women making thread to keep one weaver busy [31].

Then, the yarns are prepared for weaving by placing the skeins on a bamboo spinning frame and transferring the thread onto winders in readiness for the warping process. Taking care of avoiding any tangling, the 100 yard long threads are then lifted from warping posts and coiled into huge plastic bags, while yarn for the weft is wound onto small bamboo bobbins (see Fig. 1). In general, the lotus fabric is woven on a traditional Cambodian frame loom. The weaving components include a cloth beam, a large warp spacer-beater, and a pair of heddles supported

[1]This section refers both to In-Le Lake in Myanmar (the former Burma) and to Lake Kamping Poy in Cambodia, and the production processes in these two regions.

Fig. 1 Obtaining the fibers from the lotus flower stem. *Source* Fraser-Lu and Thanegi [11]. Photograph by Sylvia Fraser Lu, Pandonmar Lotus workshop, Kyaing-kan, In-le, 2000. Published with the authorization of Sylvia Fraser-Lu and the Fowler Museum at UCLA

Fig. 2 Preparing the fiber for weaving. *Source* SAMATOA—Photograph by SAMATOA. Published with the authorization of SAMATOA

by a transverse bar resting above the frame. The heddles are connected by rope to a pair of wooden, disc-shaped foot treadles [31] (Figs. 2, 3 and 4).

There is no warp beam on a Cambodian loom. The excess warp is stored behind the weaver and released as weaving progresses. This limits the width of cloth woven to around 24 in. (60–75 cm). The use of a temple keeps the selvages straight while water is at hand to moisten the threads during the course of weaving. Given the aquatic origin of the fabric, weavers feel that the lotus fibers need to "remain cool." The lotus fabric is woven in 100 yard (90-meter) batches, which takes about a month and a half to complete. The weavers have estimated that fibers from around 120,000 lotus stems are needed to weave a set of monk's robes. The Cambodian lotus fabric is then dyed either with chemical or natural dyes to a reddish/brown shade before being cut into patches of different sizes and machine sewn together in rows to resemble the mosaic-like appearance of community owned rice fields prevalent at the time of the Buddha [31]. Figure 2 shows the work in a Thai/Burmese loom producing the lotus fiber fabric for monk's robes.

Fig. 3 Stem once the fiber is extracted. The arteries containing the threads can be clearly seen. *Source* SAMATOA—Photograph by SAMATOA. Published with the authorization of SAMATOA

Fig. 4 Manually weaving the lotus fiber yarn. *Source* Fraser-Lu and Thanegi [11]. Photograph by Sylvia Fraser-Lu, Pandonmar Lotus workshop, Kyaing-kan, In-le, 2000. Published with the authorization of Sylvia Fraser-Lu and the Fowler Museum at UCLA

Fig. 5 The various stages of the lotus fiber yarn processing are presented in this image. *Source* Fraser-Lu and Thanegi [11]. Photograph by Ma Thanegi, Pandonmar Lotus workshop, Kyaing-kan, In-le, 1999. Published with the authorization of Ma. Thanegi and the Fowler Museum at UCLA

As stated, this process takes approximately one month and a half to complete and there is a no waste as all parts of the lotus are utilized- using leftovers to make lotus teas, infusions, and flour, which ensures the production of an entirely sustainable product.

The lotus flower fabric is an exclusive organic and natural fiber fabric. The lotus fabric is unique, very soft and comfortable to wear offering special breathable and wrinkle-free properties. It is an organic fabric for high quality fashion clothing [25] (Fig. 5).

4 The Lotus Flower and the (Sustainable) Luxury Sector

Luxury is something desirable and more than a necessity [16]. This definition depends on the cultural, economic or regional contexts which transform luxury into an ambiguous concept. However luxury is a sign of prosperity, power and social status since ancient times [18]. Christopher L. Berry in his work "The idea of Luxury" from [1] establishes that luxury has changed throughout time, and that it reflects social norms and aspirations.

The true elements of (authentic) luxury rely on the search for beauty, refinement, innovation, purity, the well-made, what remains, the essence of things, the ultimate best [15].

However this luxury has given way to the *new luxury* through its democratization (massification) that occurred when family and artisan luxury companies sagged against the large conglomerates which had a strong focus on economic aspects. Dana Thomas, in her work 'Deluxe—How Luxury Lost its Luster' [32], was very clear about the consequences of this process: "…*the luxury industry*…has *sacrificed its integrity, undermined its products, stained its history and deceived its customers.*" This may be considered a turning point to sustainable luxury.

Luxury—according to Kleanthous [20]—is becoming less exclusive and less wasteful and more about helping people to express their deepest values. So, sustainable luxury is the returning to the essence of luxury with its ancestral meaning, to the thoughtful purchase, to the artisan manufacturing, to the beauty of materials in its broadest sense, and to the respect for social and environmental issues. Sustainable luxury would not only be the vehicle for more respect for the environment and social development, but it will also be synonym of culture, art and innovation of different nationalities, maintaining the legacy of local craftsmanship [13].

4.1 Emerging Brands and Established Brands in Relation of the Lotus Flower

Within the luxury industry, it can be observed that new companies or brands –the so called "Emerging Brands" according to Hockerts and Wüstenhagen [17][2]—are based on values, and this is attractive for a select number of consumers since this kind of companies can generate a big impact due to the potential for reaching a larger market [34]. These Davids have an active attitude based on a very pronounced approach to values with the intention of generating social and environmental changes. They are well motivated to "break" the rules and promote disruptive solutions to environmental and social issues. They are less constrained by existing realities than larger organizations, have less vested interest in the status quo, and have less to lose and more to gain from innovation [28].

But, in addition, to achieve a profound social change, the role of personal values is very important: idealistic values regarding environmental and social goals that can be translated into value economic assets [5]. They have a transformational leadership behavior, inspiring and guiding the fundamental transformation that sustainability requires [6].

In turn, and also according to Hockerts and Wüstenhagen [17] there are "Established Brands" (see footnote 2) that is, the major international brands that are anchored to the usual mindset even though they have started to develop sustainable strategies [14]. A number of recent reports shows that the established brands' progress towards sustainability is slow. Even though some brands have a proactive attitude towards the challenge of sustainability, it is observed that, in general, the industry reacts to the market and consumers' demands.

[2]Actually, Hockerts and Wüstenhagen [17] talk about "Emerging Davids and Established Goliaths".

Find below two companies working on the sustainable luxury sector with the Lotus Flower Fiber. One of them—Loro Piana based in Italy—is a well-established brand, while the other—Samatoa based in Cambodia—can be called an "emerging brand."

4.1.1 Loro Piana

Until July 2013—when LVMH—the European luxury conglomerate- acquired an 80 % stake of the company for 2 billion euros—Loro Piana, an "Established Company," brought six generations of experience. Founded in 1924 by Pietro Loro Piana—with origins dating back to 1812 per the vision of Pier Luigi's great-grandfather Giacomo Loro Piana [21]—the company is a specialist in very high-end, luxury cashmere and wool products made in Italy. The company combines the latest technology, traditional craftsmanship and Italian tailoring.

In 2013 the company's expected revenue was €700 millions with a +20 % EBITDA [24].

This company offers exclusive men and women lines with a worldwide network of over 130 stores.

It has access to world class raw materials, such as vicuna, cashmere and baby cashmere, fine merino wool and, finally, the lotus flower fiber from the In-Le Lake in Myanmar. According to [21], despite Pier Luigi Loro Piana's concern that the lotus flower fiber is used to make hand-crafted monks' garments and are sacred to the Buddha, the company engaged the local community for its harvesting since "*the lotus flower fabric's pleasantly irregular appearance looks like raw silk or Antique linen…Its feel, however, was incomparable to any fabric we had ever come across before*" [22].

Given this hands-on approach, a limited number of blazers are produced each year. Packaged in a beautiful, handcrafted lacquer box, the Lotus Flower jacket—available only in its natural ecru color—is custom priced, and limited-cut lengths are offered for made-to-order blazers. For these reasons, the company has trademarked Loro Piana Lotus Flower fabric. The company innovatively created two products: one of them is a jacket called Roadster Villa D'Este,[3] specially designed to commemorate the 75th anniversary of the Elegance Contest[4] and tagged at €8,205.00, and the second product is a scarf that combines lotus flower fiber, silk and cashmere.[5]

[3]The Roadster Villa D'Este 100 % made of the lotus flower fiber'.

[4]It is a fancy competition of classic cars.

[5]This scarf composition is lotus flower fiber (45 %), silk (15 %) and cashmere (40 %), and it is tagged at €1,980.00.

4.1.2 Samatoa[6]

This company "was founded in Cambodia in 2003 by Awen Delaval[7] with the single purpose of creating an ethic luxury fashion brand under the principles of fair trade with a view to elevate artisans to world status in the international fashion market. On the one hand, it produces fabrics with natural raw materials, such as pineapple, banana, silk, organic cotton and kapok and, on the other, haute couture ethic garments. In 2012 an international panel of experts underscored the company's innovation in producing a fabric with a mix of the lotus fiber and silk, and then coloring it with natural dyes. This innovation was precisely why UNESCO awarded the company the 2012 UNESCO Award of Excellence in Handicraft.[8]

Samatoa adheres to sustainable development principles. Some of the criteria applied by the company in the social field are to be a participative organization which respects individual freedom of expression without discrimination, is against child labor, and ensures a minimum salary, union rights, time off and vacations, health and safety, no sexual discrimination, and fair wages. The company insists on no discrimination at all management level: recruitment, job allocation, remuneration, entitlement to social advantages, discipline, and work contract termination [31].

In environmental terms, Samatoa is committed to respecting specific eco systems, to the responsible use and conservation of natural resources, to the efficient use of energy, and to not use chemicals in the entire process from thread to finished products, nor any substances that are toxic to humans and the environment. The natural fibers offered by Samatoa do in no way compete with the food supply chain [31].

[6]"Samatoa" means "fair" in Khmer.

[7]Awen Delaval, a dedicated Frenchman at the heart of a fair-trade promotion association, was exposed to (and toughened by) the poverty in Cambodia during a trip to Asia. Seduced by the teaching of the Lotus Sutra, he created a plan in the same humanist vein. An ethical alternative to the powerful textile industry, contrasting productivity-driven and socially-exploitative attitudes, particularly with women, Samatoa is a change from how typical factories, run by big textile brands, operate. Having a 10-year experience as the chief of a textile cooperative, he also developed The Lotus Center Battambang which today is a unique experimentation studio for research on the lotus fibers and byproducts.

[8]UNESCO "Award of Excellence for Handicrafts" in Southeast Asia has been established to encourage craft-workers to use traditional skills and materials. The Award of Excellence program (formerly known as the SEAL of Excellence) aims to ensure the continuation of traditional knowledge and skills, and the preservation of cultural diversity in the region. In addition, the promotion of handicraft is a major contributor to sustainable economic development and poverty reduction in local economies.

5 Conclusions, Analysis and Forward-Looking Concerns

The lotus flower is considered to be a powerful religious symbol in many cultures: "*Religious robes are a Buddhist badge of identity, a visual reminder of the weaver's religious vows and honored status. While cotton robes are accepted and worn by monks throughout Burma* (today Myanmar), *robes woven from the lotus fiber are presented only to the most revered of senior monks, who, for the most part, consider them too sacred to wear. Such robes are often preserved in glass cases near the monastery shrine where they are admired and venerated with other offerings made to the Enlightened One*." Fraser-Lu and Thanegi [11].

It is also a strong cultural symbol: it was associated to art and literature in Old Egypt, China and Thailand.

And all this relates to the true elements of authentic luxury as defined by Girón [15]: **beauty, refinement, purity, the essence of things, the ultimate best**. Even if we take the elements that make up sustainable luxury, which were defined by Gardetti [13], we can see a profound and natural connection between sustainable luxury and the lotus flower fiber. This is about the ancestral meaning, artisan manufacturing, synonym of culture, and respect for social and environmental issues maintaining the legacy of local craftsmanship.

This natural connection makes this fiber potential in the sustainable luxury market to be "*very huge,*" as stated by Alen Delaval, the founder of Samatoa.[9] And this potential is reflected on the fact that "*…We received many requests from different countries and different designers"* and its "*actual production capacity is booked for* 8 *months*.*"* Delaval further added that *"The lotus fibers can be spun in different thickness to make any kind of clothing, accessories or furniture. Furthermore, because of their extraordinary property, the fibers will probably be used for others applications*."

In turn, while Pier Luigi Loro Piana said in reference to the lotus flower fiber that "*We will not lose this tradition*" [21], in the presentation of the book titled "The Lotus Flower: a textile hidden in the water" [22], he added, "*Feeling certain we had discovered and extraordinary and* '*new*' *raw material, we began to do what was necessary to be able to bring it into the Western world and make it know to our customers*." This brings about two interconnected aspects: the balance between profit-making and the concern about environmental and social aspects in a broad sense and, particularly, the concern about the local religious, cultural and artisan legacy, especially when talking about the East. This becomes more important because Loro Piana belongs to an economic group, LVMH, though many of its brands are already developing sustainability strategies.[10] This aspect is related to the Western consumer culture.

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[9]Based on an e-mail exchange with Mr. Delaval.

[10]E.g., Loewe has been the first brand of the LVMH group in developing its Sustainability Report. It did so in 2013. Another example is Loro Piana itself with its Vicuna Project in Peru, intended to save this endangered species (besides ensuring a source of raw material).

It is clear that the development of lotus flower by-products faces challenges. Within a framework of growing business momentum in the West, the first challenge is to build a local and shared vision of the intentions with this plant and its by-products. Questions such as the following would need to be answered: What does it take? What knowledge should be created or respected? How could this process evolve? How could sustainable preservation be developed? How to educate or raise awareness in the Western consumer about the Eastern religious and cultural advantages? How to promote their respect? Which would be the limits? Should there be any limits?

Other challenges may be posed in different questions: What type of business model will work for the lotus flower fiber within the framework of sustainable luxury? Could conservationist organizations be involved in this process? And finally, how can we build trust and respect in local economies?

In closing, the answers to these questions would be completely different, and they will lead to diverse strategies if we consider them from the perspective of Loro Piana (LVHM)—a established brand, or from that of the Samatoa—an emerging brand, based (from its onset) on sustainable development values.

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Flax: Sustainability Is the New Luxury

Joan Farrer and Carolyn Watt

Abstract 'Flax: increasing its value for society' was the challenge posed by cross-border researchers funded by the European Union INTERREG IV A France (Channel)—England call, as the ancient flax fiber had seen a dramatic decline in consumer appeal and market share. The resulting collaboration, ProjectFlax, delivered new innovations where novel applications in sustainable materials for human and environmental wellbeing produced premium products from an unexpected plant source. Could value in future be defined and measured not just by the aesthetics of the artefact, but by assessing the true value of materials using a holistic narrative in relation to process, the philosophy and sustainability of the application? This assessment is, we argue, *new luxury*. The purpose of this chapter is to show that flax was an unexpected source of innovation for societal advantage, appealing to consumers who desired a deeper material meaning and product differentiation—characteristics afforded by traditional expensive luxury brands. The collaboration between design, science, technology, engineering, mathematics and business (D-STEM-B) combined discipline methodologies, which resulted in new thinking and problem solving. Case study, desk-based, laboratory, practice-led, field study, quantitative, qualitative, narrative and observational methods were explored by 20 national and international, commercial and institutional flax researchers. The findings included improved agricultural and industrial production methods, composites, foodstuffs, biodegradable packaging, bio materials, fashion and interior product prototypes. The research has contributed to a knowledge transfer toolbox between D-STEM-B partners and advanced transdisciplinary working methods, which resulted in further successful funding applications and new market opportunities for flax.

Keywords Flax · Sustainable materials · Luxury · Transdisciplinary · Design · Science · Business · Wellbeing · Agriculture

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1 Introduction

Flax is the common name for the fibres of *Linum usitatissimum*, part of the linen family, and is one of the oldest cultivated crops used in textiles and foodstuffs. Throughout history, the various qualities of flax have been valued for a variety of different purposes. As a material, it ranks highly in the fabric hierarchy because its fibres could be made by hand into strong, decorative, gossamer-like woven linens and lace, were superior to other fibres and were enjoyed by the privileged. This was, without doubt, an *old luxury* fibre. The discovery in a cave in Georgia of dyed flax fibers has been dated to 34,000 BCE, suggesting that ancient peoples spun wild flax fibers to create linen-like fabrics. Flax bandages have also been discovered wrapped around mummified corpses in Egyptian tombs and in ancient Egyptian medical applications [7: 27], and tomb illustrations depict in detail the cultivation, production and use of linen cloth. Such high quality cloth could be achieved prior to the modern industrial age due to the long fine fibres, which can reach up to one metre in length, found in the core of the flax stalk. These strong fibres are laid bare when the outer pithy casing has been removed in what is known as the retting process,[1] whereby the rows of cut stalks are left to lie in the field where they are grown, exposed to wind, rain and sun in the natural environment for six weeks, and turned once or twice (these more sustainable processes with minimal use of chemicals, result in better environmental management of the land and improved working conditions for processing and manufacturing). Flax grows primarily in damp temperate climates in parts of the world that share particular latitudes; however, the resulting high quality linen is made from flax grown principally in European countries and regions of China. Flax is able to grow on the majority of soils and, in contrast to many other fibres such as cotton, natural production of flax does not require pesticides, artificial irrigation or fertilisers, resulting in a truly organic fibre.

Fine flax fibres can be easily spun into extremely fine thread by using simple hand spinning devices such as a distaff and spindle. The thread could then be dyed and hand braided into fishnets and ropes, or woven into fabric strips on primitive looms before being sewn together to make clothing and furnishings. The plant has also been cultivated for its many by-products, ranging from foodstuffs and medicines to soap, paper and dyes. The seeds of the flax plant, called flaxseed, are used to make edible oil known as linseed oil. ‘Flaxseed has a unique fatty acid profile. It is high in polyunsaturated fatty acids and low in saturated fatty acids’ (Mridula et al. 2013: 950). Today, rich omega fatty acids are known to be beneficial to health, and it is thought that regular inclusion of flaxseed in a nutritionally-balanced diet reduces levels of blood cholesterol and, consequently, the risk

[1]Retting is the process employing the action of micro-organisms and moisture on plants to rot away much of the cellular tissues and pectins surrounding the bast-fibre bundles, facilitating the separation of the fibre from the stem.

of coronary artery disease. Flax has a long history as a source of food, health and wellbeing. The healing properties of flax have been known from ancient times, evidenced when Hippocrates claimed that flax seeds can be used for relief of abdominal pains, and the oil from flax seeds has been used in food for thousands of years [5: 2]. Contemporary research attention is beginning to focus upon food production, vegetable waste and bio-resources.

The fibre's multiple uses, including luxury textile manufacture, achieved status and popularity, continuing throughout the Industrial Revolution, but began to lose market share and popularity as the fibre was replaced by oil-based fibres such as polyester, with a similar handle and strength, but which were crease resistant and could be mass produced cheaply. In the 1960s, flax did not develop a brand identity (unlike other fibres such as cotton and wool, through the auspices of Cotton Incorporated PLC and the International Wool Secretariat, respectively). Coupled with the burgeoning global trade in easy care man-made fibres, linen's luxury market niche began to lose its place in the luxury hierarchy (Miller and Mills 2012).

Flax, once known as the luxurious 'gold of the Nile', has been rediscovered in the last decade in design, science and engineering communities due to its positive environmental credentials. The chief component of flax, cellulose, is 'one of the oldest, most abundant natural polymers on earth [sic]' [14: 207]. Alongside lignin and hemicellulos, this key component of the flax fiber increases its value in the materials hierarchy because of the way it can be produced and the research and development opportunities attractive to new markets. In addition, these fibres are now much sought after as they are recyclable, biodegradable and are 'carbon positive', which means the plants absorb more carbon dioxide in the growth phase than they release during processing; yet flax fibre now accounts for only 0.7 % of the world's fibre production leading to the conclusion that its value is underexploited. Kozlowski et al. [12: 37] state:

> Green fibrous plants provide valuable by-products such as seeds, waxes, fragrances, and pigments. These may be used as food, fodder, pharmaceutics, cosmetics, and body-care items. Especially important are linseed/hemp seed. They contain substances indispensable for our brain and nervous system as well as antisclerotic/anticarinogenic lignans and unsaturated fatty acids.

Flax products have been reintroduced in new configurations in the bio-composites arena, for building materials, vehicles, aircraft and furniture, as well as in the medical sector which is an achievement. Blackburn [1] notes the importance and impact of the development of synthetic chemical products for composites used in large amounts of products, and he points out the issues and concerns surrounding these non-degradable composites, made from non-renewable resources, which are consuming remaining oil resources. There is a move towards bio-composites based on natural fibres such as flax, jute and hemp, which are lightweight, strong, resistant to corrosion, and have good sound and moisture absorption. In order to define a material as 'biodegradable', it must be able to be 'broken down into simpler substances (elements and compounds) by a naturally occurring decomposer. For material to be regarded as 'bio' the full cradle-to-cradle lifecycle of the fibre or

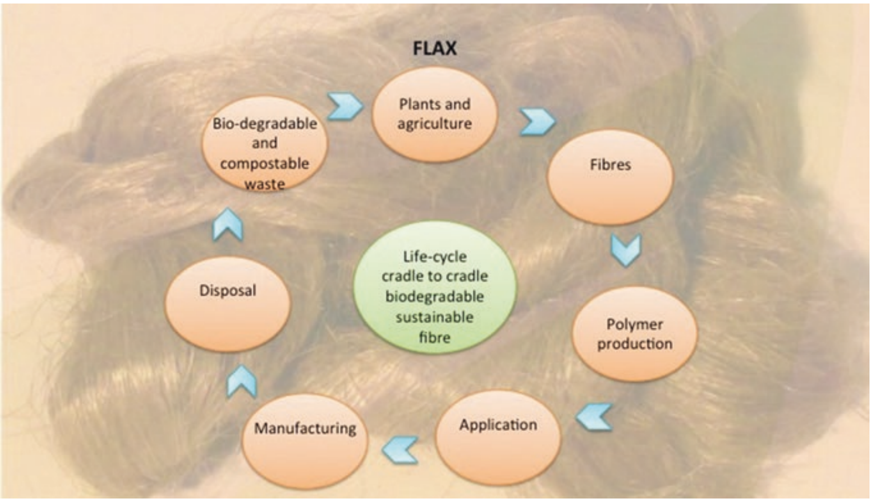

Fig. 1 Flax biodegradable fibre lifecycle (© August 2014, with kind permission of Carolyn Watt, University of Portsmouth, UK)

product must be taken into consideration (see Fig. 1). Innovative flax fibre applications are only now becoming apparent. For example, extremely diverse bio-composites can be mixed with natural fibres and/or coated in a variety of bio-resins to create a spectrum of new composite materials and applications for new luxury premium products with a cradle-to-cradle transparent supply and disposal chain.

1.1 ProjectFlax

To understand and address the issue of best practice production and consumption of materials, a multi-faceted approach is needed to inform all areas of the supply chain—the combination of arts and science collaborations enrich the research process and outcomes. ProjectFlax illustrates this approach by bringing together a transdisciplinary team of regional research centers in materials (Le Havre University, France); biomaterials, food processing and design (University of Brighton, UK); a small and medium sized enterprise (SME) (Liniere de Bosc Novel S.A, France) with experience in growing and manufacturing flax fibers and in the research and development of flax-based products; and academics with extensive expertise in biochemistry and characterization of flax materials (Rouen University, France). The partners were selected as they have complementary expertise in design, science, technology, engineering, mathematics and business (D-STEM-B) skills, as well as having advanced machinery and processing facilities used in the growing and manufacturing of flax.

The proposition that sustainability and social responsibility are key themes of new luxury are underpinned by the ProjectFlax research community, methods and development outcomes, suggesting that sustainability 'is rapidly becoming an issue of critical importance for designers and society as a whole' [24: 72]. Sustainability is not purely about sustainable environments, material goods and manufacturing, but also about developing and promoting wellbeing for people and communities to enhance quality of life. The consumer needs to identify not only with the narrative, but also with others in order to make sustainable choices. Johnson [11], a writer, speaker and freelance consultant specialising in behavioural change, sustainability and social innovation, argues that in order to change peoples' behavior surrounding sustainability it must hold meaning within their personal life. This view is further supported by Cox and Beland [4: 307]: 'The concept of sustainability suggests a growing concern for the long-term consequences of decisions, and it implies an increasing dissatisfaction with current practices'. Consumers are taking meaning from materials and product production, to give new values to goods and, in doing so, are beginning to understand the origins and ethics of products' journeys in terms of people, profit and planet.

The British and French artistic and scientific communities involved in ProjectFlax were brought together through the development knowledge exchange, new working methods, dialogues, and scholarly and practical materials development and process outputs, to successfully answer the project objective, which was to increase the value of flax for society. The team was able to learn from one another's research design, adding value to their own disciplinary practice and, in turn, took a holistic approach to the work over the project's three year period. Johnson [11] observes:

> If we are to effectively drive behavioural change, we need to locate our issue within people's existing value sets and priorities, rather than seek to extend their values sets to encompass our issue… Culturally, sustainability is a scientific issue and most behaviour change work is built on the assumption that people will attach as much importance to climate change, species diversity and resource depletion as the scientists do. It is essential therefore that when it comes to consumer behaviour change, we take their lives not our issue as a starting point.

It was therefore imperative to take not only a scientific approach to increasing the value of flax fiber, but a holistic approach incorporating the arts and humanities where applied research skills in packaging materials design, materials chemistry, engineering and characterization and analysis, biomaterials, food, fashion and environmental impact assessment tools were available. With a focus on transdisciplinary design research and collaborative working, ProjectFlax highlighted the importance of the use of transferable skills for applications of wellbeing and product design to give added value to the producer and consumer, contributing to a more authentic, transparent, effective and sustainable industry in the long term.

The resurrection of flax through the exploration of qualities such as its sustainable and wellbeing credentials offers the market a new form of desire and need. Innovation, research and development of the fibre properties of flax from the molecular scale to products and environmental impact shows advantages, such as sustainability, over many of its natural and man-made rivals, which underpins our proposal of flax being a fibre central to the new luxury concept. Now, a contemporary view of flax is emerging and will become part of new luxury answering the needs of a new generation of consumers looking for quality, craftsmanship and societal benefit. The knowing consumer buys into a subcultural brand where he/she recognizes other knowing consumers from the same intelligent tribe. This chapter comprises selected case studies originating from transdisciplinary research undertaken as part of ProjectFlax. It aims to prove innovative applications for the flax fiber, to add to its cultural and societal value alongside its physical applications, situating it as part of new luxury.

2 Methodology

Using a holistic transdisciplinary approach among arts, science and business, the international ProjectFlax research team of 20 was able to use and share a range of research methodologies from their own disciplines to investigate numerous lines of enquiry, focusing on the concept of materials development from flax, resulting in a complex mixed method approach. The science methodologies combined case study, desk-based, laboratory, field study and quantitative methods involving collaboration with national and international organisations, both commercial and institutional. From arts they included narrative and observation, qualitative methodology, practice-based and practice-led studio and workshop research to push the aims and objectives and results as far as possible within the time and funds available. Dialogue between the disciplines around the findings and innovation was difficult at times due to the different languages and the disciplines used, such as chemical equations versus design drawing. Knowledge transfer and knowledge exchange in the UK and France played a key part in the studio, workshop collaboration and created new and innovative networks for research and development which have been sustained long after the project ended. The team published in a variety of scientific journals and the work was showcased at symposia and exhibitions in the UK, France and the 7th Textile and Bioengineering and Informatics Symposium, August 2014, Hong Kong.

The goal of the research was to restore the cultural and societal value of flax in its various applications through the concept of *new luxury*. The rationale behind the partnership was envisioned by Professor Sergey Mikhalovsky, materials chemist and principal investigator from the School of Pharmacy and Biomolecular Science at the University of Brighton, UK. Mikhalovsky realised that the interconnectedness of the flax supply chain, its history and chemistry, its significance in nature and the underlying sustainable narrative linked to product development would need a team with critical differences in their approaches from arts and science to innovate and think freely. The team was transdisciplinary in composition, including bio, polymer and materials chemists, agriculturalists, business, product and materials designers, professors, research fellows, post docs, post graduates and undergraduates. Transdisciplinarity was introduced to the public by the Swiss philosopher and psychologist [20] who addressed the issue of relationships between disciplines in an academic context, purporting the notion of transdisciplinarity to create chemistry between unrelated disciplines that enable investigations and opportunities for collaboration in a third space beyond their respective contributions. ProjectFlax brought together different disciplines to create a range of approaches and solutions to environmental and human problems in order to develop ecological products and thus support the notion of an emerging new luxury based on product integrity.

3 Flax Applications

3.1 Flax in Fashion: Ethical, Responsible and Sustainable Clothing as New Luxury

The contemporary fashion and textiles industry has suffered from the emergence of ‘fast fashion’ where the retail mantra of ‘pile it high, sell it cheap’ clothing has created vast quantities of textiles waste [9]. It can also be argued that designer and luxury goods have suffered from the mass production of sophisticated counterfeit products and have achieved a throwaway status [21]. So how can designers, engineers and manufacturers differentiate their products and reinstate brand identity in the global marketplace? Brand differentiation, as is evidenced in the food industry, can come from responsible transparent ethical production, and manufacturing coupled with superior quality; therefore, in relation to flax, its history, innovative product possibilities and sustainable credentials are the essential qualities which underpin the concept of new luxury in future, imbibing products with a raft of values and differentiating these intelligent luxury brands from those of the past.

> Within the context of the contemporary global economic recession, our consumption of luxury is being questioned and indeed transformed with the notions of ‘affordable luxury’, ‘sustainable luxury’ and even ‘luxury for less’ suggesting a new discourse. At the same time the demand for luxury goods and services on a global scale is at an unprecedented level [6].

It is this concept of flax being an example of sustainable luxury when assessed from a socio-ecological-aesthetic-economic viewpoint, which places it at the forefront of a paradigm shift in the luxury market where sustainability is we argue the new luxury.

The luxury goods industry was worth an ‘estimated €217 billion ($300 billion) in 2013’ [19] encompassing clothes, leather goods, watches, jewelry, perfume and cosmetics where expensive items convey status to those who recognize the goods. Still the way we dress reflects our personality, our economic political and social standing and our status within our peer group, setting us apart from the crowd, defining us through our outward appearance, establishing a means of recognition and of signaling to others like ourselves, epitomized in luxury fashion. Christian Dior, considered by fashion scholars to be an iconic designer of modern fashion said

> I am no philosopher but it seems to me that women and men instinctively like to exhibit themselves, which in this machine age, which esteems convention and uniformity, fashion is the ultimate refuge of the human and personal and the inimitable [22].

During the twentieth century, economic prosperity for many in the developed world propelled the desire for luxury consumption and the global market for branded goods grew exponentially. However, this century has seen the position of the luxury brand shifting in its value and narrative, not least due to the concerns of a new generation of consumers who are aware that over production and consumption of goods, financial inequity and environmental degradation are uppermost. The Internet has enabled brand transparency and information exchange in the market and, in the case of traditional luxury materials, the production problems, such as water table pollution in processing of leather or, in fur farming, animal cruelty or trapping endangered species such as big cats, have brought the luxury market and its non-monetary value into disrepute. In addition, the manufacture of fine goods such as beading and embroidery, often produced by hand, in a supply chain where processes and labor conditions can be difficult to monitor, remain an issue.

The purpose of this chapter was to reflect upon the future of the luxury brand and premium materials market in the light of the falling numbers of traditional customers who appreciate and invest in old luxury goods. The question is how would this market develop as the consumer becomes more discerning, intelligent and aware of sustainable issues i.e. people profit and planet and where aesthetics and exclusivity, repeated in every luxury brand store in cities across the globe, and are no longer enough to maintain customer loyalty and sustain sales, except perhaps in successful new economies? Regarding the burgeoning of the luxury goods brand businesses globally, Tom Ford, known for his turnaround of Gucci, says about luxury:

> It is like McDonald's: the merchandising and philosophy behind it is very similar. You get the same hamburger and the same experience in every McDonald's. Same with Vuitton. We helped to create that at Gucci. It was the right thing at the right time… And it's foolish to think that customers are not going to tune out, that they aren't as bored with it as we [the designers] are [22].

As in the retail sector, the recent twentieth century in the textile industry has undergone a significant transition. The market has polarized into cheap mass-market goods on the one hand, through to high-quality products on the other. The new research and development arena is in the transition from basic or luxury functions of those materials to those with specialized narratives and/or multifunctions to attract the intelligent consumer. The objectives of these high-quality narrative textiles, have resulted in the facilitation of a paradigm shift from traditional passive textile products into active textiles, which are able to interact with the consumer from a sustainable point of view.

> Linen has written itself into the ambitions of the luxury industry regarding sustainable development (the protection and development of the sources of high-quality raw

materials, and to protecting and preserving knowledge), and of design, fashion, interiors, soft furnishings, and the contract sector [15].

Sustainability is the new luxury when located in the flax narrative, the benefits of which are easily communicated to the consumer by the brand with honest authenticity. New farm mechanization and technical developments in processing of the fiber, yarn and textiles have improved and refined the materials for a wide range of high value markets. Understanding flax's technical properties through research and development made higher quality, defect-free textiles possible, which were wear resistant. The hollow fibers created textiles that breathed and provided installation in any season, regulating the body temperature in the summer as the fibers could absorb 20 % of its dry weight in moisture without feeling damp, and yet were comfortable in the winter. In addition, flax has non-allergenic and antibacterial properties (some surgical sutures are made of flax), antistatic properties, does not attract dust and is naturally resistant to moths and mildew. The fiber takes and fixes colour well, which improves and often deepens in tone as the fabric wears and the central cores of the fibers are exposed. Flax has an affinity for dyes requiring a minimum amount of dyestuffs and development of low-impact reactive dyes and fabric finishes such as wrinkle resistant treatments and enzyme finishes which respond to the demand for eco-designed textiles has been a priority, achieving OEKO TEX and GOTS accreditation [2].

In Europe the plant is sewn between March and April, taking 100 days to reach maturity; the blue flowers bloom in June and last for one day. The plant consists of a single stalk, about a meter high, from which 80 to 100 leaves sprout. It has equally long roots and is 100 % biodegradable. When flax is harvested it is not cut but pulled out of the ground so as to preserve the full length of the fibers contained in that stalk. In June to July, when the third of the length of the stocks have lost their leaves, it is pulled and laid on the ground in swathes or rows, one meter wide. The first processing, termed retting, is a natural biodegradation process of the stalks using wind and rain. The application of rain and sunshine from July to September, and the combined action of microorganisms and bacteria naturally present in the soil, ensure the fermentation needed to separate the textile fibers from the woody part of the stalk in the most sustainable and natural process. The fibers are extracted from the stalks' external envelope and the wood at the centre of the stalk is removed (called the shave). After harvesting, the long roots that have remained in the ground fertilize the soil and make it healthier, thereby giving flax its reputation as an excellent soil improver. Renewed in rotation every six to seven years, flax farming produces optimal soil quality, therefore increasing returns on the following crops of up to 20–30 %. The next step, scotching, is an entirely mechanical process that takes place throughout the year. During this process, the two types of fiber are separated, the long fibers (line flax) and the short fibers (the toe), as well as the by-products including the shave. Flax is also a carbon sink as, during its growth, the flax plant absorbs CO_2 released into the atmosphere where 1 ha of flax retains 3.7 metric tons of CO_2 annually, on a European scale this equates to 450,000 tons of carbon pollution avoided through this farming contribution. Reduction in greenhouse gas emissions meets the requirements of the European Union and the Common Agricultural Policy, which promote a green Europe and fulfils another green requirement, as it is an economic plant when it comes to water consumption. Flax is grown in countries with the temperate climate, so it requires no irrigation – just rain. Natural resources are sufficient to feed the plant, this needs little nitrogen, little cultivation, and requires very little input put of fertilizers and pesticide products to preserve its natural resistance. Compared with cotton, for example, flax requires five times less input also preserving the quality of groundwater. Flax is a zero waste fiber where everything is either used or processed for textiles, paper, matting, flax seeds, oil, varnishes, linoleum, gardening installation, animal litter, compost and beauty products. The fiber and its derivatives are an ideal material for developing high-performance bio composite and for medical applications, all products made from it can be recycled and it is 100 % renewable. Quality linen handle improves in suppleness and softness the more it is washed because the pectin that binds the fibers in the growing phase dissolve more every time it comes into contact with water; therefore, the fabric becomes gradually a luxurious material as it ages and, as it is the strongest natural textile fiber, it is long-lasting.

Traditionally flax was a luxury fiber, sought-after by the aristocracy 'put bussos around her limbs, prepare her bed with royal linen pay attention to the white linen of the lingerie' [23] this fabric known as bussos was cited in The International Standard Bible Encyclopedia which denoted a variety of flax, where the cloth woven from it was very delicate, soft white or yellow and very expensive due to the effort and time involved in growing, processing, spinning and weaving the material by hand. The cloth was highly sought-after and produced in the Nile Valley, it was known for its extreme fineness, which played a key part in Egypt's economy, because like grain it was used as currency.

The Chairman of the Comité Colbert, [15] said of linen:

> Know-how and its transfer from generation to generation are the very foundations of the luxury industry. A living heritage that we nurture, either through essential on-going training of the artisans… or by acquiring other highly qualified businesses or workshops (as Chanel has done several times).

Linen is also a premium material in that it is a natural polymer and evidence exists that it was used in one of the first composites found in the armor of Alexander the great 256–2323 BCDE (Duval 2009). Layers of laminated linen cloth (Pliny) enabled mobility on the battlefield and was made of 11–20 layers of linen fused with a linseed oil based bonding agent and compressed during the dying process with performance factors similar to that of Kevlar. Flax compares with glass and carbon: in stiffness, they are equal to glass and about a third of carbon but, when the density is taken into account, flax performs better than glass fiber. Furthermore, when looking at the specific stiffness in bending, the values of flax approach source of carbon fibers [2].

Linen spun from flax is a lustrous material with a soft, flexible handle and can be woven into superfine decorative and functional fabrics. Linen is considered to be superior to, and more durable and sophisticated than, cotton and remains an expensive status symbol understood by affluent consumers who value its characteristics and green credentials, and recognize and appreciate others who wear it and belong to the same 'club'.

Linus in Latin means *most useful flax* and the scientific name emphasizes just how much the plant was respected, providing soil improvement, natural biodiversity, materials, food and more; it is a plant with societal, environmental and economic credentials, steeped in history. Nevertheless, even though linen is synonymous with particular contemporary labels (such as Armani Italy) and does well if the trend is right or it is seen on catwalks as a sophisticated fashion classic, its market share is diminishing except for predicted growth until 2020 in the BRIC countries (Russia, India and China). There is a luxury business opportunity to develop high quality limited edition products for those consumers who understand its sophisticated message, which set them apart from the rest. It is not unimaginable to have a whole store, e.g. 'The Flax Shop', with products developed entirely from a sustainable source such as flax. These signs denote and communicate an understanding of a narrative and meaning of the material, which are key components of, and define, the new luxury concept and consumer. Importantly, as consumers become increasingly aware of green issues and desire products produced by best practice, the brand name may become less important as the material and its production credentials from a sustainable point of view, become the new luxurious 'must have'.

3.2 Flax in Agriculture: Food and Medicine Become New Luxury

Flax is not only a source of fibre for fabrics and composites but the plant also has a long history in the food and pharmaceutical industries. Today, cold-pressed flaxseed oil and ground flax seeds are increasingly sold as health foods as awareness of health issues such as obesity and diabetes drive us towards healthy eating and improved lifestyles. The perception of eating a natural diet, with plenty of whole foods and organic produce, is quickly becoming the new luxury in food terms, creating a hierarchy of consumption and price when compared with those who use cheaper, pre-packaged and processed, and mass produced food. One of the ingredients attracting the most interest is polyunsaturated fatty acids (omega 3, 6 and 9), which have anti-oxidant effects with a potential to protect cells from the free radicals generated through metabolic processes. Flax has an exceptionally high lignin content, the principle one being secoisolariciresinol diglucoside (SDG) which acts in a similar way to omega fatty acids. It has been suggested that SDG has beneficial hormone-modulating qualities that could prevent tumor formation and prevent the generation of new blood vessels in existing tumors. Like polyunsaturated acids, SDG can also quench cell-damaging free radicals. Flax seed can be added to most foods in cooking in various forms to increase its nutritional value, due to these qualities which will enhance human and livestock feed, markets for flax seed are 'expected to increase owing to the unique properties of this ancient crop' [17: 889].

Research developed as part of ProjectFlax in the UK on lignin produced from flax seed has shown that the component SDG is non-toxic to renal cells in the flax plant (the most sensitive to extraneous factors) in a laboratory model. Professor Mikhalovsky (School of Pharmacy and Biomolecular Sciences, University of Brighton) is currently investigating whether SDG could protect cells when they are exposed to the destructive effects of free radicals, which can lead to disease. In addition, encouraging data from the project has demonstrated the inhibition of autophagy in hela (tumour) cells in the laboratory by SDG. Autophagy is a mechanism whereby cells induce their own enzyme-mediated digestion. In normal circumstances this process can prevent the onset of disease (e.g. cancer) by removing abnormal cells from the body. However, in established tumour cells, autophagy can compromise drug treatments by shielding neighbouring tumour cells from chemotherapeutic drugs. Thus, careful targeting of anti-autophagic agents (such as SDG) could assist in anti-tumour chemotherapy. Currently, chloroquine (a drug used in the treatment of malaria) is being tested in clinical trials for this purpose. However, SDG may be more effective since it is able to block autophagy at two different stages of the process compared with one for chloroquine. Researchers have also shown that SDG from flax is an efficient binder of metals. Using mass spectrometry to elucidate binding constants for SDG against target metals, Dr Flavia Fucussii's findings (School of Pharmacy and Biomolecular Sciences, University of Brighton) indicate that dietary flax SDG could have sufficient metal affinity properties for extracting accumulated toxic heavy metals from the body, such as lead, mercury and aluminium. Toxic heavy metals are suspected of causing a variety of threatening conditions including thyroid issues, heart disease, neurological conditions and autism. The inclusion of flax in a nutritionally-balanced diet could therefore have a number of health benefits.

3.3 *Flax in Wellbeing: A Return to Natural Healing Materials as New Luxury*

Another area for ProjectFlax has been to evaluate the potential of the flax plant using innovative fabrics, materials and coatings for 'smart textile' applications. Smart materials are ever more apparent through responsive and adaptive fibres, combined with technology employed to monitor vital signs. These fabrics have a multitude of functions such as communicating data, processing information, sensory functions in healthcare, and fabrics that carry medicine, restrict and control pressure on limbs, and can be used internally in the body as a scaffold. In hospital textiles, flax has many applications for implants, tissue engineering, hygiene and healthcare products, packaging, bandages and wound dressings, hospital sheets and staff uniforms. ‘As the global population continues to increase, the prevailing demographic profile moves towards great life expectancy and an ageing populace whose expectations for enhanced healthcare continue to grow’ [13: 4]. Previously, smart and performance textiles were developed through space and military research; however, there is an increasing market for these innovations in the civilian population.

Within ProjectFlax, pharmacy and biomolecular sciences research teams at the University of Brighton, led by Dr Iain Allan, found that when flax seeds are exposed to fluids they have the fascinating property of exuding copious amounts of gel-like mucilage, which is a diverse mixture of polysaccharides and proteins, quite similar in nature to human mucus. Mucilage possesses an abundance of charged groups of a molecule within its structure, which makes it a good candidate for loading with chemotherapeutic drugs (with opposing charge), which can be slowly released at a liquefied appropriate target site within the body. The research team has focused on the creation of mechanically stable mucilage hydrogels, which can be loaded with active agents such as antimicrobial agents or anti-inflammatories (Fig. 2). Such gels can be applied to the mucosa (e.g. oral or vaginal) to deliver a slow-release chemotherapeutic dose. This could provide direct therapy to damaged mucosa and also offers the capability to deliver drugs systemically, bypassing the liver.

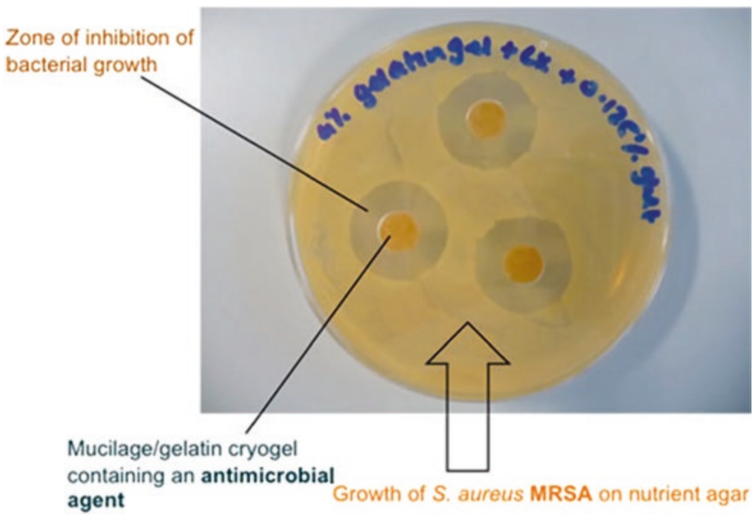

Fig. 2 Demonstrates the ability of an antimicrobial agent to diffuse from the gels and prevent bacterial growth (shown by the clear zone surrounding the gels created from flax mucilage) (© Spring 2012, with kind permission of Dr Iain Allan, School of Pharmacy and Biomolecular Sciences, University of Brighton, UK)

Mechanically stable mucilage-containing gels in the form of cryogels are highly absorbent, interconnected structures with a sponge-like morphology that are formed by freezing a pre-gel formulation. As illustrated in Fig. 3, this sponge-like gel has a porous structure, with the pore walls here represented in yellow. The mucilage portion of the wall can bind antimicrobial agents, which will be controllably released at the wound site. Mucilage cryogels have a number of potential applications. These cross-linked materials have good mechanical properties enabling their make up to take the form of a patch (Fig. 4) that when applied can closely follow the contours of the skin. The patches can be infused with active drugs; their highly porous nature also provides an ideal environment for infiltration with human cells. Current work at the School of Pharmacy and Biomolecular Sciences, University of Brighton, includes evaluating the patches and cryogels for use as dermal tissue regeneration scaffolds. These can potentially be used to treat burns victims and reconstruct skin damaged by chronic ulcers. The intention is to screen the cryogels and woven textiles as carriers for application to the skin surface.

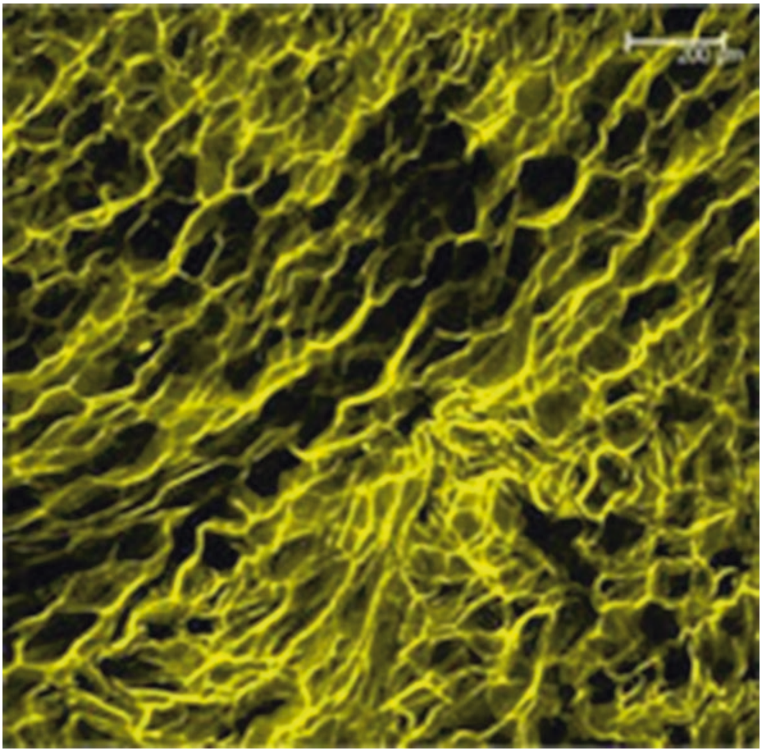

Fig. 3 A confocal laser scanning microscopy image of a mucilage/gelatin cryogel (© Spring 2012, with kind permission of Dr Iain Allan, School of Pharmacy and Biomolecular Sciences, University of Brighton, UK)

Fig. 4 A prototype mucilage/gelatin hydrogel patch (© Spring 2012, with kind permission of Dr Iain Allan, School of Pharmacy and Biomolecular Sciences, University of Brighton, UK)

These cryogel films were inserted into, and combined with, knitted and woven fabric structures (Fig. 5) with the aim of creating wound dressings with antimicrobial agents. Research has taken place into the infusion of flax fibres with antimicrobial agents for the production of wound dressings. Flax fibres have a porous structure, with absorption and strength properties superior to those of cotton,

Fig. 5 Knitted cryogel sample (© March 2014, image by Carolyn Watt, with kind permission of Sophie Forster, MDes Knitwear student, University of Brighton)

ensuring maximum efficacy when the antimicrobial agent chlorhexidine was added to flax fibres and allowed to penetrate into the fibre pores. After thorough rinsing, the fibres were found to have been saturated with both bacteriostatic and bactericidal activity against *Staphylococcus aureus* and *Pseudomonas aeruginosa*, two key bacteria responsible for serious infections. There is a growing concern that antibiotics are losing their potency. A recent World Health Organization report [25], *Antimicrobial resistance: Global report on surveillance 2014*, has revealed that antibiotic resistant bacteria pose a 'serious, worldwide threat to public health' and urges that we need to 'take significant actions to improve efforts to prevent infections'. *Staphylococcus aureus* is a bacteria that can cause potentially life-threatening local and systemic infections. Methicillin-resistant *S. aureus* (more commonly known as MRSA) is well known as a principal cause of hospital-acquired infection characterised by broad-spectrum antibiotic resistance. The Centres for Disease Control and Prevention [3] state that 'people who have MRSA germs on their skin or who are infected with MRSA may be able to spread the germ to other people. MRSA can be passed on to bed linens, bed rails, bathroom fixtures and medical equipment'.

Photodynamic therapy (PDT) is a potential alternative to antibiotic therapy and is being investigated as a treatment for antibiotic-resistant bacterial infections. PDT combines the application of a non-toxic photosensitive dye with exposure to light of a specific wavelength, resulting in the generation of reactive oxygen species, which are lethal to bacterial cells. In research and development, the ProjectFlax team has demonstrated that dyed flax fibres can successfully be used for lethal photosensitisation of drug-resistant bacteria. Flax fibres were autoclaved,[2] soaked overnight in metachromatic dye toluidine blue O (TBO) and dried. The flax fibre is able to absorb these light sensitive dyes with a greater capacity than cotton, the most commonly used material. The fibres were then exposed to MRSA so that the bacteria adhered to the outside of the fibre. The fibres were exposed to red light for one hour. Exposure of TBO-infused fibres to light resulted in a 99 % reduction in bacterial viability of MRSA. No antibacterial effect was found when flax fibres dyed with TBO were kept in the dark, or when fibres were exposed to light in the absence of TBO. The microbial burden on natural fibres, such as those found in bed linens, could be reduced by infusing them with photosensitising agents and exposing them to a controlled light regime. This application could reduce bacterial contamination and infection on bed linen and patients' clothing. Ultimately, these materials could shorten the time required for recovery of patients, so reducing the financial burden on healthcare providers and improving quality of life for patients. This case study illustrates added value design for the consumer, contributing to improved outcomes for health and wellbeing to the end user. By building on traditional health applications of flax, the fibre is modernised for today's healthcare challenges.

[2]An autoclave is a pressure chamber used to sterilise equipment and supplies by subjecting them to high pressure saturated steam at 121 °C (249 °F) for around 15–20 min, depending on the size of the load and the contents.

The use of flax in healthcare is not only innovative, but also sustainable. Transdisciplinary methodology and collaborative working within ProjectFlax was necessary in order to develop such medical applications. Like the health food and fashion and textile industries, there is a growing movement towards naturally-derived and sustainable materials within medicine, proving flax to be the new luxury across each of these fields.

3.4 Flax in Design: The Results of Innovation in Addressing Physical and Cultural Issues as New Luxury

New luxury embodies the concept of closed loop design, with an energy efficient and zero waste manufacturing, retail and disposal chain, and where environmental and human ethics are fundamental, to create a circular economy through a holistic supply, production and disposal approach. The role of design, underpinned by arts and design education, is fundamental to the notion of new luxury, combining sustainable philosophies where the informed designer, who creates the desire for a luxury product, could contribute to societal change by having a deeper knowledge of, and make better choices in, materials, processes and economics.

Farrer and Finn [7: 36] observe: 'Fashion textiles design has much to answer for in contributing to the problems of unsustainable practices in design, production and waste on a global scale'. This is due to designers fueling the desire and need for customers to constantly buy more fashion garments, which are often quickly discarded, in good materials at ever cheaper prices. 'However, designers within this field also have great potential to use their extensive skills to contribute to practical solutions' [7: 36–37].

The role of the designer is critical, as often the problem or issue is the result of poor design. Thus, solutions to unsustainable practices can be 'designed into' a self-sustaining supply and demand model, communicating the issue but also the solution to the end user. For example, we should use the luxury food industry as a model, where in organic sustainable farming all parts of a slaughtered animal and its by-products are used. Thus, luxury food producers have realized that there is a philosophical brand narrative to promote value and market differentiation and secure consumer loyalty. So, too, new luxury can be defined by sustainable practices appealing to a new type of consumer, one who relates to a holistic, and zero waste, circular economy production process which defines the new luxury concept. Flax fiber has the credentials for this new luxury profile. Product and medical materials innovation using flax may encourage the exploration and exploitation of this material in a range of applications developed through design, engineering, chemical and agricultural technologies.

New luxury also takes into account designing for the appropriate product lifetime. Fashion, by definition, creates built-in obsolescence and waste, visible in the 'churn' of new products in retail which is a direct result of over manufacturing of goods for an unsatisfied consumer, often using long lasting oil-based materials or natural materials unethically produced, with their associated adverse environmental impacts. How can this be termed luxury? Whereas using a sustainable, organic fiber such as flax, which has a light ecological footprint in processing and is a versatile research and development material for the body and built environment could define a new consumer and new luxury. Flax fibre has been used in products for health, sport, wellbeing and leisure, in the automotive industry as well as in the design and conception of both interior and exterior cladding and soundproofing for buildings. The material can be allowed to biodegrade when no longer required or can survive for centuries, should the application require, this is the new luxury with a value added product lifecycle that discerning consumers seek. According to Wahl and Baxter [24: 82]: ‘The necessary shift towards more appropriate and sustainable modes of participation requires that design and education contribute to a widespread increase in social and ecological awareness through trans-disciplinary design dialogues’. Innovation in education enables practical and holistic solutions to be discovered.

3.4.1 ProjectFlax Design Competition

Flax fibre is now being re-examined and contemporised by designers and scientists in order to meet the demands of modern culture and is illustrated through work undertaken by staff and students at Le Havre University, Rouen, France and University of Brighton, UK. The staff and student participants in ProjectFlax, showcased in this section, were from fashion and textiles, design and craft, engineering, pharmacy and biomolecular sciences and agricultural disciplines.

In January 2011, University of Brighton students from the fashion and textiles, design and craft courses within the Faculty of Arts, and from the Schools of Environmental Engineering and Pharmacy and Biomolecular Sciences competed in a flax competition and were given a brief by the co-investigator and first author of this chapter: ‘It is the year 2050. Resources are scarce. Sustainable materials are at the heart of our existence…’. The students were asked to develop a range of materials using flax fibers, fabrics and resins in various forms for any applications for ‘blue sky thinking’ conceptual ideas, with the potential to develop products, functions or services, real or virtual for the flax fiber. The relevance of the brief to the various disciplines was to create a community of learners who will spearhead the new luxury market underpinned by sustainable design principles [8].

The successful integration of this live teaching project within the curriculum in 2011 enabled a change in educational approach and discourse, with a view to curriculum development and teaching in the community of learners. Textile design students worked with team members from science and arts from the University of Brighton to combine the sustainable and nutritional benefits of the flax plant into a complete range of packaged foods. The competition allowed students to consider materials and fibers outside of their discipline of textiles and to act as a catalyst in teams outside their comfort zone. Combining the idea of bio-plastics, resins and flax's health benefits, the students' winning concept, 'Nature's Shell', consisted of edible packaging aimed at adult snacks, microwavable meals and the three stages of weaning in toddlers and preschool age children (Fig. 6).

In 2012, the ProjectFlax competition ran again and the winning student team created an entire brand named 'Flax Pack', which captured the versatility of flax fibers in product design (Fig. 7), leading to a more sustainable range for the music festival-going audience. This project targeted food packaging and edible products, but also biodegradable tents, chairs and ponchos, simultaneously addressing the issue of the huge amount of waste generated at festivals in fashion, textiles, composites, foodstuffs and agricultural impacts. These students, as future designers, expressed their view of the new luxury, and were able to modernize the use of flax fiber in order to meet today's cultural and societal expectations.

In 2013, the competition was integrated with the subsequent INTERREG project Building Research and Innovation Deals in the Green Economy (BRIDGE) and was open to University of Brighton students across the two disciplines: design and craft; and fashion and textiles. The winning project focused on new luxury, with an emphasis on closed loop manufacturing in a particular rural geographical location, centred on sustainable dye processing and waste issues from the wine-making industry.

Fig. 6 'Nature's Shell' poster concept by Carolyn Watt (© January 2011, with kind permission of Carolyn Watt, University of Portsmouth, UK)

Fig. 7 'Flax Pack' student project example (© January 2012, with kind permission of University of Brighton student team)

3.4.2 Undergraduate Module

ProjectFlax informed the undergraduate module entitled 'Material and its Form—Flax 2012'. In this module students were able to work with flax fiber in order to find new material methods and applications for flax in woven form. Their methods ranged from cutting, tearing, burning, immersing in water and freezing techniques, combined with the use of resins and glue mixes exploring molding and stiffening of the fabric. Many of the conceptual results were realized through the use of computer aided design (CAD) and hand drawn designs. Many students integrated the use of sewing techniques and traditional craft-making methods, resulting in architectural temporary shelters and protective material designs that pushed flax fibers and fabrics to their limits. Layered flax fibre was resistant to piercing and fabrics were extensively tested, using glues to heighten the rigidity of the material. Taking inspiration from Mongolian outerwear lined with waste flax, wool and linen as body protection, a winning project developed the material concept of flax as a sustainable alternative to the synthetic fibre Kevlar®. The designer created a prototype garment and tested its stab proof properties.

ProjectFlax offered students the opportunity to share knowledge, ideas and techniques in open discussions and tutoring sessions with peers and staff members from a variety of disciplines. This created a new experience for students to experiment with new materials and ideas in order to increase the value of flax and raise awareness of design issues surrounding sustainability.

3.4.3 Furniture Design

Driven by a motivation to design products based on ecologically sound principles of material selection and production, Dr Jyri Kermik, lead academic at the University of Brighton in the Department of Design, was involved latterly in ProjectFlax, investigating cultural archetypes and regional material resources to facilitate new luxury in design innovation. Kermik's international design presence is founded on expertise in materials technology, sustainable and environmental concerns, and experimental design applications. His research developed a new material composite prototype which he called PlyFlax. This combined fine plywood bonded with flax fabric, vacuum formed into an organic furniture design using minimal materials. This ecological flax material research project and chair design began with an exclusive invitation to contribute to the sustainable international 2012 EcoDesign show held as part of Helsinki Design Week and World Design Capital 2012, which offered a key meeting point and showcase for the design community. Kermik's research into flax and plywood experiments aimed to demonstrate the potential of regionally grown natural fibers for future design applications. This combined the advantages of composites with the enhanced performance of 'stressed skin' structures normally associated with material innovation in early aviation, led in Europe by the Estonian manufacturer Luterma. Interlocked layers of birch veneer, with their own inherent structural strength, are further reinforced with a skin of flax fibers allowing thinner plywood shells without compromising their strength or flexibility. Flax fibers, woven into a fabric sheet, perform in a similar way to glass/carbon fibers. The strength and viscous-elastic properties of natural fibers, and their visual quality, are captured and embedded within a matrix of bio-resin, a type of biodegradable glue made from organic components including flax. The ergonomic concept of the 'Woven Wind' (Fig. 8) expresses a design metaphor adopted from Japan, where flax is referred

Fig. 8 'Woven Wind' (© Summer 2012, with kind permission of Dr Jyri Kermik, University of Brighton, UK)

to as that which encapsulates both the sustainable qualities of the materials used as well as the natural movements of the materials used in the construction of the PlyFlax recliner, explored during the design process.

4 Conclusion

The chapter tells the narrative of the flax fibre, its importance through history as a valuable crop for materials for the body and built environment, using ProjectFlax as the focus for an international and transdisciplinary research and redevelopment team which aimed to reposition flax as a premium and new luxury fibre for the future. Through discussion of a selection of case studies from the UK and France, during the three year project the flax research team generated an array of innovation possibilities relating to arts and science applications for economic development. These were high value tailor-made inventions for both human and environmental wellbeing, underpinned by the sustainable agenda of people, profit and planet. Flax R&D was discussed in relation to the design of ethical, responsible and sustainable clothing, leading to the notion that these philosophies would define new luxury. Flax in agriculture reinforced the idea that foods and natural effective medicines would become new luxury at a price and, seeing a return to natural healing materials, flax will be viewed as new luxury from a D-STEM-B combined applied research innovation perspective. Finally, flax in design shows the results of innovation in addressing physical and cultural issues as new luxury.

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Great Potential of Stinging Nettle for Sustainable Textile and Fashion

Sanjoy Debnath

Abstract Nettle is a common herbaceous plant, which regroups 30–45 species. It is part of the Urticaceae family such as ramie (Asian nettle, *Boehmeria nivea*) and belongs to the genus Urtica. The stinging nettle (*Urtica Dioica*) is the most prominent species in Europe and Himalayan ranges. This fibre also belongs to an ancient textile fibre. In this chapter deals with different aspects of sustainable process of production of fibre, methods of fibre extraction and their advantages, properties of nettle fibre, products from nettle and its blends. A comprehensive effort has been made to revamp the potentiality of sustainable development of fashionable textile and industrial materials from nettle fibre as well as form its byproducts. Overall, chapter covers various nettle-based handicraft and apparel products for luxury sector and their proper disposal.

Keywords Nettle fibre · Extraction of nettle fibre · Properties of nettle fibre · Sustainable nettle textiles · Application of nettle fibre

1 Introduction: *History, Production, Yield, General Introduction About Luxury Fibre, Utilisation of Fibre, Sustainability,* etc.

Nettle is one of the common herbaceous plants which clusters around 30–45 species. This bast fibrous material is part of the Urticaceae family such as ramie (Asian nettle, *Boehmeria nivea*) and belongs to the genus Urtica. The stinging nettle (*Urtica Dioica*) is the most prominent species in Europe. Since early 77

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BC, nettle fibre has been used for making hand-spun yarn and from it they prepare hand-spun twines using a fly wheel length of 30 cm [1, 2]. In those days, two methods of spinning nettle fibre for netting-lengths were used wherein fibres were coiled into basket pulled out and spun: (a) by rolling on thigh with palm of hand and (b) by using a spindle rotated on the thigh or leg by rolling. These hand-spun twines are used for fishing purposes. Recently, research investigation by Bergfjord et al. [3] established the Lusehøj textile (National Museum of Denmark B26436), found in 1861/2, was wrapped around cremated human remains and placed inside a bronze urn. The fabric is a dense and balanced tabby weave with approximately 16 threads/cm in both thread directions. The yarn is fine and evenly spun, having yarn diameter ranging 0.3–0.5 mm and twist direction of S-twist twist used in both warp and weft. After investigation through different scientific identification studies (scanning electron microscopic, polarised microscopic view and specific chemical test) they confirmed that the fibre used was nettle and it was around 2800 years old (940–750 BC) which matches the typological and contextual dating. Findings also revealed that those nettle fibres were imported from Kärnten-Steiermark region in the south-western area of Austria.

Nettle grows on rich soils and up to 1.20 m high. It has been established that yields and fibre content of originally produced nettle were higher in the third year of cultivation than those achieved before cloning process was adopted in nettle cultivation [4]. The fibre yield ranged 335–411 kg/ha in the second year and from 743 to 1016 kg/ha in the third year. Previously, It has been established that highest strength of nettle fibres falls in the range of the fibre strength of cotton, i.e. 15–50 cN/tex [5].

Baltina and Lapsa [6], scientists from Latvia reported that nettle cultivation in their country produces textile grade fibre. To obtain large number of fibres, special nettle clones from *U. dioica* L. should be used. However, the nettle does not require planting every year, rather it can be grown for several years. The obtained yield of fibre is less than that of flax and hemp. The bast content in nettle straws is about 20 % and it is less than in flax and hemp. The fibre strength varies in a wide range and has greater unevenness. The interesting part of the nettle plant is that the longer the plant life, stronger the fibres that can be obtained from them. Moreover, it is not necessary to use wide nettle plant spacing, rather, it decreases the amount of bast content and strength of the fibres.

In India, Uttarakhand, Himalayan nettle, widely available in the wild, is an underutilised biomass product [7]. The durability and eco-friendly nature of nettle fibres extracted from these plants are an added advantage to their versatility for use across seasons. As a natural fibre suitable for both winter and summer garments, Himalayan nettle has been of interest among both lifestyle and sportswear garment manufacturers in the textile industry. Indeed, there is a high export potential for nettle fibres. In the domestic market, multiple uses of nettle make it ideal for the handicrafts sector, which also provides value to the tourism industry. According to the Uttarakhand Bamboo and Fibre Development Board (UBFDB), more than 15,000 tonnes of raw nettle is available in the state [7].

2 Sustainable Fibre Extraction: *Different Methods of Fibre Extraction from Bark, Their Process, Merits and Demerits*

2.1 Extraction Methods of Nettle Fibre

Huang [8] has suggested that the best fibre properties can be obtained after several processes. In this he recommended that after harvesting the green bundled plants are retted for 2 weeks in pond. After this the bast portion can be separated easily from the woody core nettle plant. These retted fibres are unsuitable to produce better spinning performance. They proposed 15 stages involving biological and chemical process for efficient cleaning of nettle fibre from green harvested nettle fibres to process successfully in spinning machinery for yarn preparation. Overall though the process produces well separated nettle fibres with good spinning performances, huge amount of chemicals and steps are involved in making the nettle fibre ready for spinning.

In another study by Dreyer et al. [9], the green nettle plants were retted followed by drying and then fibres separated by mechanical extractor. These mechanically extracted nettle fibres were allowed to treat separately with three different treatments, viz. chemical, enzymatic and steam exploded processes. During comparison of these three treatments, they concluded that the enzymatic process of fibre separation of coarse nettle has good potential for producing fine and strong nettle fibres. Similar amount of fibre separation can be obtained from chemical treatment wherein alkali has been used as a major chemical. They concluded that considering the environmental impact and other related aspects, the enzymatic process is the best among these three methods of fibre separation of nettle fibres whereas the chemical treatment leads to environmental pollution and steam explosion required huge amount of heat energy. Considering the above aspects, Bacci et al. [10] have experimented different methods of retting and fibre extraction. From their studies it can be confirmed that both controlled microbiological retting with the combined use of anaerobic and aerobic bacteria and vat enzymatic retting, especially when a solution of Pectinex Ultra SP-L with EDTA (ethylene di-amine tetraacetic acid) was used, led to improvement in fibre quality.

3 Evaluation of Properties: *Physical and Chemical Properties of Nettle Fibre*

3.1 Physical Properties

Physical properties especially the strength is much superior to commonly used natural fibres like cotton, silk, wool and base fibres. The average fibre length, diameter and tensile strength vary between 43 and 58 mm, 19 and 50 μm and 24

Table 1 Comparative properties of some single bast fibres

Fibre	Young's modulus (GPa)	Strain to failure (MPa)	Ultimate stress (%)	Density (g/cm^3)	Average diameter (μm)
Nettle	87	2.1	1594	0.72	20.0
Flax	58	3.3	1339	1.53	23.0
Hemp	35	1.6	389–900	1.07	31.2
Ramie	20–128	1.2–3.8	400–1000	1.56	50.0
Sisal	9–21	3–7	350–700	1.45	100–300
Glass	72	3.0	2200	2.54	5–25

and 62 cN/tex respectively [11, 12]. Bacci et al. [11], highlighted that unlike flax and hemp fibres, nettle fibre lies along the length of the plant stem and beneath the surface of the outer bast layer and the fibres present on this surface are fine and long. However, the extension is little higher than jute fibre (2 %). Surprisingly, nettle fibre fibres are very light and their density is 0.72 g/cm^3 which is half of the other natural fibres. Table 1 presents nettle and some important bast fibres and compared with glass fibre [13, 14].

The cultivated wild nettles exhibited longer stems and a mean fibre content of 50–66 % [15]. Though, the relative diameter of single wild nettle fibre is finer (14.51 ± 0.19 μm) than that of cultivated nettle fibre diameter (22.11 ± 11.94 μm) in UK.

Recent studies by Haugan and Holst [16] developed theoretical model for distinguishing natural fibres like jute, nettle, cotton, etc. and found that the fibril structure and their angle is different for all fibres based on polarised microscopic views and birefringence results. Figure 1 depicts sign of elongation of nettle fibre. The modified Herzog test was performed for jute and nettle fibre as shown in Fig. 2.

Bodros and Baley [13], also studied the cross-sectional view of nettle stem by SEM (under 1000×) presented in Fig. 3. It depicts, fibre bundles are located at the inner cortex. It is also visible clearly from figure about the lumen at the centre. The fibres' cross-sections are mostly polygonal. They considered circular cross-section and estimated the average fibre diameter to be 19.9 μm (±4.4).

It has been reported that typically 5–8 % is the moisture regain behaviour of nettle fibre [21].

Davies and Bruce [17], found that nettle fibres are brittle due to small strain to failure, which resembles the flax fibre brittleness. They concluded that the flax fibre behaved in a linear elastic manner to the point of failure, but the nettle depicted limited viscoelastic effects. The static Modulus of the fibres was independent of fibre strain. The dynamic modulus increased with increased strain at a rate of 13 GPa/% strain and 6 GPa/% strain for flax and nettle fibres respectively.

An interesting study on comparative stress strain properties of nettle and flax fibre has been investigated by Bodros and Baley [13] (Fig. 4).

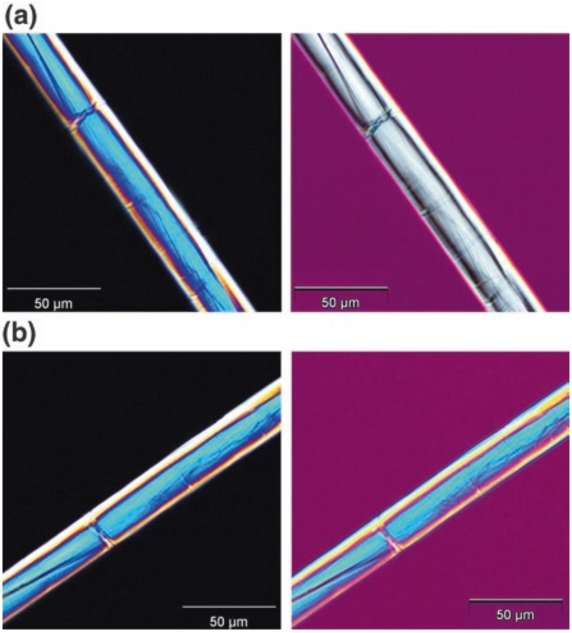

Fig. 1 Demonstration of sign of elongation. **a** $\alpha = 45°$. **b** $\alpha = 135°$. Fibre is nettle. At $\alpha = 45°$ zero-order grey is clearly observed, which proves the expected positive sign of elongation [16]

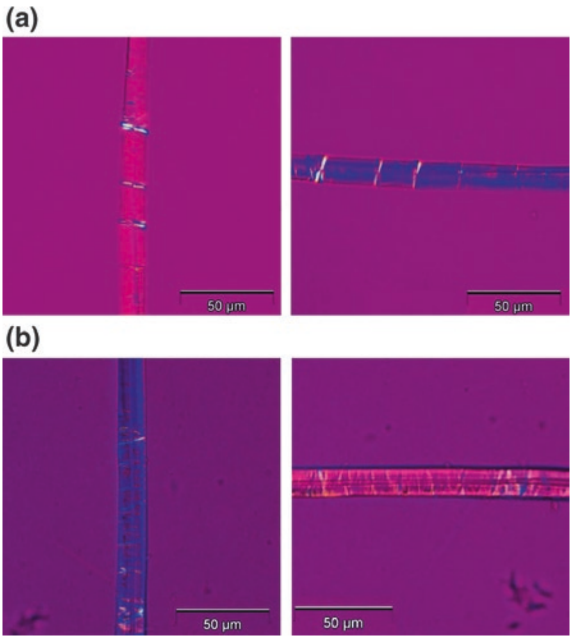

Fig. 2 The modified Herzog test performed on (**a**) nettle (S-twist) and (**b**) jute (Z-twist). To the left the sample orientation angle $\alpha \approx 0°$, to the right the sample orientation angle $\alpha \approx 90°$ [16]

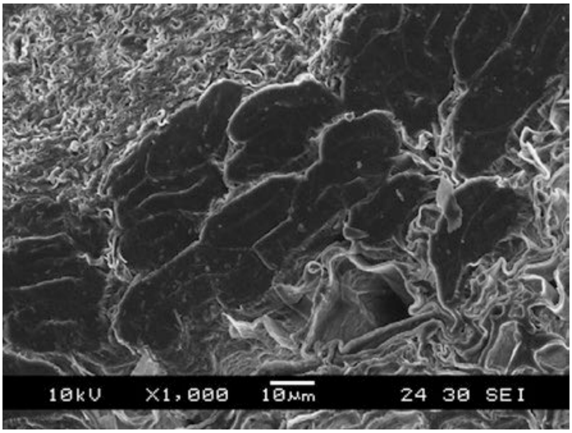

Fig. 3 Cross-section of a stinging nettle (*Urtica dioica*) stem under SEM [13]

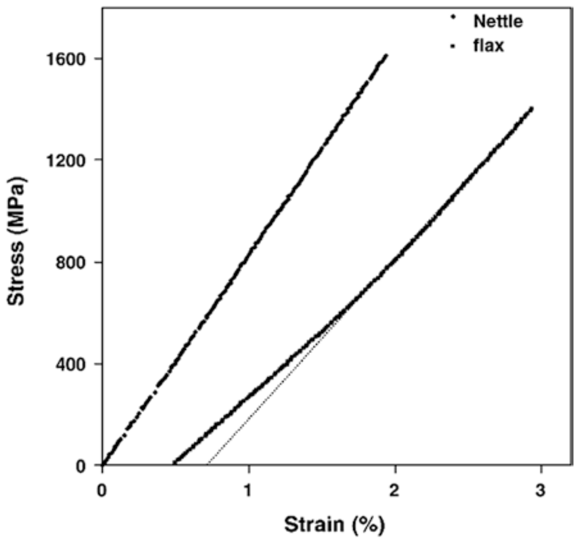

Fig. 4 Stress/strain curves of nettle and flax fibres [13]

3.2 Chemical Properties

As far as the nettle fibre is concerned, major chemical composition elements present are cellulose 79–83.5 %, hemicellulose 7.2–12.5 % and lignin 3.5–4.4 % [11, 18].

Distinguishing between the bast fibres is possible based on X-ray microdiffraction method, but as the method requires the use of a synchrotron it is not readily available; moreover, it is costly. Bergfjord and Holst [19] proposed a simple procedure for identifying different bast fibres measuring the fibrillar orientation with polarised light microscopy and detecting the presence of calcium oxalate crystals (CaC_2O_4) in association with the fibres. This procedure required a small amount of fibre material.

3.3 Mechanical Properties of Stinging Nettles

Bodros and Baley [13] adopted a process to measure the single nettle fibre tensile strength where the gap between the two jaws and cross-head speed were maintained at 10 and 1 mm/min respectively. Young's modulus, stress and strain at failure are measured for 90 fibres. The average tensile properties are a Young's modulus of 87 Pa (±2.8), a tensile strength of 1594 MPa (±640) and a strain at failure of 2.11 % (±0.83). The ultimate stress is greater for nettle fibres in comparison to ramie and equivalent to that of flax [20]. Harwood et al. [15] used advanced textile instrumentation system to evaluate the relative fibre diameter (Sirolan TM Laserscan), length (Uster High Volume Instrument), strength and cleanliness (Uster Microfibre Dust and Trash Analyzer) of extracted fibre using standard procedure.

4 Sustainable Development of Luxury Textiles and Other Industrial Applications: *Sustainable Development Different Luxury and Fashionable Value Added Textiles from Fibre, Yarn and Fabrics, Their Properties and Probable Uses of Nettle in the Luxury World*

4.1 Sustainable Chemical Processing of Nettle and Value Added Textile, Composite Product Development

Research work reveals that nettle fibre needs to bleach prior to dyeing so that it can be treated as cellulose [21]. Nettle naturally has an off-white colour and will therefore require bleaching prior to any dyeing. Hydrogen peroxide bleaching as preparation of the fibre irrespective of its original shade is most essential for removal of the extraneous matters present in the fibre. These bleached nettle fibres facilitate better levelling and dye uptake during the dyeing process. Though, the natural colour nettle is often too deep to remove completely while bleaching with hydrogen peroxide treatment hence, two-stage sodium hypochlorite bleach followed by hydrogen peroxide bleach is suggested. These two stages of bleaching are required especially to dye nettle fibre with light colour shades. As far as dyeing is concerned, nettle fibres, unlike other natural cellulosic fibres, can be dyed effectively with reactive dyes or in some cases with direct dyes. If the clothes are to be used for work wear where more sustainable dyes are likely to be required, reactive dyes, vat dyes or sulphur dyes would be the right selection.

One has to concentrate upon some important properties as far as the sustainable luxury apparel is concerned, like shrinkage, pilling, etc. It has been reported that nettle fibre has good shrink resistant behaviour [21]. They have good dimensional stability and more interestingly, fibres tend to have higher strength when wet than in their dry state. As far as the resistance is concerned, Matthew [21] also confirmed that nettle fibres are extremely durable and resistant to abrasion and pilling. There is immense possibility to use this nettle fibre for sustainable development [22] in making packaging material, upholstery, tarpaulin, geotextile, bags and carpets, etc.

Today, people are more conscious about eco-friendly processing for sustainable development and in the same line, Vogl and Hartl [1], discuss about the different aspects of production and processing of organically grown nettle fibre. Further, they also emphasised its potential use in the natural textile industry in spite of its different important industrial applications. Bhardwaj and Pant [23] demonstrated nettle and acrylic blended textiles. In their experiment they used 70:30, 50:50 and 30:70 nettle:acrylic blended fibres for development of value added nettle–acrylic blended fashion textiles. It has been reported and concluded that 100 % nettle of linear densities of 16_s Ne and 24_s Ne yarn are not possible to spin successfully due to fibre stiffness and poor pliability. However, in blends of 70:30 nettle:acrylic also huge breakages during spinning were produced. Other blends are quite acceptable in terms of yarn hairiness, evenness, imperfections and tensile properties. Shaolin et al. [24] in China used nettle fibre grown natively and used to develop nettle as core-spun yarn for coarse yarn used in development of fashionable upholstery.

There are huge potentials to develop various textile and industrial products for different technical applications out of nettle fibres. Various parts of the fibre nettle plant can be used as food, fodder and as raw material for different purposes in cosmetics, medicine, industry and biodynamic agriculture [1]. Developing new natural fibre composites is one of such areas wherein nettle fibres have good contribution to impart the final composite strength. Bodros et al. [25]. Bodros and Baley [13, 26] focused that nettle fibres being renewable resources have a lower environmental impact in comparison to mineral fibre (glass) composites. They measured the mechanical performances of stinging nettle fibres and compared to flax and other lignocellulosic fibres. The stress/strain curve of stinging nettle fibres (*U. Dioica*) shows they have a linear behaviour which can be explained by the orientation of the cellulose microfibrils. In composites, the average tensile properties are a Young's modulus of 87 GPa, a tensile strength of 1594 MPa and a strain at failure is 2.11 %. However, in the light of biocomposites from nettle Saheb and Jog [27], commented that since nettle unlike other natural fibres contains moisture so for maximum utilisation of strength in composites the moisture has to be removed prior to composite manufacturing process.

In one of the experiments, Kuciel et al. [28] developed and tested biocomposites based on poly-hydroxybutyrate (PHB) filled with four types of natural fibres—wood, kenaf, horse hair and nettle. They found that nettle fibre formed microfibers in the composite structure which enhances the strength of the total composite (Fig. 5).

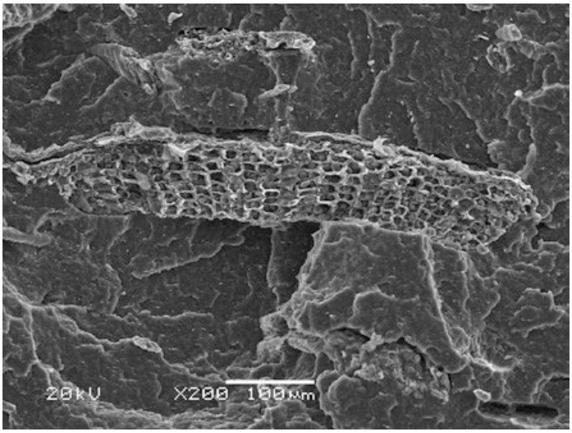

Fig. 5 SEM image of fracture PHB +15 % nettle fibres, single nettle fiber build from many microfibers [28]

4.2 *Nettle Yarn Spinning for Value Added Products*

English [29], explained in this research about the history of spinning, weaving and knitting machines, wherein, nettle fibres have been used traditionally for spinning of yarn and those yarns are further used for apparel fabrics apart from their industrial applications. Dunsmore [30, 31], also explained the importance of nettle fibre processing and hand spinning of nettle yarn considering different situations in Nepal. She also described the hand weaving of nettle fabric and different possibilities of fashion apparels out of sustainable nettle fibre. Zuo et al. [13], applied different spinning systems and techniques, for sustainable spinning of the nettle fibres. Their results show that the nettle fibres cannot be used for spinning singly because the main length of nettle fibres is very short, discrete coefficient of length and fineness is varied. However, admixed with other fibres, the test-yarn qualities are somewhat acceptable. Their research output can be useful for developing sustainable and fashionable products from the wild nettle fibres.

Choudhary et al. [7], reported that at the primary level, the sector involved in nettle processing, has high involvement of women, who harvest the plant from the forest, extract the nettle fibre and spin the thread. Traditional technology for extracting bast and spinning thread has been small-scale with high inefficiencies both in terms of labour and energy. Weavers use these threads to produce different fabrics, including scarfs, shawls and cloth material. Market acceptance of the end product has been low to date due to roughness of the fabrics and limited colour choices. To overcome these problems, Choudhary et al. [7], developed special spinning process to spin 100 % nettle and nettle–cotton blended yarn. Their process sequences involve: straightening, cutting, first crushing, washing, conditioning (degumming), second crushing, pre-carding and softening. After these processes the main carding followed by drawing and spinning are performed. With the intervention of these processes the nettle processers can fetch more money because the yarn productivity is higher and of better quality. Choudhary et al. [6], finally explained the value-chain of Himalayan nettle for sustainable development of the nettle product at Uttarkhand, India.

Yan et al. [32] studied the spinnability of nettle fibre in textile process apart from its basic physical and mechanical properties. They made an effort to spin in different spinning systems and technologies. In all the cases spinnability of the nettle fibres has been studied. Their results show that the nettle fibres cannot be used to spin alone because overall lengths of the nettle fibres are very short, discrete, coefficient of length and fineness is varied widely. However, nettle can be mixed with other fibres for better spinnability. On the contrary, the test results of yarn qualities are not satisfactory for pure nettle yarn.

Spinnability of nettle fibres was studied in friction spinning system by Shaolin et al. 2005. In friction core-spun yarn of nettle, nettle fibres blended with short flax fibres as wrapped fibres and polyester short fibres as core yarn were developed. Influence on yarn performance of spinning speed, friction roller speed and core yarn percentage was researched by orthogonal test method. They also optimised the spinning parameters of friction core-spun yarn technology range of nettle fibre. A crop of the perennial stinging nettle plant (*U. dioica*) was established in Leicestershire, UK in 2005 by Harwood et al. [15] and sampled weekly throughout the growing season in 2006 and 2007 for investigation of fibre content and growth characteristics. They studied its suitability for spinning on cotton and woollen systems and found that nettle fibre was suitable for woollen spinning. The fabric comprising 80 % wool and 20 % nettle fibre was found optimum and produced for corporate upholstery use. The high variability in fibre length and lack of uniformity of nettle fibre prohibits its use in cotton spinning system. Further they concluded that the relatively low yields of fibre obtained from the plant made low value non-woven markets which was unattractive and uncompetitive at that point of time. However, the greatest price for nettle fibre is to be found in the higher end and fashionable textile markets.

4.3 Nettle for Sustainable Traditional Handicrafts

The stem and fibre of stinging nettle are used to prepare traditional handicrafts in several Balkan countries as reported by Dogan et al. [33]. This nettle fibrous material in Bulgaria locally known as *Kopriva* is used for sustainable development of cloth, sack, cord and net manufacturing application. In Romania, nettle is known as *Urzica*, and its use is substitute of cotton for fishing net and paper making. It is known as *Kopriva* in Serbia, where nettle fibre is considered as one of the major textile fibre and used for spinning industry to produce textile products. Overall, there are wide ranges of possible handicraft products (doormat, flower vase, wall-hangings, door-chain, carpet, hand-bags, table-mat, beach umbrella, lampshade, etc.) out of nettle either from fibre or yarn or fabric or combination of these. All these products have huge profit margin due to high cost to benefit ratio. Most of the handicraft products fall under fashion items. Similarly, Dunsmore [30], in her findings explained different handicraft products made out of nettle fibres and hand-spun yarn from Nepal. This study also elaborates the sustainable rural livelihood through cultivation of nettle to handicraft product development out of nettle. This handcraft making from nettle fibrous material for rural hill people created an alternative source of income during the lean period of agricultural activities. Economic development of the nettle processing community of Nepal has been through proper marketing strategy and exporting the fashion textile and handicraft products to Europe and America. Bacci et al. [10] also supported that for sustainable handicraft products from nettle it is very essential to go for enzymatic retting to obtain best quality fibre. Deokota and Chhetri [34], reported in their research the handloom and handicrafts are moved side-by-side to promote nettle-based products in Nepal. These include, coarse hand-woven cloths, sacks, bags, fishnets and *namlo* (headstraps to carry load) which are sold in the local market or in some cases bartered for food or other necessary items in some rural communities. Anonymous [35] demonstrated various sustainable fashion products made out of nettle like hat, jacket, room decoration and various handicraft products, which can be made out of nettle and its blends.

4.4 Nettle Apparel: Its Laundering Behaviour and Disposal

Nettle can be blended well with other fibres to develop fashion apparel as suggested by Matthew, [21]. Under the luxury apparel category, it can be used in some apparel such as fashion dresses, jackets and suiting; heavy weight fabrics are more suitable for jackets where hard wearing properties can be obtained. Due to unique appearance of nettle fibre, nettle fabric has also a unique look and is suitable for development of winter garments. It has been suggested that nettle, nettle–wool, nettle–cotton, nettle–ramie and nettle–flax are possible natural fibre blended material that can be used for development of 100 % natural sustainable textile materials [1, 8, 15].

Laundering plays an important role for any textile material as far as its repeated use is concerned. Nettle-based fabrics can withstand laundering at high temperatures [21]. These should only be used for heavily soiled garments. Unlike flax fabrics, nettle-based fabrics are also prone to becoming creased during washing and this will require the use of a hot (steam) iron during pressing. Dyes have a tendency to bleed and suitable separation during washing should be taken care. If required, tumble-drying requires a high temperature setting. Unlike cotton, nettle can be treated with a crease resistant finish, which can improve the “easy care” nature of the nettle fabrics sustainably. Treated fabrics should be laundered in accordance to instructions as these may recommend lower heat settings during drying and ironing though nettle can withstand high laundering temperature.

Since nettle is annually renewable so no such issue of depletion of natural resources arises (Fig. 6). It has been also reflected through this Fig. 6 that except

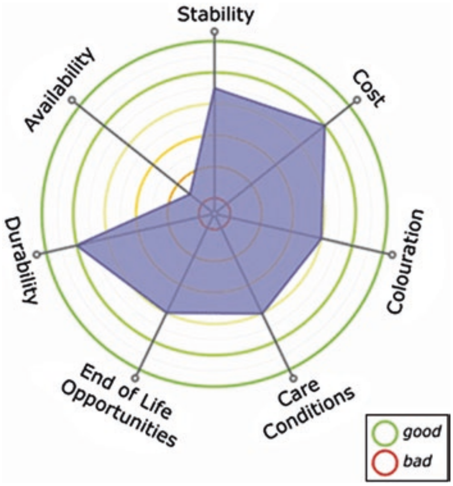

Fig. 6 Polar diagram of comparative aspects of nettle fibre [21]

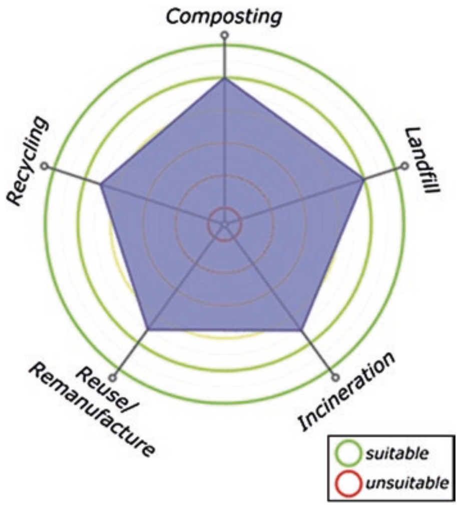

Fig. 7 Disposal of nettle textiles [21]

the availability of nettle fibre, most other aspects like, disposability, durability, colouration, etc. are acceptable compared to other natural fibres. Hence it can be figured out from these facts that nettle can well be used as sustainable luxury textiles. Characteristics/options defined by the polar diagram are proportionally represented and approximate. As such they do not represent any industry standards. Apart from these, fabric construction and weight and content of other blended fibrous material (in case of nettle blended products) will influence the perceived ranking.

After subsequent usage of the nettle-based textiles, it can be disposed off using all end of life opportunities (Fig. 7). It can be handled in a similar way as other natural cellulosic fibres materials are disposed. Nettle fabrics also have huge potential to be reused or re-manufactured and can also be used as a source of cellulose feedstock for regenerated cellulose products. Being naturally biodegradable, the fibres can be composted in some cases if required [21] as presented in polar diagram.

4.5 Probable Uses of Nettle in the Luxury World

There are immense evidences of using nettle products in the luxury world. Considering the holistic approaches available from different sources, the various applications of nettle fibre are in the form of fibre, yarn, fabric and composite structures. Hand-made braided structures are prepared in different rural areas near which nettle is grown. These braids are used to make luxurious and fashionable items [33, 30] like hand-bags, door-chain, wall-hangings, decorative items for rooms and car interior, flower vase, etc. Fibre/yarn/fabric or combination of these structures is coated with natural/synthetic resin to make the stiff to semi-stiff composite structures. These composite structures including paper from nettle are generally used to make different luxury products like lampshade, fruit basket other table-top decorative items [33]. As far as apparel is concerned, nettle in the form of blended structure, wherein nettle–cotton, nettle–flax, nettle–wool, nettle–viscose, etc. are used to weave union or blended fabrics [33, 35]. These fabrics are mostly coarser and heavier in nature due to inherent coarseness of the nettle fibre. Close-woven structure for winter apparel and open-woven structure for summer apparels are common applications of these products apart from fashion garments [21]. The economically established society is able to embrace the usage of costlier and health friendly natural fibre products as compared to economically underdeveloped backward society.

5 Conclusions

This chapter discusses about the stinging nettle fibre's uses in sustainable textile and fashion. This fibre can be cultivated and hence no question of depletion of forest trees as well dependency on petroleum reserve. It has been found from the above study that though the stinging nettle is one of the oldest textile fibres but with the intervention of modern synthetic/manmade fibres its application has been restricted. With latest scientific knowhow this nettle fibre can be extracted sustainably to a greater extent without affecting its quality. Simultaneously, the byproducts released and extracted during the fibre extraction process as well as different potential components can be uses for various value added sustainable products. There is huge potential in textile and other non-textile industries like pharmaceutical due to its medicinal values both for human as well as animals, composites for bio-composite and high strength, application for sustainable fashion textiles and natural dyes from its own plant extraction to produce ethnic sustainable textiles. Hence a comprehensive effort needs to be taken to revamp the potential of sustainable development of fashionable textile and industrial materials from nettle fibre as well as from its byproducts.

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Sustainable Luxury Natural Fibers—Production, Properties, and Prospects

T. Karthik, R. Rathinamoorthy and P. Ganesan

Abstract Increasingly, the world is realizing that better use must be made of precious natural resources. Today, with the enrichment of people's awareness on environment problems and the demand of environment-friendly fabric, natural fibers have received a great deal of attention due to their great importance of "green" and health protection properties and have been widely used in many fields, such as textile industry and daily life. Traditional resource of four natural fibers, cotton, wool, silk, and flax is after all limited. So, many new plant fibers, such as hemp, apocynum, mulberry bast fiber, pineapple leaf fiber, banana fiber, bamboo fiber, kapok fiber, and so on, have been exploited in recent years. The luxury sector, particularly fashion has a high environmental footprint and is responsible for a significant amount of waste. Designers committed to sustainable processes face a severe lack of options in terms of the actual goods used to make their products, with everything from fabric to embellishments being in short and expensive supply. This chapter aims to give an insight into the comprehensive details of conventional as well as unconventional sustainable luxury fibers which are going to be dominated in luxury fashion industry in the forthcoming years.

Keywords Sustainability · Luxury · Natural fibers · Silk · Milkweed · Lotus fiber · Pine fiber · Soy fiber

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1 Introduction

Environmental awareness has prompted many industries, particularly in developed countries, to consider more sustainable ways of operating. Now, industries increasingly are looking directly at natural inputs in a more positive and proactive manner: Natural inputs are considered not only as technically valid components, but also as elements that can contribute to the premium pricing of final products because of their superior environmental attributes and their compatibility with socially responsible production and disposal requisites [1].

The luxury sector, particularly fashion has a high environmental footprint and is responsible for a significant amount of waste. There is an emerging demand for sustainable luxury, which a number of key industries are well placed to develop and promote to consumers. Emerging biomaterials offer new design considerations that fully engage the sustainability challenges of the twenty-first century [2]. A typical, nonsustainable garment can make use of over 8000 toxic chemicals in textile creation processes. However, these same processes are what we can thank for many of the materials that have come to define luxury fashion [3].

Designers committed to sustainable processes face a severe lack of options in terms of the actual goods used to make their products, with everything from fabric to embellishments being in short and expensive supply. This results in two major dilemmas: First, creative concepts become casualties of an inability to source the right materials to see it through to execution. And second, attempts to creatively source those materials, by direct trade or other means result in a product so costly the idea must be canned. Hence the raw material selection plays an important role in sustainable luxury textile and fashion arena [4].

This chapter aims to provide the comprehensive details of conventional luxury fibers such as silk and animal fibers and unconventional fibers such as lotus, milkweed, pine, and soy protein fibers related to their production, properties, and prospects as sustainable luxury fashionable products in the market.

2 Conventional Luxury Fibers

2.1 Silk Fiber

Silk is the ultimate luxury raw material and fiber. It is the darling of the haute couture set for the luxurious feel and drape; villain of vegans and PETA (People for the Ethical Treatment of Animals) for the doomed silk worm who labors to spin the fine fiber and then is gassed or boiled alive. There are many indigenous varieties of wild silk moths found in a number of different countries. The key to understanding the great mystery and magic of silk, and China's domination of its production and promotion, lies with one species: the blind, flightless moth, *Bombyx mori* [5].

2.1.1 Life Cycle of a Mulberry Silk

The life cycle of silk worm is shown in Fig. 1. A *B. mori* egg hatches in 10 days and becomes a larva—the silkworm caterpillar. The silkworm larva will voraciously eat mulberry leaves almost nonstop for 35 days increasing its weight 10,000 times from a tiny speck to a chubby grub. Silkworms are very delicate and will go off their feed from loud noises, temperature fluctuations of more than a few degrees above or below 76°, or even strong smells. When it is full grown, the silk worm (called a pupa) climbs a twig and begins spinning a cocoon. This stage of silkworm life is called pupating. The silkworm produces a fibroin protein compound in two salivary glands called sericteries that is mixed in the mouth of the silkworm with a gooey substance called sericin and forced out through an opening in the silkworm's under lip. When this stream of sticky fluid comes into contact with air, it solidifies and becomes a continuous strand of silk that becomes the silkworm's cocoon. The silkworm will spin a thousand yards of silk fiber in 3 days to form its completely enclosed cocoon. To fashion its cocoon, the silkworm will continually weave its head in a figure eight pattern, an estimated 300,000 times while continually spinning and secreting its silk fiber.

When the transformation is complete, the newly formed *B. mori* moth secretes an alkali fluid that begins to dissolve a hole in the cocoon so that the moth can emerge. The silk farmers do not want their silk cocoons damaged so they kill the

Fig. 1 Mulberry silk worm life cycle. *Source* central silk board, India

worms by tossing the cocoons into boiling water or hot ovens before they transform into moths and emerge from their cocoons. A small percentage of silkworms in cocoons are left to live so that a few moths will emerge to lay the next generation of silk machines. The sightless, flightless, and toothless moth will mate almost immediately after emerging from the cocoon and lay 500 silkworm eggs during their first 4 or 5 days and then die [6, 11, 15].

2.1.2 Sustainable Luxury Silk

The raising of domesticated silkworms and the life of wild silkworms is, by nature, sustainable. Silk fabric when produced by weavers on handlooms has a near zero energy footprint and satisfies most of the guidelines for sustainable fabric production.

Organic Silk

The organic silk production is the more environmentally friendly, nonviolent, and sustainable practice of silk cultivation. Zero chemicals or treatments are required for raw silk, which is readily biodegradable. The silkworms are allowed to live out their full lives and die naturally. Organic silk is a highly sustainable crop with cocoons being produced when the silkworms are about 35 days old. The silkworm continues it's natural cycle to morph into a moth. Then it lays eggs and dies naturally about 5 days later. Natural silk colors are produced but some organic silk is dyed with natural dyes. Raw silk has the versatility to be blended with just about any other fiber. Blends with cotton and other fibers will produce a silken sheen and added softness [7, 12].

Organic silk farming has reaching effects by also promoting the sustainability of mulberry trees, which are the silkworms food source. One mulberry tree will feed roughly 100 silkworms. One acre of renewable trees sustains silkworm life to produce 30–35 pounds of raw silk. Highly sought after natural reddish or golden silk colors are produced, depending on the specific silkworm breed and its feed. These trees, in turn, provide a valuable renewable resource for local production of baskets, furniture, even folk remedies [15].

Peace Silk

Silk production has sparked an interesting debate among environmentalists and animal rights activists. In traditional silk production, thousands of silkworms are killed to make just a small amount of material. Each cocoon is made from a single silk thread about a mile long, but when the caterpillar emerges from their cocoon as a moth, the silk cocoon is broken apart, which essentially destroys the silk thread. In the manufacturing of regular silk, the silk worms inside their cocoons are immersed in boiling water to kill them so they do not pierce and damage the cocoon when they emerge from it.

The manufacturing method of peace silk entails that no silkworms are harmed or killed in the production process by allowing the silkworms to emerge from their cocoons. With peace silk the silk is extracted after the silkworm has completed metamorphosis and emerged from the cocoon as a moth. The broken cocoons are then collected and the segments of threads are mended using a spinning process. Each cocoon is checked individually to ensure the moth has emerged before the silk thread is spun. Because the one continuous silk fiber woven by the silkworm has been broken into many smaller strands by the emerging moth, the cocoon is degummed to remove the sericin and then spun like other fibers such as cotton or hemp rather than being reeled onto spools of one continuous strand [8]. This silk is slightly discolored by the alkaline solution secreted by the moth to create the hole and the peace silk is not as strong and has a slightly different look and feel to the knowing designer than conventional *B. mori* silk. This specialized production is a laborious process but the result is the quality of silk is softer and finer in comparison to regular silk and it has a soft pearl natural finish instead of a satin look. This process of silk production ensures there is no killing, no cruelty, and at the same time the eco-friendly fabric quality is totally protected. Peace silk is more expensive because it takes more time and skill to salvage and spin the abandoned cocoons and less people are trained in this type of sericulture [9, 10].

Wild Silk

The *B. mori* silkworm is not the only silkworm that spins a silk cocoon that can be used to produce silk fabric for silk clothing and these are called as wild silks or peace silks because the silk caterpillars are allowed to live complete and natural lives in the wild without being sacrificed for fashion. Wild Silk (Tussah or Tussur) is 100 % natural, organically produced by worms that thrive in their natural habitat. They complete their full life cycle and emerge as moths before mating and dying as nature intended. Wild silk is very labor-intensive. Indigenous people collect the cocoons and hand spin the fibers or handloom into cloth for sale. Wild silk is earth-friendly and protects lands otherwise threatened by deforestation. As well, employment is provided for the local villagers. These wild caterpillars spin a silk that is different in texture and color from the domesticated *B. mori* and the wild silk cocoon strands are shorter because they come from cocoons that have been damaged by the wild silk moth's emergence from the cocoon [11].

Eri (from the domesticated silkworm *Philosmia rinini*) is a fine silk that is almost as white in color as the *B. mori* silks. Even though Eri is spun from the cocoons of domesticated silkworms, it is a peace silk because the Antherea assamensis silk caterpillars are not destroyed in the cocoon but are allowed to emerge as moths and live a full lifecycle. Eri silk has the look of wool mixed with cotton but feel and softness of silk.

Matka Silk

Matka is an Indian term for “rough handloom silk fabric” made from very thick yarns spun out of pierced cocoon in the weft (peace silk) and organzine in warp. The yarns are obtained from short ends of silk from Mulbery silkworms and spun by hand without removing the gum. As such, there are slubs and irregularities that give the fabric unique characteristics. It looks something like tweed, but the fibers are all the same color. It is lustrous and strong like other silks, and it promotes to use of peace silk and sustainable processes. Matka silk is biodegradable [12].

Recycled and Vintage Silk

A vintage silk dress, if it is free from rot and stains (which sadly never come out) is a great investment. Silk, when cared for, can last for thousands of years—silk textiles over 4000 years old have been found in Chinese tombs. Vintage silks lend themselves perfectly to recycling and reworking. Recycling old silks seems like a great alternative. Since the fabrics rarely degrade, it makes perfect sense to reuse and restyle [15].

2.1.3 Silk in Sustainable Luxury Fashion

Silk has always been associated with luxury and wealth. The silk makes individual to feel important and when people wear an authentic silk piece, the confidence level goes up a couple of levels immediately for sure. Silk is used for a variety of fashion-related pieces. It can be used for skirts, dresses, blouses, scarves, pajamas, and lingerie.

Samant has adapted the grainy, tactile peace silk to high-end couture, producing stylish sherwanis, boucle-like jackets, and ethereal dresses. The waste generated when harvesting and beginning to process the cocoons presented an opportunity for Samant to develop a new kind of silk with a much coarser weave yet a feel like wool, he has used this textile in panels on men’s jackets [13]. Waste produced at the fabric cutting stage becomes the textured layers of appliqué and decoration which characterized, for example, the latest collection which also featured catwalk models adorned with headdresses of silk worm cocoons and reels of yarn as shown in Fig. 2.

It is not entirely clear how much the ethical aspects of the peace silk and support for traditional weaver’s livelihoods influence customer’s purchase of his clothes. Besides being organic, an “ahimsa” silk processed from cocoons without killing the larvae inside, has thermal properties and is mostly used to make shawls and stoles. Syiem’s initial challenges included convincing weavers to supply the fabric in new dimensions, but he adds that since the fabric is dyed with vegetable dyes, it severely limits the brand’s color palette to shades of white and natural earthy tones. To compliment the handlooms, he avoids using machine-made

Fig. 2 Upcycled cocoons and upcycled applique adorn model's headdresses [13]

embellishments or fasteners and relies instead on drawstrings, knots, and buttons made from natural materials [14]. Syiem's Meghalaya's Silk root Khadi handlooms showed at fashion week are shown in Fig. 3.

If the primary concern from the consumer is healthy and organic silk then consider raw silk, noil silk, muga silks, or eri silks that are undyed or dyed with low-impact, fiber-reactive dyes. If the primary concern from the consumer is about the ethics of silk raising then choose wild silk, spun silk, or eri silks which do not destroy the silk worms to harvest the silk cocoons. If concerned about sustainability and eco-friendly silk, then seek silks dyed using low-impact and fiber-reactive dyes or vegetable dyes without finishes.

Fig. 3 Meghalaya's silk root Khadi handlooms at London fashion week [14]

2.2 Cashmere

Cashmere is perhaps the most widely recognized of all the luxury fibers. Cashmere wool is the best sustainable and renewable fiber with virtues to protect the user from the surrounding rudiments. Fibers from these garments will not peel and will retain its form for many years, even for generations. More than 3000 tons of cashmere is made every year with the majority of them from Mongolia, followed by Australia, New Zealand, Iran, and Afghanistan [15]. The Cashmere goat and their product are shown in Fig. 4.

Cashmere is prized for its exceptionally fine texture and is strong, ultra light, and soft. It provides a superior insulative function without bulkiness, and the fibers are highly adaptable and easily spun. Like wool, cashmere has a high moisture content that allows the insulating properties to change with the relative humidity in the air. It is however, weight for weight, warmer than wool. The finest Cashmere is obtained from the neck area of the goat. Cashmere goats produce a double fleece that consists of a fine, soft undercoat or under-down of hair which is mingled with a straighter and much coarser outer coating of hair called guard hair. In order to sort the fine under-down and be processed further, it must be dehaired. Dehairing can be a mechanical or manual process that separates the coarse hairs from the fine hair. After dehairing and washing, the resulting cashmere is ready to be dyed and converted into yarn, fabrics, and ultimately garments [11].

The ever-growing lust for the beautiful and soft cashmere fabrics encouraged the breeding of cashmere goats. During the past century, making of cashmere wool has increased up to that extent that it has become unsustainable, and is posing a threat to the environment. What were once beautiful, unspoilt grasslands are now becoming deserts, ravished by the goats breed for their cashmere clip. This is now creating a devastating effect on the ecological balance of the planet. The impact is more visible in Mongolia. The country produces 90 % of the cashmere fabrics sold worldwide. The increase in demand for these products is taking their toll on the country's environment both socially and ecologically [16]. Sustainable cashmere fabrics are made from nonallergenic natural goat fibers. They are animal-friendly, sustainable, and do not wrinkle. They posses durability with little or no pilling,

Fig. 4 Cashmere goat and its products [15]

and become softer with the age. The luxurious fibers from the pashmina goats have inspired many designers, and are preferred by consumers who are luxury lovers [17–19]. With all the exposure of ecological living, sustainable cashmere fabrics are sought by consumers who want to own luxurious clothing line and also remain eco-chic.

The Sustainable Cashmere fiber could be produced by [19]

- Harvesting the fiber from healthy goats that have been raised ethically and treated humanely their entire lives
- Raising the goats respecting their natural instincts, social structure, and needs, and still produce a luxury product
- Growing the goats who have never been tied or tethered, never been treated with chemicals or hormones, and have grazed only overgrown, untreated, unusable farmland, and their fiber has been processed without the use of chemicals or industrial coloring
- Hand combing of our sustainable cashmere is painless and innocuous—the goats are not maimed, wounded, or killed to harvest their fiber and have an average life span of 10–15 years, that is easily double that of goats raised intensively for milk or meat production

2.3 *Alpaca*

Alpacas are a domesticated species of South American *camelidae* family that resemble small llamas. They produce one of the world's most luxurious fibers that are softer than cashmere and lighter, warmer, and more durable than wool. Alpaca is an enigmatic fiber which is valued for its fine, soft, and silky characteristics [15]. Alpacas have provided vitality, sustenance, and warmth to the Peruvian people for over 6000 years. There are nearly 3 million Alpacas in Peru, representing about 80 % of the entire world's population.

Alpacas graze at elevations of 10,000–14,000 ft on the harsh altiplano of the Peruvian Andes. As a result, alpacas have incredibly insulating coats that are warmer and stronger than wool, yet remarkably lighter in weight. Their thick, luxurious coats naturally grow in over 40 shades, ranging from white to black with all the grays and browns in between. The Alpaca of various shades are shown in Fig. 5.

This provides a glorious palette when left undyed, although the lighter shades of fleece dye to beautiful shades as well. Alpaca's unique durability and delicious softness make it one of the most luxurious fibers in the world [16]. Alpaca fleece has some similarities to sheep's wool, but unlike wool its fibers have a minimal lanolin content, which makes it almost hypoallergenic. It is naturally impermeable, thermally responsive, and has a low flammability point. It is a soft, durable, luxurious, and silky natural fiber. Its softness comes from the small diameter of the fiber, and is to merino wool. Its glossiness is due to low height of the individual fiber

Fig. 5 Various natural shades of Alpaca [20]

scales compared to sheep wool. Alpaca fibers have a higher tensile strength than wool fibers. The alpaca has a very fine and light fleece. It does not retain water, is thermal even when wet, and can resist solar radiation effectively. These characteristics guarantee the animals a permanent and appropriate coat to protect against extreme changes of temperature. Although it feels soft to the touch, the hard surface of the fiber makes alpaca a very durable yarn. It has excellent thermal insulation properties with an apparent lightness of weight [20].

There are two types of alpaca: Huacaya (which produce a dense, soft, crimpy sheep-like fiber), and the Suri (with silky pencil-like locks, resembling dreadlocks but without matted fibers). Suris, prized for their longer and silkier fibers, are estimated to make up 19–20 % of the North American alpaca population [20].

Alpaca fibers are processed in a similar way to sheep wool. They are sheared annually or in their native Andean habitat, generally sheared once every two years. Alpaca farming has a low environmental impact and is therefore an interesting alternative for some sheep farmers. Furthermore in their native South American habitat, alpaca herds are less intensively managed than many sheep herds in the developed world. In addition the financial precedes from their fiber benefits poorer rural communities. In terms of sustainability, alpaca is a natural fiber made of protein so it will naturally biodegrade when disposed of and blends into the earth within a relatively short period of time when compared to synthetic or man-made fibers which take a long time to degrade and has a negative impact on environment [21–23].

2.4 Vicuna

The vicuna is the smallest of the wild South American camelids. It lives in the plains, grasslands, and mountain regions of the Andes, at altitudes of 4000–5500 m. Vicuna is the world's most valuable natural fiber, and fabrics produced from it can command up to $3000/m. Vicuna fibers are extremely warm and are possibly the finest of all the animal fibers, with a diameter of 6–14 μm [11, 15].

In the past the huge commercial demand for Vicuna fiber and unrestricted hunting had resulted in the species becoming almost extinct, and it was declared an endangered species. In the mid 1970s, as a result the trade of vicuna fiber was prohibited worldwide. The conservation efforts of Peru, Argentina, Chile, and to a lesser extent Bolivia has led to a dramatic comeback of vicuna herds [20]. As the vicuna population grew, all four countries relaxed the laws and sustainable commercial harvesting is now practiced, it is a cash crop that can benefit some very poor communities. Peru has taken the lead in vicuna conservation; it has introduced a traceable labeling system that shows that a garment has been created through a government-sanctioned "Chacu." Chacu is an Inca term for a ritual tradition where the animals are communally captured and shorn and then released back into the wild. They are tagged to ensure that they are not mistakenly herded again for another two years. The Vicuna and its luxury products are shown in Fig. 6.

Recent crossbreeding with alpacas has resulted in offspring that is called Paco-Vicuna which has a coat that is as fine as that of the alpaca but with a longer fleece than that of the vicuna. This makes the paco-vicuna easier to shear, and it can also be shorn annually rather than only once every three years. The outer guard hairs are easily removed from the shorn fleece. The wool is very sensitive to chemical treatments therefore it is always left in its natural color, which is a rich golden honey [24, 25].

Fig. 6 Vicuna and its luxury products [25]

Loro Piana is one of the world's most prestigious fashion houses, whose passion and dedication are to the sourcing of sustainable raw materials. Close cousins of the humble camel, vicuñas have been brought back from the brink of extinction by luxury fashion brand Loro Piana. Each year, only 13,000–17,500 pounds of vicuña become available to Loro Piana, a major purveyor of vicuña garments—a fraction of the 22 million pounds of cashmere the company works with annually. The Italian tailoring house Kiton makes only about 100 vicuña pieces a year; an off-the-rack sport coat costs at least $21,000, while the price of a made-to-measure suit starts at $40,000. A single vicuña scarf from Loro Piana is about $4000. Ermenegildo Zegna produces just 30 vicuña suits a year. Vicuna has a luxurious lineage going back to antiquity and Loro Piana has smartly secured its supply. Loro Piana Vicuna itself comes in a rather limited array of colors as the fine wool does not take to dying very well and loses its natural beauty. Vicuna typically came in natural colors because of this but Loro Piana has succeeded in adding some variation using very sophisticated dying methods. These are namely warm and very Loro Piana colors like beige, cream, caramel rusty reds, and browns. Handling and seeing the cloth is amazing. The color texture and feel are extremely seductive. The cloth is also available through Loro Piana in scarves, knitwear, and in their Interiors (home furnishings) line in limited numbers [26].

2.5 Guanaco

The guanaco is a vulnerable animal native to the arid, mountainous regions of South America. Guanaco are found in the altiplano of Peru, Bolivia, Ecuador, Colombia, Chile, and Argentina. Guanacos are elegant and fine boned and stands approximately 3 ft 6″ (1.06 m) at the shoulder and weighs around 200 lb [15]. Guanacos have a double coat similar to cashmere; guanaco has a rough outer coat containing guard hairs beneath which lies an extremely soft, silky undercoat, fine fiber that ranges in color from honey brown to dark cinnamon. The undercoat accounts for 80 % of the fleece and once dehaired, the resultant spun fiber is of luxury quality, superior to that of alpaca and second only in quality to pure vicuna fiber. The outer coat consists of much coarser fibers, guard hairs, these are a much darker cinnamon (the belly and neck contain white guard hairs) and act to keep debris and moisture out [27].

Like their domestic descendant, the llama, the guanaco is double coated with a coarse guard hair and soft undercoat, which is about 16–18 μ in diameter and comparable to the best cashmere. The average sheep has a micron of 15–30, fiber itself has fewer scales than sheep's wool, it has a much softer, less scratchy feel, and handle. Guanaco fiber has an average length of about 30 mm. It has more thermal capacity than almost any other animal fiber. Microscopic air pockets make garments that are lightweight with high insulation values [15, 28]. It is also naturally water repellent. It does not shrink during washing or processing and has a lesser tendency to feel when washed. It has a high luster, giving garments a high visual appeal [28]. The guanaco and its luxury products are shown in Fig. 7.

Fig. 7 Guanaco and its premium products [29]

Guanaco fiber is particularly prized for its soft, warm feel and is found in luxury fabric [30]. The guanaco's soft wool is valued second only to that of the vicuña. It is finer than cashmere and three times warmer than wool (Lichtenstein). Dormeuil's exclusive fabric Guanashina® is recognized as one of the most luxurious in the world. Guanashina® is a blend of three precious and rare fibers, Kid Pashmina, Baby Cashmere, and Guanaco, creating an inimitable effect in both appearance and handle.

2.6 Camel Hair

Textiles from camel hair are some of the finest, humanely harvested animal fibers in the world. Camels, those two-humped, desert animals that have played a hardy form of transportation in many historical adventures, also provide us with some of the most amazing fiber for fabrics. Today's luxury apparel market vies for camel hair yarns and textiles, as the slow and humane process of obtaining the fiber makes it one of the scarcest in the world.

The camels have been domesticated for over 3000 years and have been primarily used as pack animals. They shed their coats naturally and the fibers are collected and separated. This down fiber is extremely fine, soft, and warm. Unlike wool, camel fiber lacks the pronounced overlapping scales, and therefore does not feel very well. The fiber structure of camel hair is similar to that of cashmere and it also grows a down undercoat covered by an outer coat of long, coarse guard hairs [11].

The production of camel hair is a five-step process of collecting, sorting, dehairing, spinning, and finally weaving or knitting. Collecting or gathering camel hair is carried out by one of several methods: Combing and shearing, or natural shedding during the molting season. The camel sheds its winter coat in clumps of both outer hair and inner down, which is still hand collected. The second stage

Fig. 8 Bactrian camel and its luxury product application [31]

is sorting, where coarse hairs are separated from the fine soft hairs. It is then washed removing all dirt and debris. The third stage is the final dehairing; this is a mechanical process to remove the balance of the coarse hairs, dandruff and any vegetable matter, before the raw fiber is spun. It is only the softer undercoat that is used for premium textiles, either as pure camel hair or blended with lamb's wool. If it has been blended, usually the camel hair is likely to be of an inferior quality or possibly even recycled [15].

The best-quality hair producing Bactrian camels live in the extreme climatic conditions of Inner Mongolia in Northern China and Outer Mongolia. Camel hair is also often blended with extravagant cashmere, obtained from the fine-haired cashmere goats, for a highly luxurious material sought after by high-end apparel manufactures and designers [31]. The coarse fiber is also extremely waterproof, which is why the Mongolian herdsmen use it for coats and the outer layers of their yurts. The Bactrian camel with the luxury fashion products are shown in Fig. 8.

The very best camel hair is from the underside of a Mongolian baby camel and is said to be almost comparable to cashmere in softness. Camel hair is a golden tan color with varying tones of red. Traditionally it is left in its natural color, as this is part of its unique selling point, although contemporary developments in dyeing technology allows it to respond to dye as successfully as wool [32].

2.7 Angora

The wool of Angora (Ankara) rabbit (Fig. 9) is known as Angora wool or Angora. Angora wool is produced only by Angora rabbits and it is the lightest natural fiber ever known; exhibiting original qualities of fineness, luster, and feel, for the production of high value-added luxury items. Angora is often considered one of the "noble" fibers. Angora (Ankara) rabbit is the only animal breed that produces the finest and the longest white silky wool amongst other wool producing animal

Fig. 9 Angora rabbit and the luxury product [32]

breeds such as sheep, goat, lama, alpaca, and camel each at outputs of 5000–30,000 tons annually [11, 15].

Angora hair is unusually long owing to the prolongation of the active phase of the hair follicle cycle: the hair grows for approximately 14 weeks, whereas that of the rabbit with ordinary (short) hair grows at the same rate but for only five weeks. This is due to the presence of a recessive gene in Angora rabbits. The interval between hair collections is a decisive factor in hair length. Though the period of shearing varies due to the length of fiber that is targeted, the Angora (Ankara) rabbits are generally shorn every 3 months, 4 times in a year; which approximates to a total amount of 1 kg. As the Angora wool is shorn from the rabbits, there is no hardship to the rabbits and no rabbits die in the production of Angora wool. The length of Angora hair accounts for its textile value, because it permits cohesion in the thread [32].

Wool is obtained through different shearing or collection methods such as electric or manual shears, scissors, plucking, or depilation:

1. Most commonly used hair collection method is shearing: it is preferred due to its advantages; it is less stressful for the rabbit, less time, and labor consuming, provides protection against cold, and provides possibility of obtaining more wool through shorter shearing intervals. It takes 10–20 min to shear an Angora (Ankara) rabbit.
2. Clipping method (with scissors) increases the amount of sheer wool (less than 10 mm length) because of the post-shearing corrections. It is very important that the skin should not be harmed during clipping. Especially, the nipples are very sensitive to injuries.
3. While plucking thick ended, immature hair is collected. This process takes 30–40 min. In China, wool is hand plucked to obtain the maximum amount of wool.
4. Depilation has long been the technique of choice in France, synchronizing the reactivation of hair follicles with a well-structured coat with good guide hairs. Since the 1980s French breeders have been using a depilatory fodder sold under the name Lagodendron.

A point to be considered very carefully is that Angora (Ankara) rabbit production is labor-intensive and also requires great expertise. The slightest mistake may result in the loss of productive adults: the animals have to be over a year old to return a profit. Hair collection is always a delicate operation and careless sorting irredeemably downgrades the product. Above all, not all climates are suitable: excessive heat and intense light are very bad elements for especially albinos. In cold countries, or in countries with cold winters, the solution is to use buildings that shelter the animals against the rigors of the winter, and to regulate the temperature of the interiors. Recently, denuded animals require special care, however. The feed requirements of Angora (Ankara) rabbits are also very important: a poor, deficient diet will always mean qualitatively and quantitatively poor hair production. The quantity and quality of wool are primarily very much dependent on genes and inheritance of the breed; though factors including feeding, hygiene, age, sex, weight, season, climate, and pregnancy also affect the production and quality of wool. Therefore, selection of pure breed Angora rabbits with high wool production capacity is essential for the sustainability of high quality wool standard [33].

Angora fibers are short, and therefore usually mixed with other soft fibers, such as cashmere and lambs wool. After processing and spinning the yarn may be used (as with other animal fibers), for blends and also to create novelty effects in woven fabrics, but generally angora is more popular for knitwear yarns [15]. Angora is generally viewed as a luxury fiber, and most angora wool products are very expensive, which is reflective of the laborious harvesting process and the small number of cottage industry style producers. China currently dominates world angora production, and is responsible for over 80 % of the 3000 ton global yield.

3 Unconventional Luxury Fibers

Regional textiles are increasingly rare. Most of our clothing comes from familiar sources such as cotton, linen, silk, wool, and man-made fibers. Yet in Philippines, traditional blouses are made from pineapple fiber. In Scandinavian countries, stinging nettles produce fibers that resemble linen. In Japan, special kimonos are made from banana plants that have been nurtured to be especially tender. There is even silk taken from spider webs, rather than silkworm cocoons. It is often difficult and costly to translate traditional fabric-making techniques into mass production.

3.1 Lotus Fiber

Lotus (*Nelumbo nucifera*) is one of the most ancient angiosperms originally planted in South America and now grown in semitropical and temperate zones such as Western Asia, Middle Asia, North America, India, China, Japan, etc. Lotus has a long planting history and abound resources in China. As the collection of ornamental, edible, and medicinal values, lotus is a kind of special crop with unique research value. Almost all parts of lotus, i.e., leaves, flowers, seeds, and rhizomes can be used for both edible and medical purposes [34].

3.1.1 History of the Fiber

The lotus flower is adored for its characteristic of rising above the muddy water, indicating how one can rise above defilements of life. Apart from motivation for life, the plant also provides fibers which are used for making a rare kind of cloth matching with the flawless virtues of the silk. Fibers extracted from the lotus flowers of the Myanmar lakes are spun by hand and woven within 24 h making a fabric similar to silk [35, 36].

Extracting fibers from lotus stems have been in practice since 1910. Later during the 1990s designers of Japan setup workshops to create a foreign market for their fabric. But due to low demand in Japan, lotus fiber fabric remained a rare and handmade textile. Lotus plant is believed to have healing abilities and wearing a fabric made from lotus fibers is also believed to have the same effects. Lotus plants are pure by virtue, and they radiate this purity through their fibers. By wearing lotus fiber fabrics, one feels calm, peaceful, and meditative. It also cures the wearer from headaches, heart ailments, asthma, and lung issues. The fabrics are 100 % organic, and hence are environmentally friendly.

Lotus weaving was conceived nearly a century ago when a woman named Daw Sa U picked a lotus flower from Inle Lake to offer at a Buddhist temple. A variety of lotus called *Padonma Kyar* grows wild in the shallows of the lake and produces a large, fragrant pink flower. Daw Sa U saw thin fibers trailing from the end of the lotus stem and was inspired to create a thread from the fibers, and from those threads she wove the first lotus robe (*Padonma Kyathingan*), which she offered to a venerable Buddhist monk from Golden Peacock Hill. In return, the monk renamed her Daw Kyar U (Madam Lotus Egg) and she continued to create lotus robes throughout her life, including small robes for the Buddha statues at Hpaung Daw U Pagoda, the most sacred shrine on the lake [36, 38].

3.1.2 Production of Lotus Fiber Yarn

The entire process of fiber extraction, spinning it into yarn and making the fabric is completely handmade making the process time consuming. This also limits the quantity of the fabric produced. Stems of the lotus plants are collected, cut, snapped, and twisted to expose their fibers. Ideally, the lotus flower should be in full bloom when the stems are picked, and the deep pink flowers contain the best lotus fibers. Various stages in extraction of fiber from the lotus stem is shown in Fig. 10.

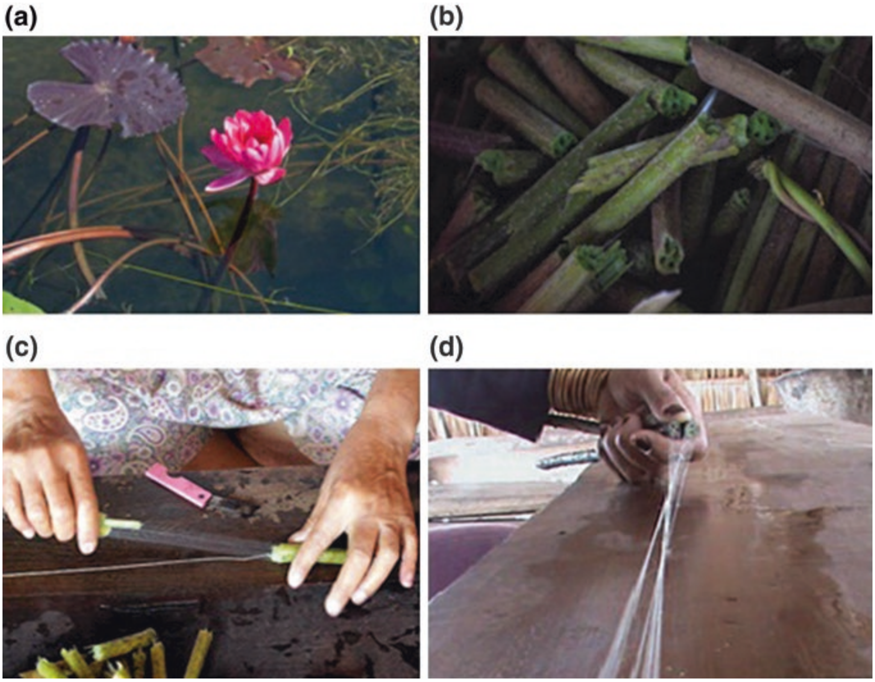


Fig. 10 Various stages of extraction of fiber from lotus stem **a** Lotus flower with stem. **b** Broken lotus stem. **c** Extraction of lotus fiber from stem. **d** Hand twisting the bundle of fibers for weaving [34, 36]

Once a stem is picked, its fibers are extracted within 3 days while still fresh. The lotus leaf stems are gathered in the morning. On a small wooden table, after removing the nubbly prickets with a coconut husk, a handful of about five stems are simultaneously cut, which are quickly snapped off and twisted to reveal some 20–30 fine white filaments that are drawn and rolled into a single thread which is coiled onto a plate. Then, the fibers are spun, washed, and woven. It takes approximately 15 women making thread to keep one weaver busy. A small neck scarf requires about 4000 lotus stems, a large scarf requires about 40,000 stems, and a full set of monk's robes (30 m) requires about 220,000 lotus stems and 60 weavers to complete over a 10-day period [34, 36].

Fibers extracted from the stem are spun into yarn (Fig. 11). Extracted fibers are placed in the skeins on a bamboo spinning frame preparing them for warping. Yarns are made by placing the fibers on a bamboo spinning frame and transferring the thread into winders for warping. With much care, not to get tangles, threads are made; up to 40 m long. The threads are then taken from the warping posts, and are coiled into huge plastic bags. Yarns for the weft are wound into bamboo bobbins [38].

Fig. 11 Lotus yarn [38]

3.1.3 Weaving of Lotus Fabric

Lotus fabric is woven on a traditional Cambodian frame loom. Weaving components include a cloth beam, a large warp spacer–beater, and a pair of heddles supported by a transverse bar resting above the frame. The heddles are connected by rope to a pair of wooden, disk-shaped foot treadles. There is no warp beam on a Cambodian loom. The excess warp is stored behind the weaver and released as weaving progresses. This limits the width of cloth woven to around 24″ (60–75 cm). The use of a temple keeps the selvages straight while water is on hand to moisten the threads during the course of weaving. Given the aquatic origin of the fabric, weavers feel that lotus fibers need to "remain cool." The lotus fabric is woven in 100 yard (90-m) batches, which take about a month and a half to complete. The weavers have estimated that fibers from around 120,000 lotus stems are needed to weave a set of monk's robes. The cambodian lotus fabric is then dyed either with chemical or natural dyes to a reddish-brown shade before being cut into patches of different sizes and machine sewn together in rows to resemble the mosaic-like appearance of community-owned rice fields prevalent at the time of Buddha. Figure 12 shows the handweaving, dyeing, and the resultant luxurious lotus fiber fabric [34–37].

3.1.4 Properties of Lotus Fabric

The lotus fabric looks like a blend of linen and silk, with unique properties, such as being light, soft, and special breathable. It was not as warm as the cashmere but it breathed like linen without wrinkling badly and repel stains as well. Cool in summer and warm in winter, lotus fabric is highly breathable and wearable

Fig. 12 Weaving of lotus fabric and its application [37]

year-round. With a texture similar to raw silk and linen, lotus fabric is soft, lightweight, and naturally waterproof. Besides its supposed calming powers, the Burmese claim that it helps relieve headaches, neck aches, and health issues related to the throat, lungs, and heart [35, 38].

As Myanmar opens its doors and shares its cultural treasures with the world, lotus weaving stands out as a unique cultural heritage that will not remain "undiscovered" for long. Recently, Italian fashion designer Loro Piana developed a line of lotus clothing and introduced it at the Parisian design fair. His 100 % lotus double-breasted sport jacket valued at around €4000 ($5600) made waves in the luxury fashion world. Japanese buyers have also shown great interest in the lotus fabric.

Due to the limited number of lotus plants on Inle Lake and the thousands of lotus required for a single garment, lotus stalks are now being brought in from elsewhere in Myanmar to meet the growing demand. For long-term development of this micro-industry, sustainable lotus growing and harvesting practices are needed, as well as respect for the lake's fragile ecology, the Intha ("sons of the lake") people and culture, and the Guardian Spirit of the Lotus [38].

3.1.5 Future of Lotus Fiber in Luxury Market

As one of the world's top fashion labels, Loro Piana's latest extraordinary venture has the announcement of the "discovery" of a natural and antique raw material, never before used in the textile industry of Western countries: the Lotus flower fiber (*Nelumbo Nucifera*). Extracted from the stems of these sacred flowers which grow naturally on Burma lakes, especially on Lake Inle, this extraordinary raw material has an unmistakeable morphology, similar to perforated tape, light in weight and breathable. It is one of the finest aquatic fibers ever weaved.

The resulting fabric has the appearance of antique linen or raw silk, with an irregular weft; it is soft, exceptionally breathable and crease-resistant. Available only in its natural color (ecru), it will be offered during the forthcoming months in extremely limited quantities (20/30 cuts) and packed in special Burma lacquered boxes, resulting from the local century-long craftsmanship. The Lotus flower represents for Loro Piana another opportunity to support a magic, marvelous world threatened with extinction. Through cooperation with the local population, this material can be introduced to and appreciated by enthusiasts of extreme quality and nature. The development of this project will give the native people, the Intha, the possibility to work in their original environments, so this very antique tradition will not be lost. On the contrary, it will become the means to support future generations, thus allowing this art to survive.

3.2 Milkweed Fibers

Milkweed, a perennial plant can adapt to adverse soil conditions, is being considered as an alternative source of fiber in recent years. Milkweed belongs to the genus *Asclepias*, with over 80 distinct species of which 45 are indigenous to the United States [39, 45]. It previously belonged to the family *Asclepiadaceae,* but is now classified into the subfamily *Asclepiadoideae* of the dogbane family *Apocynaceae*. Farmers and scientists joined hands in the late 1980s to develop milkweed as an alternative fiber source. *Asclepias* species produce their seeds in follicles. The seeds, which are arranged in overlapping rows, have white silky filament-like hairs known as silk or floss. The follicles ripen, split open and the seeds, each carried by several dried floss, are blown by the wind [40, 42, 46].

After Second World War, the use of floss gained importance though it was difficult to be spun. It was mainly considered for stuffing material. The shortage of kapok during the world war was a major reason for this. The floss is made of fibers with a large lumen and very thin walls that have an elastic springiness characteristic of the kapok fiber. The fibers also have a waxy coating that makes them water resistant.

Fig. 13 Different types of milkweed pods and fiber [42]

3.2.1 Types of Milkweed Species

The four important species of milkweed are:

1. Incarnata Swamp Milkweed
2. Speciosa Showy Milkweed
3. Syriaca Common Milkweed
4. Tuberosa Pleurisy Root

All the species produce tough fibers in their stems which can be used to make cloth, twine, etc. and were traditionally harvested from the dead stems in autumn and winter, a fairly simple process [39–45]. Dry summers produce the strongest fiber. The different milkweed fiber pods are shown in Fig. 13.

3.3 Pine Fiber

Pina fiber is the ingenious fabric derived from the leaves of the Spanish Red Pineapple and is the finest of all Philippine handwoven fabrics. Pineapple fibers are an ivory white color and naturally glossy. This delicate and dreamy cloth is translucent, soft, and fine with a high luster.

3.3.1 About the Plant

Piña fiber is extracted from the leaves of the pineapple plant, Ananas comosus (*Linn*) Merr. The plant, particularly the native or “Red Spanish” variety, has leaves that yield excellent fibers for handweaving. The crop is replanted with new plant in about 3 years and during this period the fruit is harvested only twice [48]. The

Fig. 14 Pine plant [48]

plant has a very short stem, which produces at first a roses of leaves and latter grows longitudinally as shown in Fig. 14. Each plant after fully grown bears a fruit. Between the second harvest and replantation in the third year, the plants are uprooted and are either thrown away or brunt in the fields rendering them practically as agriculture leaf fiber being multicellular lignocelluloses fiber is about nearly 10 times coarser than cotton [11].

3.3.2 Scrapping of Pineapple Leaf

Pineapple plant is widely cultivated for the fruit in tropical and subtropical regions of the world. The leaves of pineapple plant contain approximately 3 % of strong white silky fibers. These fibers can be extracted from the leaves either by retting or mechanical means, leaf fibers are obtained from the leaves of monocotyledonous plant. The fiber occurs in bundles in aggregates of individual cells, with the ends over lapping so as to produce continues filament throughout the length of the leaf. The fibers are concentrated in large quantity nearer to the lower surface of the leaf. The leaves are generally thicker and fleshy often with hard surface. The fibers are held in position by the cellular tissues of the leaf by gummy and waxy substance [49–51].

The machine used for scrapping the pineapple leaf has three rollers, (i) feed roller, (ii) leaf scratching roller, and (iii) serrated roller as shown in Fig. 15. The leaves were fed through the feed roller and then passed through the scratching roller. The upper surface of the leaves is first scratched by scratching roller blades to remove the waxy layer and then passed through the serrated roller where the closely fitted blades of the roller macerates the leaf and produces several breaks on the leaf surface for easy entry of the retting microbes [51].

Fig. 15 Scrapping machine of pine leaves [50]

3.3.3 Extraction of Pineapple Leaf Fibers

Extraction of fibers means separation of fibers from the commenting subtonics such as pectin's or lignin's, wax resins, fats, and other carbohydrates, fibers from vegetable plants are extracted by any one method, retting or mechanical. The choice of extraction method will largely depend upon the quality of fibers to be regained. After extraction the fibers are thoroughly washed and dried. For extraction of fibers, the leaves are to be harvested and used due to presences of gummy matter near about 17–18 % on the total weight of fibers. The extraction of fibers can be done by three methods [49, 50].

(a) Hand extraction method
(b) Retting Method
(c) Raspador method
(d) By decorticating machine

Pineapple Fiber Extraction by Hard Working Hands

In spite of all the advancements in mechanization introduced, hand extraction is the most prevalent method for extracting fiber pineapple out of pineapple leaves. In this method, pineapple leaves are scraped using a coarse stone or knife as shown in Fig. 16 and the extracted pine fibers are shown in Fig. 17.

The outer layers of the leaf are removed and what remains is the fine fiber. Hand scraping of the leaves must be done in the first 3 days after harvesting. If left any longer, the leaves will become dry and the fibers will be difficult to extract. The gathered leaves must be sorted to remove any damaged, diseased, or broken leaves.

Extraction of Fibers by Retting Method

This is very old and conventional method used for obtaining fibers from pineapple leaves. This method is very economic but it is very much time consuming.

Fig. 16 Hand scrapping of pine leaves [49]

Fig. 17 Extracted pine fibers [50]

The first stage of obtaining the fibers from the pineapple leaves is called as retting which consists of softening of pineapple leaves in water. In fermentation bacteria developed into the process degrade the partition of the softer cells of the leaf leaving the fiber cells unaffected there by facilitating the separation of fiber bundles (2–4″ in length). After retting the leaves are removed and dried. After drying the leaves are subjected to breaking. It is the first mechanical process to which pineapple leaves are subjected. This is done manually by beating with hammer [53].

Raspador Method

The pineapple leaf fibers are also extracted mechanically by using the machine called "Raspador" which was invented and patented in France. The machine consists of a rotating beater mounted on a shaft. A number of blades are mounted on the circumference of the beater for beating purpose as it is driven by an electrical motor. As the beater rotates one end of a bunch of leaves (6–8 in numbers) are fed slowly between the beater and the feed plate while the other end is held firmly by the operator when the leaves are halfway through it is pulled back and the other half is fed in the same manner. Due to crushing, beating, and pulling action the pulpy material gets removed. The leaf fibers are then washed and allowed to dry [52].

Decorticating Machine

To increase the pineapple leaf fiber production and enhance the quality of the fibers SITRA has developed a decorating machine. The main principle consists of alternatively beating and scratching of the pineapple leaf as they are fed at constant rate through a pair of feed rollers. Both plain and toothed beating blades are placed alternatively to perform beating and scraping action [54].

3.3.4 Pineapple Leaf Fiber Properties

The physical properties of pineapple leaf fiber are as shown in Table. From table it can be studied that fiber tenacity and L/B ratio of the pineapple leaf fiber suggest that pineapple leaf fiber is superior to jute and therefore stringer and finer yarn (finer than 100 % jute yarn) could be spun using pineapple leaf fiber. Porosity and swelling of pineapple leaf fiber indicates its suitability for good dying, moisture absorption, and feel. Moisture regain of pineapple leaf fiber is about 12 % due to this pineapple leaf fiber has higher dye absorbing tendency as compared to cotton fibers.

3.3.5 Weaving of Pine Fabric

Handwoven piña cloth embroidered intricately were greatly prized then and believed to have matched, or even surpassed, the most intricate laces or other luxurious handiworks in vogue in Spain and France at the time. Piña cloth was such an important novel cloth material that in 1571, it was used to pay royal tribute or poll tax imposed on the inhabitants. Piña cloth weaving reached its peak of perfection in the late eighteenth century and in the first half of the nineteenth century. Piña cloth became one of the most sought after handwoven materials because it was a suitable wear to tropical climate and due to its uniqueness and beauty, it offered the most feminine and refined look in an age of elegance and romanticism. The handweaving of pine fibers are shown in Fig. 18.

Since pineapple fabric is handloomed by only a few weavers, it is very precious and scarce, which also makes it expensive. One meter of pine fabric costs as high as US$16/m. It is used for table linens, mats, bags, and other clothing items.

Fig. 18 Handweaving of pine fiber fabric [54]

Because it is lightweight but stiff, this sheer fabric can be used in any creative design. These handwoven fabrics can be colored with vegetable dyes originating from leaves, and barks of different trees [47, 55].

Pina fiber is often blended with cotton, abaca, and silk to create wonderful light, breezy fabrics. When woven with silk, it is called piña seda or piña-silk. Piña jusi is blended with jusi (abaca or silk) for strength and sheerness and is less expensive than 100 % piña. Filipino designers are using pina fabric for domestic ethnic designs (like the barong). Recently, Philippine fibers have been promoted to top fashion houses and piña pineapple fabric was officially reintroduced to the world. Global fashion designers are always searching for innovative materials and new ideas to give them an edge in the industry. Pina fibers have the potential to greatly influence fashion [53, 55, 56].

3.3.6 Pineapple Fabric Benefits

- Regal and timeless are the two words that come to mind. In fact, piña is often traditionally used for wedding attire
- lightweight
- blends well with other fibers
- similar in appearance to linen
- softer than hemp
- more texture than silk
- washable and easy care
- no dry cleaning

3.4 Soy Protein Fiber

Although natural protein fibers such as wool and silk have good physical properties and have been used extensively in the textile industry, they are relatively expensive to use and process. In silk, a large quantity of mulberry leaves is required for the production of a very small quantity of silk resulting in an increased cost of production [57].

Soybean protein fibers (SPF) are manufactured fibers, produced from regenerated soya *Glycine Max* soybean proteins in combination with synthetic polymer (polyvinyl alcohol) as a predominant component. The invention of SPF is the contribution of mankind to the protection of natural rare minerals, the protection of resources, the care of the environment, and the consideration of the global balance. It is an active fiber, a new green textile fiber is an advanced textile fiber. It is also known as "vegetable cashmere" or "soy silk." It is made from the soybean cake after oiling by new bioengineering technology. The main component of soybean fiber is it possesses the superiorities of many natural fibers and synthesized ones and it is quite similar to those of cashmere and silk, featuring fine denier, low density, and good tenacity and elongation. The resulting fabric can give cashmere-like hand touch, silk-like luster, cotton-like moisture conduction, and wool-like warm retentiveness [58].

3.4.1 Manufacturing of Soy Protein Fiber

The manufacturing process of soybean fiber is presented in Fig. 19.

Five main production stages can be identified:

1. Separation: "clarifying" the soya bean meal and precipitating out the protein.
2. Solubilisation: dissolving the resulting washed and dried curd to form the "spinning" solution.

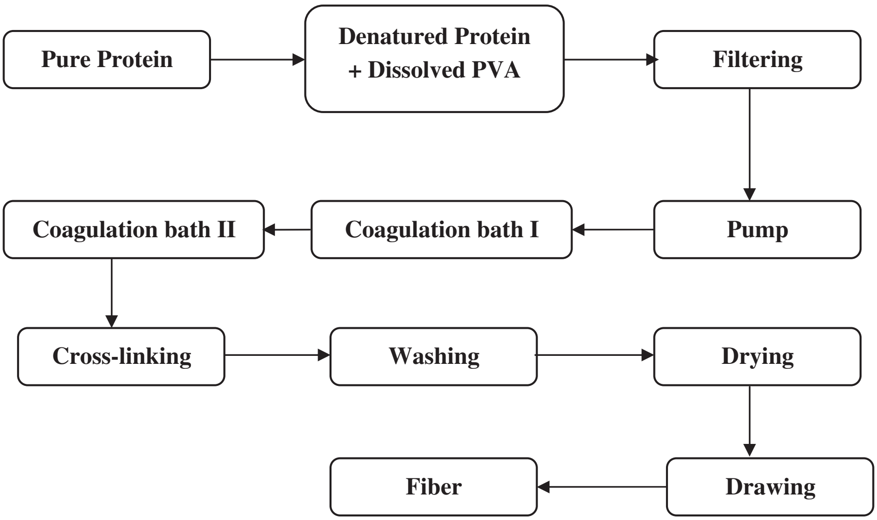


Fig. 19 Manufacturing process of soybean protein fiber [58]

3. Hardening: forcing this solution, when sufficiently ripened, through spinnerets into a coagulating bath resulting in the formation of fibers.
4. Insolubilising: stretching and hardening this fiber, often using formaldehyde.
5. Controlled washing and drying followed by cutting into staple lengths.

3.4.2 Woven Fabric

Weaves made of soybean fiber blends with other natural or chemical fibers have so far been used in shirting and home textiles. A series of such products, too, has already been developed. Their special feature is the luster and soft hand found in silk. Their economic effects are extremely high. SPF are soft and smooth as well as absorbent; it is ideal for products that are worn close to the skin such as underwear, sleepwear, sportswear, and children's and infant's clothes, bed sheets, towels, and blankets [59].

3.4.3 Characteristic of Soybean Protein Fiber Fabrics [60, 61]

- Cashmere feel—The fabric made of Soybean Protein Fiber is soft, smooth, light. It has cashmere feel, but smoother than cashmere; it is as comfortable to the skin as human's second skin.
- Luxurious appearance—To the senses of the consumer, the appearance of a garment's shell fabric shows luster, drapability, and a fine degree of weave. The shell fabric made of soybean protein fiber shows the luster of real silk; its drapability is also very good, giving people the sense of elegance; the textile woven with high-count yarn has fine and clear grain, suitable for high-grade shell fabric for shirts.
- Good comfort—The knitting shell fabric which uses soybean protein fiber has a soft and smooth handle, and the texture is light and thin, with the sense of blending real silk and cashmere. Its moisture absorption performance is equivalent to cotton, and its permeability is greatly better than cotton, ensuring comfort and health while worn.
- Good chromaticity—The natural color of soybean protein fiber is light yellow, very like the color of oak silk. It can be dyed with acidic or active dyestuffs. Particularly when dyed with active dyestuff, the color of product will be fresh and lustrous. With good fastness to light and perspiration, it also has good dyeing brilliance and dyeing fastness in comparison with real silk products.
- Good mechanical and physical performances—The breaking strength of single filament of this fiber is over 3.0 cN/dtex, higher than the strength of wool, cotton, and silk, and only slightly less than terylene and other commonly used high-strength fibers, while the fineness can reach even 0.9 dtex. At present, 6 dtex high-quality yarn can be woven in cotton spinning equipment with 1.27 dtex cotton-type fiber, to develop high-grade, high-count, and high-density shell

fabric. Because the initial modulus of soybean protein fiber is quite high, the boiling water shrinkage is low, and so the size stability of shell fabric is good. In common cleaning, there is no worry about the shrinkage of textile, the anti-crease performance is also outstanding, and it is easily and quickly cleaned and dried.

- Health care function—The soybean protein fiber, with its good affinity to human skin, contains several amino acids and has good health effects. In the fiber spinning process of the soybean protein fiber, the addition of Chinese herbal medicine with the effects of sterilization and anti-inflammation will combine with the side chain of the protein in the manner of a chemical bond. The medical effect is outstanding and permanent, avoiding the disadvantage that the medical effect is less long-lasting when functional products of cotton goods are developed with the after-finishing method.
- Anti-ultraviolet—Its anti-ultraviolet property is superior to cotton fiber, much more superior to viscose and silk. The absorptive of ultraviolet radiation could reach up to 99.7 %.
- Far-infrared function—The emissivity of far-infrared could reach up to 87 %, have the function of heat effect, promoting microcirculation of skin, enforcing the immunity, etc.
- Skin evaporation—Its amino acid can activate the collagen protein in the skin, resist tickling and evaporate the skin.
- Antibacterial—Soybean protein fiber has antibacterial properties that resist colibacillus, staphylococcus aurous, and candica albicans. Fabrics made from soya protein fiber and linen or other fibers are ideal for functional underwear and summer wear.

3.4.4 Recycled Soy Fabric Fiber

Known as "vegetarian cashmere," soy protein fiber is soft and supple with luxurious luster and elegant drape. It has a cashmere feel, but is smoother on the surface. The moisture absorption is similar to that of cotton but its ventilation is superior. Soy fabric has high breathability, excellent absorbency, great color retention, natural wrinkle resistance, and does not shrink from heat as much as other natural fabrics. Soy fabric is extremely durable, with a breaking strength greater than cotton, silk, and wool. The structure and pigment of the fibers make soy fabric easy to color with low eco-impact dyes. And its ultraviolet resistant properties protect it from fading and splotching. So it has vibrant longevity of color. Soy fiber fabric also contains bacteria resisting compounds that actually help protect the body from harmful bacteria [58].

This exceptional eco-friendly fiber is made from the renewable resource of the unused soy protein remaining after the production of other soy products like tofu, soy milk, and soy oil. While this is a chemically intensive process it is a closed loop system, meaning they reuse the chemicals over and over rather than dumping them after a single use. This practice of converting waste materials into other products of better quality or higher environmental value is known as "upcycling." Our "upcycled" soy cashmere is blended with organic cotton and a little spandex for the perfect fit to create an eco-friendly fabric that is both sensual and practical [60].

3.5 Future Prospects of Milkweed, Pine, and Soy Fibers in Premium and Luxury Products

The search continues for the ideal natural fiber—organically cultivated with zero or minimal artificial assistance, ethically manufactured, sustainable, processed without chemical aid, with reusable by-products, and completely biodegradable. Global fashion designers are always looking for innovative materials and new ideas to give an edge in the industry. The applications of nonconventional fibers are limited mainly due to inadequate supply of raw material.

The milkweed fibers have more positive properties to be used as premium and luxury products due to its silk-like lustrous, better moisture transfer properties, and light weight. Milkweed floss is similar in density to high quality down. Milkweed floss transmits 62 % of the maximum amount of perspiration uptake allowed by air. Floss is highly resilient. It has a noncollapsing lumen in both wet and dry applications. The genus *Asclepias* contains over 80 distinctive species, of which approximately 45 are indigenous to America. The milkweed plants are presently gathered in the wild state. For better yield, the milkweed plant needs to be cultivated rather than gathered from wild state. If cultivated, they are perennial and need little irrigation and attention compared to cultivation of cotton fibers. The milkweed plant can adapt to almost any soil condition from swampy and moist to sandy and arid. It is a perennial plant and hence, once planted does not require replanting each season. This encourages as an alternative crop because theoretically it should be easy and economical to cultivate. Like cotton, the milkweed seeds are planted in the month of April/May and harvested in the month of September/October which produces good quality fibers compared to fiber harvested in the second season in the month of March/April. In cultivation, only 3–5 % of the flowers produce mature pods. The analysis showed reveals that, approximately 400–500 matured milkweed pods are required to get 1 kg of milkweed floss. The average yield of milkweed plants is in the range of 550 kg/ha, which is lower when compared to cotton fibers. Successful commercialization of milkweed as a crop is dependent upon mechanized harvesting, handling, drying, and floss processing system. To improve the yield of milkweed plants, first thing to be considered is selection of superior strains and hybrid seeds and then the proper cultivation methods. Currently, Natural Fibres Corporation, Ogalla, US is cultivating and marketing the milkweed floss commercially at a price of $ 28/kg. As they are monopoly in this market, the prices are relatively high. The prices will come down when many players enter this market. Currently, Monark Company (Encore3, USA) has commercialized the knitted milkweed fabric for premium sector [61].

Pineapple fiber fabric, due to its inherent qualities of being a bit stiffer than cotton and not as soft as cotton make this fabric unlikely to replace cotton at the fabric of choice for textile production. The major end use of Pina fiber is the Barong Tagalong, wedding dresses, and other traditional Philippine formal dress. It is also used for table linens, mats, bags, and other clothing items. Because it is lightweight but stiff, this sheer fabric can be used in any creative design. The traditional decoration for this fabric is a style of hand embroidery called *calado*. An embroidered piña garment is called piña calado. These handwoven fabrics are colored with vegetable dyes originating from leaves, and bark of different trees. Pina fiber is often blended with cotton, abaca, and silk to create wonderful light, breezy fabrics. When woven with silk, it is called piña seda or piña-silk. Piña jusi is blended with jusi (abaca or silk) for strength and sheerness and is less expensive than 100 % piña.

Pineapple textiles are not a viable large-scale substitute for cotton; however, this fiber can help to lessen the demand for cotton in the future. The large-scale international production of pineapples is associated with the environmental and social problems; however, a useful textile can now be made on a large scale from a by-product of pineapple cultivation. Pineapple fiber can be blended with cotton to reduce the need for cotton cultivation on a world level. In the future, pineapple fiber should be looked at as only a supplemental textile fiber to cotton. There is still a relatively high price tag on pina cloth and a limited number of suppliers worldwide. The variety and styles of pina cloth are still somewhat limited at this time. Filipino designers are using pina fabric for domestic ethnic designs (like the barong). Recently, Philippine fibers have been promoted to top fashion houses and piña pineapple fabric was officially reintroduced to the world. Pina fibers have the potential to greatly influence fashion. Consumers can play a pivotal role in the reintroduction of pina fabric with demand and support for natural fibers for clothing [62].

In order to fully revive this traditional industry, cooperatives need to work together for development, funding, and international fair trade. Currently, designers and retailers are making the most money. The key is to increase profits for the local weavers. Through the return to their ethnic roots and age-old traditions, the piña salvation is just beginning to enter the limelight. Businesses are striving to meet current export orders to Japan, Hong Kong, USA, France, and UK. International awareness, promotion, and marketing of pina cloth will help change the regions economy by putting piña fabric industry on the map. A research team from Brazil has developed a new form of plant fiber-based plastic that is claimed to be stronger, lighter, and more eco-friendly than plastics currently in use. The nanocellulose fibers can be almost as stiff as Kevlar, but that the plastic differs from many in widespread use because the source material—such as pineapple and banana—is completely renewable. The pineapple leaves and stems, or the closely related curauá, could be a promising source of readily available nanocellulose. The leaves and stems are placed in a kind of pressure cooker, where certain chemicals are added to the mix. After several heat cycles, a fine powder is produced which could be used for manufacturing of automotive composites [63].

Soy fabric has sparked the interest of designers to utilize soy yarn to weave into garments. Most of the styles produced so far tend to be relaxed and casual. Soy is breaking into the marketplace with a promising future ahead of it. China, the largest textile manufacturer and exporter, has begun mass producing soy-based yarn. Right now soy clothing is mainly found as underwear, socks, scarves, sheets, and yoga or exercise apparel. It is also a popular choice for very soft, comfortable baby clothing. Soy can be blended with other textiles like cotton, bringing the benefits of each to fabrics and beautifully colored using low-impact dyes. A big selection of clothing is hard to find and since the nature of soy is to be very soft most styles are casual and relaxed [64].

Bombay Dyeing has a range of soy bath towels in their premium home range, available at select retail outlets across the country. Naina's Apparel Private Limited, another Mumbai-based export house, have featured soy in their collections (for retail and export), but in limited pieces, due to higher manufacturing costs. Faeries Dance an earth-friendly fashion shop carries soy fabric clothing with a little style and fun. That green sweater at the top of the page is a soy fabric blend from their line [65].

4 Conclusion and Recommendations Going Forward

Environmental and social impacts of the fashion industry are growing, but there are many ways that we can not only reduce negative environmental impact, but also increase positive environmental and social benefits through informed choices of materials and intelligent design. The search continues for the ideal natural fiber (where it all begins)—organically cultivated with zero or minimal artificial assistance, ethically manufactured, sustainable, processed without chemical aid, with reusable by-products, and completely biodegradable.

The term "Luxury" is a buzz word in the high-end fashion industry. The luxury comes for a textile material is not because of the designer or because of a brand. The terminology comes from the quality of the material and also due to the sustainable/eco-friendly manufacturing process. Hence, the products are often with high price range. In order to fulfill the requirements of the ever-changing market, designers always look for new colors, fabrics, styles etc., to offer designs to the market. In today's world, fashion is not limited to esthetic look of the garment but also functional features of the garment play an important role. Further, due to increase in expectations of the consumers, designers as well as manufacturers are also focusing on the new dimensions of fashion by using unconventional fibers.

The chapter mainly focused on utilizing the natural conventional and unconventional fibers in the era of luxury textile fibers and fabric, with the idea of reducing the carbon footprint level of each manufactured luxury product. The shift toward lighter, softer fabrics is changing in today's textile market. In addition to improved milling techniques and an increased appetite for novelty, changing life styles have brought a dramatic transformation in the fabrics that high-end consumers are looking for.

In the first section of the chapter, the possible animal fibers like silk, cashmere, alpaca, vicuna, guanaco, camel hair, and angora fibers were discussed along with their verity and availability. The section also discusses about the different limitations and advantages about the animal fibers in the sector of luxury fashion and textile. The specialty hairs presently have vital spectra in the ever-changing fashion world. Utilization and application of specialty hair is the emerging trend, growing slowly yet steadily. The qualities of specialty hair fabrics appear different individually though found to be similar in most of the cases. It is no secret that the world's softest garment fiber comes from a docile and adorable animal called Angora rabbit and it has huge commercial value. These fibers possess excellent thermal characteristics and hence provide the necessary comfort in cold weather clothing. Innovative blends of these fibers with wool, cotton, and other fibers need to be explored to produce value-added products with improved yarn quality characteristics at an acceptable process cost is still a challenge for the spinners.

The second part of the chapter details the unconventional textile fibers like lotus, milkweed, pina, and soy fiber. Where, the fiber separation methods, fabric manufacturing technologies, and the benefits and limitations of individual fibers were enlightened in detail with respect to the luxury-based textile applications. Till date, most of the pineapple fibers are used for making traditional dresses. Recently, pine fibers have been promoted to top fashion houses and pina pineapple fabric was officially reintroduced to the world. Pina fibers have the potential to greatly influence the fashion. As pina fiber production gains momentum, thousands of jobs for weavers will be created. This will lead to huge potential and economic rewards for indigenous weavers, their families, and their communities.

Among the discussed conventional and unconventional fibers many of the fibers were still in the research level. The commercialization of the product or development of fibers in the industrial aspect or in the bulk quantity is not achieved due to the technical problems. Especially in the unconventional fibers, the availability of the raw material is abundance, the utilization in the manufacturing sector is very meager. Hence, the opportunities in this unconventional fiber research opens a new era for the fashion designers and fabric manufactures to explore more in the luxury sector. At the same time, unlike the synthetic or artificial materials the impact of those products on the environment and ecosystem is considerably less. The luxury sector in the textile and fashion industry has very high-end users, hence, the researchers can focus on reducing the carbon footprint of the individual manufacturing process of the material, from plant cultivation to fabric manufacture rather than the cost reduction by using artificial materials and process.

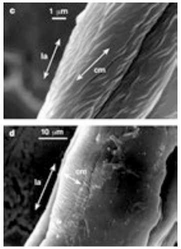
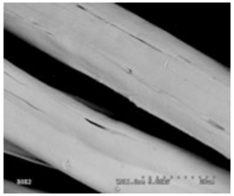
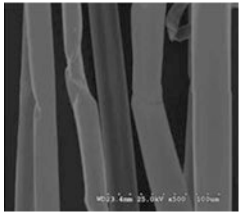
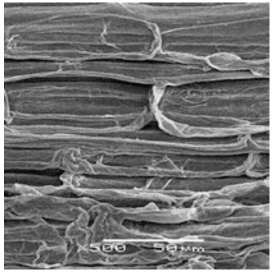
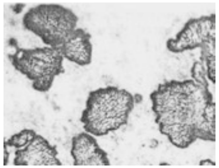
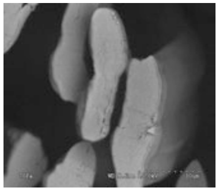
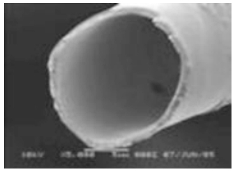
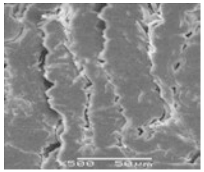
The application areas are not limited with the apparels. The textile materials are nowadays used in various sectors especially based on the luxury requirement. Home furnishing sector is one of the major markets where the luxury textile materials widely have been used. These fabrics will bring luxury and elegance to homes and other interiors where only the finest quality will suffice. Fabric used for decorations such as curtains, bed sheets, covers, and so on, must have their properties which make them ideal for specific purpose. Natural fiber is usually made of natural supplements and often expensive to be used in this sector. However, as its name suggests natural fabric is more durable, soft, luxurious, and resilient. Some of the commonly used natural luxury fibers that are used to make fabric are silk, hemp, wool, horsehair, cashmere, mohair, camelhair. Rubelli, Ralph Lauren, and Etro textiles are the world's leading top three luxury home textile producers. Most of these companies are still completely handmade on traditional looms, the way it was done hundreds of years ago. For rubelli, the handmade products are the iconic trademarks. All textiles are produced from natural materials—linen, silk. The Ralph Lauren textiles have excellent quality and great design. Impressive upholstery and drapery fabrics always become an outstanding and memorable detail of the interior. The most popular designs include floral, leopard, and geometric patterns. The hallmarks of Etro textiles are the famous Paisley motif which gives to them oriental flavor and sumptuous look. The founder of the brand Gimmo Etro from the beginning has set the goal to produce the most luxurious and quality fabrics made only from natural fibers—silk, cashmere, cotton, and linen.

The next important potential sector is luxury brand automotives upholsteries. The high-end cars like Mercedes, Lamborghini, Jaguar, and Rolls-Royce., were utilizing textile fiber-based upholsteries either with functional requirements like sound and thermal insulation or with the decorative aspects. Recently, Rolls-Royce Motor Cars Ltd recognized the trend of individual personalisation and subsequent rise in bespoke customer commission. The importance of luxury fiber was apparent in Serenity, a Phantom Extended Wheelbase, created in the finest quality raw silk, hand painted and hand embroidered with a tree in full bloom, evoking an atmosphere of calm tranquility. The fabric has been designed to provide texture to the interior of the motor car. Each thread has been hand placed to reflect light and bring the motif to life. The designers feel that bringing the evoked notions of the Emperors from the Far East into a car design makes them more luxury. Hence the designers selected the materials and textures used in this culture, where the silk defined opulence, the color of the raw silk we used could often be found in robes worn by the Japanese Royal Family, and the Blossom motif in full bloom, which envelops the motor car, is to this day often viewed as a symbol of hope and renewal.

In all the cases, the primary and important factor which influences the customer is the appearance of the product, how pleasing they are matters much. However, nowadays the customer also bothers about the environmental impacts of the products they purchased. Hence, the companies were more focused on these kinds of sustainable fibers. This ultimately reduces the carbon footprint and improves the sustainable nature of the product. The designers and fabric manufacturers who focus in this sector have huge potential with the conventional and unconventional fibers. This chapter is an insight to the available details of various luxury-based fibers. The impending scope of these fibers were also heartening the researchers and manufactures in the era of sustainability and luxury.

Appendix

Physical and chemical properties of unconventional fibers

	Pine	Soybean fiber	Milkweed	Lotus
Plant family	Bromliaceae	Fabaceae	Asclepiadaceae	Nelumbonaceae
Genus	*Anans cosmo's*	*Glycine*	*Asclepias*	*Nelumbo nucifera*
Longitudinal appearance	Ovuliferous scale with two-layer structure, sclerids 	Bean-shaped 	Smooth, single cell, cylindrically shaped, without any convolution 	Strips and cracks 
Cross section		Bean-shaped 	Oval to round 	Slitting 

(continued)

Table (continued)

	Pine	Soybean fiber	Milkweed	Lotus
Diameter (μm)	–	–	20–50	3–4
Linear density (tex)	2.44–3.56	6.2 tex	0.11	2.54
Length (mm)	3–9	38	20–30	50–150
Strength (cN/tex)	30–51	2.5	16–25	1.71
Elongation (%)	2.5–3.5	18–21	1.5–3.0	6–7
Moisture regain (%)	11.5–12	8.6	10.5–10.9	9.3
Density (g/cm^3)	1.5260	1.29	Wall density—1.4	–
			Considering lumen—0.27, wall thickness—1.4 μm	–
Chemical composition	α cellulose—69.5 %	–	Cellulose—55 %	Cellulose—77.42
	Hemicelluloses—16–19		Hemicellulose—24 %	Hemicelluloses—6.87
	Pentosans—17.8		Lignin—18 %	Lignose—10.73
	Lignin—4.4		Extractables—3 %	Pectin—1.34
	Fat and wax—3.3			Lipid wax—1.05
	Pectin—1.1 Nitrogenious matter—0.9			Water soluble matters—2.59
Crystallinity (%)	57.5	–	32–39	–
Degree of polymerization	1178	–	4000	–

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Part II
Sustainable Production Processes

Sustainable Processing of Luxury Textiles

Mohammad Mahbubul Hassan

Abstract Luxury textile industries are in a big dilemma. On one hand, they need to uplift their brand value, and on the other hand they need to support sustainability as the consumers of luxury textiles are rich and literate. They are particularly more concerned about the sustainability issues. Like those of other textile industries, the luxury textile industries are under intense consumer as well as stakeholder scrutiny. The demands of consumers are not only limited to the marketed products being safe, but also that they are processed sustainably under safe and humane conditions. The sustainability issues are based on four main pillars: environmental, social, ethical and economic. The recent recession showed that weakening of social and economic pillars affect the environmental and ethical pillars. When recession starts to have an effect, the environmental and ethical pillars become neglected. In this chapter, what type of fibers are used in luxury textiles, what is meant by 'sustainability' and why it is important in luxury textile industry, how it is measured and the future trends to make luxury textile processing sustainable are discussed.

1 Introduction

Sustainability in textile processing is a recent realization and is being increasingly recognized in the developed countries. Textile processing industry is conceived as one of the largest industrial polluters, but employs a large number of people. Luxury textiles are also processed in the same way as traditional textiles are processed and therefore have similar effect on the environment. Unlike traditional textile processing industries, luxury textile processing industries are small boutique-type industries and sometimes do not have properly trained staffs. Therefore,

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there is a chance for unethical work practice. However, the consumers of the luxury textiles are literate and are from the upper segment of the society than the average consumers. Increased media focus on sustainability, provenance, and the environment is striking a chord with consumers, in all types of products including luxury textiles. Consumers start to question how safe is the fashion apparel they are putting on their bodies, what are the impacts they have on the environment and how ethically they are manufactured?

To achieve a greater degree of sustainability in our industrial processes and systems related to luxury textiles, we need to achieve a better balance between the social, economic, ethical and environmental aspects of textile production. Most of the times, emphasis is given on economic aspects of textile production; social, ethical and environmental aspects are neglected. The recent recession showed that weakening of social and economic pillars affected the environmental and ethical pillars [1, 2]. Luxury textile industries have to overcome this kind of mentality and have to make production processes truly sustainable. For textile industries, the main concerns are: environmental pollutions (air, water, and land), resources, safety of workforce, consumer safety and satisfaction, and communication of sustainability issues with brands and retailers. Global and regional brands and retailers are focussing on the increasing performance demand of the growing middle class consumers of the emerging economies including China and India. In this chapter, fibers used in luxury textiles and their processing, importance of sustainability in luxury textile processing, assessment of sustainability, environmental impacts of luxury textile processing and their carbon footprint, and future trends in sustainable processing of luxury textiles will be briefly discussed.

2 Fibers Used in Luxury Textiles

Before beginning the discussion on sustainable processing of luxury textiles, it is necessary to discuss briefly what fibers are used in luxury textiles. The fibers used in luxury textile can be categorized mainly into two groups as follows.

The following are the major fibers used in the manufacture of luxury textile products (Fig. 1).

2.1 Fibers from Insects

The main luxury fiber produced by insects is silk, which is known as the “Queen of Fiber”. It is produced by the larvae of several insects, categorized as silk worms and also by some other insects (mainly spiders). Silk is prominent for its exceptional luster as well as for its strength, elasticity, softness, and handle properties. Silk is a natural fiber that mainly comprises fibroin and sericin proteins. In raw silk, two silk fiber strands are joined together by a gummy protein called sericin,

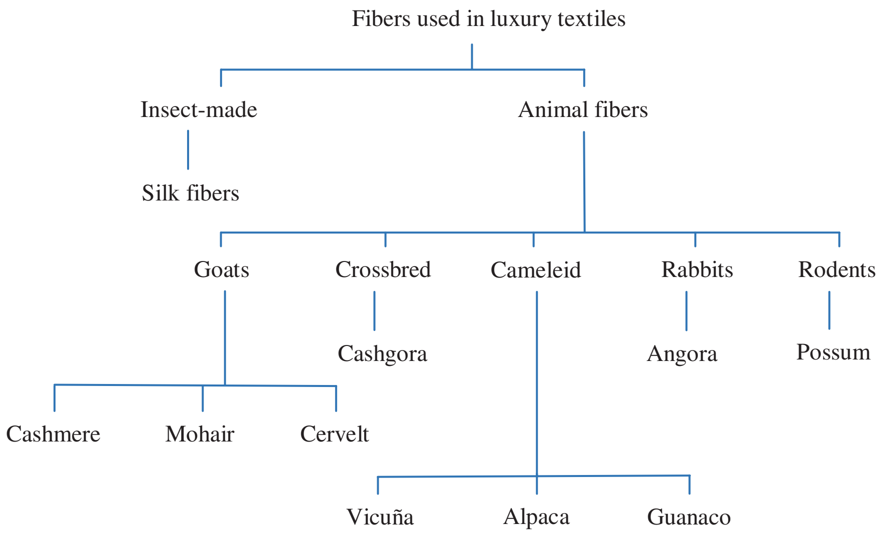


Fig. 1 Classification of fibers used in luxury textiles

Fig. 2 Silk cocoons and a fabric made with silk fiber

which is removed by a process called 'degumming' to ease dyeing and also to make the fiber soft. The silk fiber used in making various consumer goods is mainly fibroin protein. Silk fibers are not only used for making neckties, coats, jackets, and fashionable ladies wear, but also in manufacturing rugs and carpets. Because of its high tensile strength, silk is also used as natural non-absorbable sutures [3, 4]. Silk suture is still used, mainly to secure surgical drains and is marketed by several companies under various brand names such as PERMA-HAND® by Ethicon, Inc. (USA), DemeSILK™ by DemeTech Corporation (USA), SILK by Teleflex Medical, Inc. (USA), SofSILK™ by Covdien PLC (Ireland), etc. Figure 2 shows silk cocoons and a printed fabric made from silk fiber.

The four main types of silk are mulberry, muga, eri, and tussah/tussar made by quite different insects. The mulberry silk is produced by the larvae of domesticated *Bombyx mori* and it is the most popular of all silks. The larvae of this moth feed on mulberry leaves. It is produced mainly in China, India, Bangladesh, Thailand, and Japan. The muga silk is a wild silk produced by the larvae of the silk worm of *Antheraea assamensis* and is mainly produced in Assam of India. The larvae of this moth feed on som (*Machilus bombycina)* and sualu (*Litsaea polyantha) leaves.* Eri silk is made by the larvae of *Samia cynthia*, which feed on leaves of castor oil (*Ricinus communis*) plant. Tussah silk is produced by the larvae of several species of silk worms, belonging to the moth genus *Antheraea* including, *Anther aeamylitta, Anther aeapernyi, Antheraea roylii* and *Antheraea yamamai.* These silkworms live in the wild forest in trees of *Terminalia* species as well as other fruit-bearing plants like Indian-laurel (Terminalia elliptica), Arjun (Terminalia arjuna), Jambul (*Syzygium cumini)* and Oak (e.g. *Quercus stellata*) found in South Asia and eat the leaves of the trees they live on [5, 6]. Tussar is valued for its rich texture and natural deep gold color.

2.2 Goat Fibers

The following goat fibers are used in luxury textiles.

2.2.1 Mohair Fiber

Mohair is a specialty keratin fiber similar to wool and collected from the Angora goat. It is characterized by its excellent luster, durability, elasticity, resilience, soil and abrasion resistance, excellent moisture management, and heat insulation properties. Mohair fiber is free from medullation and kemp. Currently, South Africa is the largest producer of mohair but it is also produced in the USA (Texas region), Turkey, Argentina, Lesotho, Australia and New Zealand. Although mohair has scales like wool, the height of scales of mohair is 0.4 μm, which is less than half of the height of scales of wool and therefore they have considerably a lower tendency of felting unlike wool.

2.2.2 Cashmere Fiber

Cashmere fiber is obtained from a goat called cashmere and these goats are available predominantly in the Indian-Himalayan province called Kashmir. Locally cashmere fiber is known as Pashmina. Cashmere is acknowledged as one of the finest and softest animal fibers known to the textile industry. It is characterized by its fine texture, strength, warmth, and light weight attributes. It is mainly used in making the famous ‘Pashmina shawl’ in Kashmir. The cashmere fiber is finer than

Fig. 3 Scarves made with cashmere fiber

the merino wool and the average diameter is less than the range 12.7–17.6 μm. However, most cashmere fibers can be differentiated from superfine merino wool fiber by the nature of their cortical cells, the cortex of Cashmere contains mainly orthocortical and mesocortical cells, whereas merino wool fiber contains mainly orthocortical and mesocortical cells.

China is the largest supplier of cashmere fiber, which is also harvested in Mongolia, Afghanistan, Pakistan, Iran, Turkey, and other central Asian countries (e.g., Uzbekistan). Cashmere has slightly lower sulfur and nitrogen content, 3.4 and 16.4 %, respectively compared to wool fiber, which has 3.7 and 16.5 % sulfur and nitrogen respectively [7]. Tucker et al. [8] and Roberts [9] analyzed cashmere fiber to its amino acid composition and found that the amino acid composition of cashmere is similar to the amino acid composition of wool, except that cashmere fiber has slightly higher cysteine and tyrosine but lower proline than wool. Cashmere fiber is also quite expensive but not as expensive as vicuña, Cervelt and guanaco. It is now used in the manufacture of scarves, coats, jackets, trousers, blankets, and other products (Fig. 3).

2.2.3 Cervelt Fiber

Cervelt $^{(TM)}$ fiber falls under the type of deer fiber category, which is harvested from the down side of a particular type of red deer (*Cervus elaphus,* hence the fiber is called Cervelt) available at Douglas Creek area of New Zealand. It is claimed that only 20 g of fiber can be collected from a single deer. The collected fiber is quite clean and has very small level of lanolin. The fiber is one of the finest (only 13 μm) of all animal fibers, finer than the finest cashmere. The fiber is not straight but has curls. The yarns made from them can be characterized by their high tensile strength, elasticity, warmth, softness, and handle properties and the fabric made from it is lighter than the fabric made with cashmere fiber. Yarns are made from them by woolen spinning process, but produce much finer yarn than wool yarns. Cervelt fibers are used in the manufacturing of high-end woven and knit fashion garments including jackets, overcoats, socks, etc., for men and

Red deer | Cervelt fiber-made scarf | Cervelt fiber-made socks

Fig. 4 A red deer, scarf and a pair of sock made with the Cervelt fiber harvested from red deer

women. While Cervelt was used in luxury European fashion houses like LVMH, Hermes and Giorgio Armani, it was the first time the fiber had been used in socks. The fiber is extremely expensive and a pair of socks can cost $1700 [10]. Various products made of Cervelt fiber have been marketed by a New Zealand-based company called Douglas Creek Ltd. (Fig. 4).

2.3 Rabbit Fiber

The fiber collected from the Angora rabbit (Fig. 5) is called Angora fiber. It is dissimilar to mohair fiber, which is obtained from Angora goat. Angora fiber is quite popular because of its softness, fineness, fluffiness, and warmth. The finest Angora is collected from the top and back portion of the animal. It is finer than cashmere fiber and the average fiber diameter is between 12 and 16 μm. Because of lack of elasticity, Angora fiber is usually blended with wool. China produces 90 % of world trade while Chile, USA, and Eastern Europe are also significant producers. The fiber is quite expensive (similar to cashmere fiber) and each kilo can cost $350–$500.

Fig. 5 Angora rabbit from which angora fiber is made and a sweater made with angora fiber

Angora rabbit | Sweater made with angora fiber

Huacya alpaca Alpaca fleece

Fig. 6 Huacaya alpaca and its fleece

2.4 Camelid Fibers

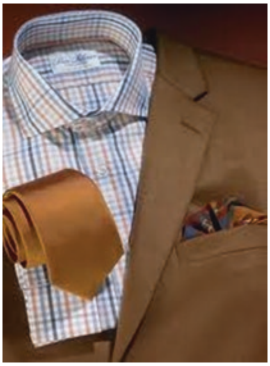
Camelid fibers are collected from a family called Camelidae, and they are large camel-like animals including llama, alpaca, vicuna and guanaco. Yarns are made from the camelids similar to the wool spinning process.

2.4.1 Alpaca Fiber

Alpaca fibers are produced by alpaca (*Lama pacos*), a camelid, which resembles the llama but smaller in size than the llama. Alpaca has two breeds, Suri and Huacaya. The alpaca fiber obtained from Huacya alpaca (Fig. 6) is short and curly but has elasticity and crimp, which makes it suitable for making knittings. On the other hand, the alpaca fiber obtained from Suri alpaca is long and straight and also has crimp, which is suitable for woven fabrics. Alpacas are single coated animals, thus the fleece does not need dehairing. Peru is the major alpaca producer with 90 % of world trade. Alpaca fiber is used in the manufacturing of woven and knittings, similar to wool. These items include blankets, sweaters, hats, gloves, scarves, and a wide variety of textiles.

2.4.2 Vicuña Fiber

Vicuna fiber is harvested from the animal called vicuña, which is the smallest of the Camelids. Vicuña was the royal fiber for the Inca royal family in the Andes mountainous region of present Peru. Vicuñas are mainly available in the central Latin America, mainly in the belt of Peru, northwestern part of Argentina, northern Chile, Bolivia, and Ecuador. The fiber collected from vicuña is quite fine, ranging from 12–15 μm and yields vary from 85–550 g average to 200 g per animal. The surface of vicuña fiber is scaly, similar to wool fiber. Vicuña fiber is used for making apparel (such as socks, sweaters, accessories, shawls, coats and suits), and home furnishings (such as blankets and throws). A vicuña wool scarf can cost around US$1500 and a men's coat costs up to $30,000.



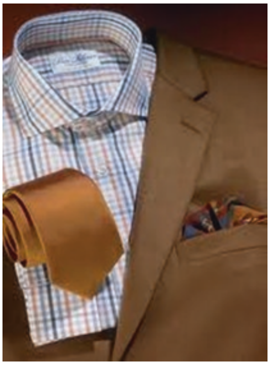


Fig. 7 Guanaco camelid, and also a fabric made with guanaco fiber

2.4.3 Guanaco Fiber

Guanaco fibers are harvested from the animal called guanaco (a family of camelids) herded in the regional belt of central Latin America including Peru, Bolivia, Ecuador, Colombia, Chile and Argentina. It is similar but slightly coarser to vicuña fiber, but similar to the finest cashmere fiber. It costs slightly cheaper in price than vicuña. It is also used for making scarves, overcoats, trousers and socks (Fig. 7).

2.5 Crossbred Fibers

The main crossbred fiber is obtained from an animal, which is a crossbreed between cashmere-producing feral goat and mohair-producing Angora goat. The mean fiber diameter of the cashgora is outside the region of cashmere fiber diameter, i.e. 18–23 μm, and is also free from medullation. The cashgora fiber has elegant sheen which is absent in mohair fiber, even in cashmere fiber and is also easier to spin compared to cashmere and mohair fibers. Cashgora fiber is used in making various types of clothing including jackets and suiting. It is also used in making blankets. The cashgora fibers are mainly produced in Australia and New Zealand.

2.6 Rodent Fiber

Possum fiber is the only rodent fiber, which is obtained from brushtail possum (*Trichosurus vulpecula*), a native to Australia, Indonesia and Papua New Guinea. It is a nocturnal rat-like animal, but bigger than a rat. Possum fiber is mainly produced in New Zealand from a brushtail possum. In New Zealand, there are no predators available for the possum resulting in an overwhelmingly increased

Fig. 8 A possum, and also possum fur, and a fabric made with possum fiber

population, to a level that they are now treated as a pest. The New Zealand Government spends millions of dollars each year trying to control the population of possums. The value of possum was realized only recently, when its fur and fiber found applications in luxury textiles. The surface of the possum fiber is dissimilar to other animal fibers (e.g., wool, angora, etc.) as it has no scales and the surface is smooth which causes high possum fiber shedding when apparel is made from possum-blended merino wool fiber. The fiber is hollow longitudinally, which gives it high warmth, softness and smoothness. They are usually blended with merino wool to make various knitting for women and men. Its fur is also used in making fashionable coats and jackets for ladies and men (Fig. 8).

3 Sustainability of Textile Processing

3.1 What Is Sustainability?

What do the words 'sustainable' and 'sustainable manufacturing' mean? According to the report of the UN World Commission on Environment and Development (better known as 'Brundtland Report'), the definition of sustainable is 'meeting the needs of the present without compromising the ability of future generations to meet their own needs' [11]. The concept of sustainability was originally conceived in Europe in the eighteenth century and was intially introduced in forest and wildlife management; the motto was 'never harvesting more than what the forest yields in new growth' [12]. The word 'Nachhaltigkeit' (the German term for sustainability) was first used with this meaning in 1713 [13]. In 1962, Rachel Carson wrote a book 'Silent Spring' which highlighted the danger of accumulation of pesticides in our environment and linked it with the damage to animal species and to human health. In 1975, the report of 'The Club of Rome' was the first, which predicted that many natural resources crucial to our survival would be exhausted within a century [14]. It was the 'Brandtland Report' which adopted the concept of sustainability and gave it the widespread recognition it enjoys today.

3.2 Why Sustainability Is Important?

The concept of sustainability was developed in the 1970s to combat climate change, damage to the environment, energy shortage, human population, and exploitation of resources. It is believed that the climate change is the result of human activity creating an increased carbon dioxide level in the atmosphere. One of the main contributors in global climate change and global warming is the manufacturing industries. The greenhouse gasses emitted during industrial production are split into two categories: **direct emissions**, from the production facilities, and indirect emissions, that occur off-site but are associated with the production facilities. **Direct emissions** are produced by burning fuel (coal, gas, and electricity) for power or heat, and from leaks in industrial processes or equipment. Most direct emissions come from the burning of coal and gas. For instance, gas and electrical energies are used in textile manufacturing industries and therefore, emissions associated with the generation of gas and electricity by burning fossil fuel at a power plant to make electricity are also associated indirectly to the manufacturing industries. Direct emissions are almost double of indirect emissions [15]. Therefore, it is necessary for the manufacturing industries to adopt sustainable manufacturing processes. Legislative requirements are increasingly being placed on manufacturing industries, supply chain, and businesses to incorporate sustainability into their activities.

Sustainable manufacturing is defined as the production of manufactured goods that use processes that do not pollute the environment, conserve energy and natural resources, and are economically sound and safe for employees, communities, and consumers. Every year, the population of our earth is increasing, which consumes resources multiple times compared to decades ago. For example, the high use of fossil fuel to meet the demand of the manufactured goods, foods, clothes, electricity by the consumers forced farmers and industries to use increased levels of fertilizer and chemicals, which pollute our air and water resources, release high quantity of greenhouse gasses, and also cause the extinction of various species of aquatic and land animals, birds, etc. The resources available in this world are not unlimited and for the survival of our future generations we must leave clean and green environment, and enough resources. Sometimes unethical methods are practiced for getting expensive fiber for making high-end fashion materials, many animals are cruelly killed.

3.3 Assessment of Sustainability

There are few tools available to assess sustainability and therefore it is difficult to understand a manufacturing industry or business contribution to broad sustainability objectives. Ness et al. [16] categorized sustainability assessment tools within the broader objective of lifting the understanding of sustainability assessment from the environmental-focused realm to a wider interpretation of sustainability. They categorized sustainability tools into three main categories: indicators/indices, product-related assessment, and integrated assessment tools. Of the tools available, the Life-Cycle Assessment (LCA, which is also known as life-cycle analysis), calculation of carbon footprint and Higg Index are few tools mostly used to measure sustainability.

3.3.1 Life-Cycle Analysis (LCA)

They are developed to quantify the impacts of industrial processes over their full life, from raw material inputs to disposal of a manufactured product (cradle-to-grave). It has recently been applied to agricultural food and fiber products. The complexity and interpretation difficulties for agricultural LCAs are illustrated by a benchmarking exercise, published by the European company MADE-BY [17]. There are four acknowledged stages to an LCA:

- Goal and Scope Definition: The product, process or service to be assessed is defined, a functional unit for comparison is chosen and the required level of detail is defined
- Inventory Assessment: An inventory of relevant energy use, material input and environmental releases is quantified for each process, then combined in a process flow chart and related to the functional unit
- Impact Assessment: The effects of use and emissions generated are quantified into impact categories
- Interpretation: Results are reported and opportunities to reduce impacts on the environment are systematically evaluated

A life-cycle assessment provides many benefits that allow to:

- Gain broad and comprehensive perspective of any product, system or service carbon footprint in order to reduce it, offset it or both
- Benchmark the performance of alternative or competitive materials, products, designs or packaging systems to identify the best performance and cost-intensive scenarios
- Support marketing claims of more sustainable products, systems, or services

Extensive literature survey found that no systematic and detailed LCA has been carried out for segmental or full processing of luxury textiles. Therefore, discussion will give emphasis mainly of environmental and ethical issues. In the points below mainly environmental impacts of processing of various luxurious textiles are discussed.

3.3.2 Environmental Impacts of Luxury Textile Processing

Silk processing

Manufacturing of luxury silk textiles has less impact on the environment, than that of many other luxury textiles made of other natural (e.g., wool), and synthetic

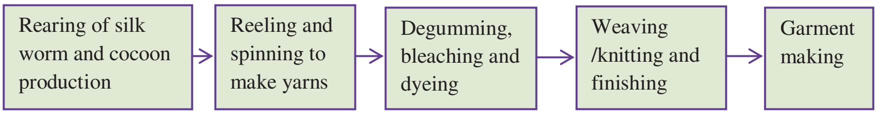


Fig. 9 Typical steps and procedures in the chain of production of garments from silk fiber

fibers (e.g., polyester). The silk worms feed on mulberry leaves, which do not require the use of pesticides or fertilizers to grow.

Figure 9 shows the typical steps and procedures in the chain of production of garments from silk fiber. Silk degumming is carried out with alkali and detergent. Traditionally, degumming is carried out by soaking the silk fabric in a solution of 3–5 g/l Marseilles (olive oil soap) for 6 h at 40–50 °C and then boiled off for 2–6 h in a solution of 8–10 g/l soap at 90–95 °C [18]. It produces effluent and degumming by chemical-free microwave treatment, alkaline electrolyzed water, enzymes, organic acid, plasma treatment, and ultrasound have been investigated as an eco-friendly degumming process [19–23]. Electrolyzed water at pH 11.5 achieved 25 % removal of sericin, but caused tensile strength loss due degradation of fiber. All other silks also degummed in a similar way. Various enzymes also have been investigated for degumming eri, muga and tussah silk fibers [24]. It was found that alkaline degumming caused molecular weight and secondary structure change in eri silk [25]. Sarma et al. [26] investigated a biosurfactant (reetha) for the degumming of muga silk, which provided acceptable levels of degumming. None of the investigated treatment is ideal, as all of them increased tensile strength loss compared to the degumming treatment with neutral soap.

Silk is woven on a wide variety of looms, handloom and mechanized looms. However, most of the luxury silk products are made in handloom, which doesn't have much environmental impact. Luxury silk products are usually made by hand, by small boutique industries with using minimum chemical treatments.

Mulberry silk is bleached and dyed, but other silk fibers are never bleached and dyed for making garments. For some applications, only degummed silk is used without carrying out any bleaching, but for dyeing and printing, the natural color of the silk fabric is destroyed by bleaching mostly with hydrogen peroxide. Bleaching is carried out at low temperatures and therefore has low energy demand than the bleaching of other natural fibers such as cotton and linen.

Dyeing of silk is usually carried out with acid dyes in acidic conditions, which limits damage to the fiber. Sometimes silk is also dyed with acid dyes at mild alkaline conditions which may cause degradation of fiber. Silks are dyed also with natural dyes to give an impression that the whole material is natural but sometimes potassium dichromate, stannous chloride or copper sulfate is used as a mordanting agent to improve wash fastness of the dyed silk. However, copper beyond a certain limit is also under the eco-standard norms as objectionable heavy metals [27]. Potassium dichromate is a possible carcinogen and mutagen [28, 29]. Unethical practice is used to artificially increase the weight of the fabric (weighting of fabric) by soaking in a solution of heavy metals including chromium and lead, which may have serious health effect on the wearer as well as the workers involved in these treatments as they can be exposed to these chemicals. Wash fastness of dyed luxury textiles is an issue, but many leading dyestuff manufacturers developed dyes that show excellent fastness to washing and light. Leading chemical and dyestuff suppliers guide their customers (textile manufacturers) regarding restrictions of certain dyes and textile chemicals.

Nanotechnologies, such as nanosilver and nanogold have been investigated for dying and antimicrobial finishing of high-end luxury textiles [30–32]. Although they provide some levels of antimicrobial protection, the brightness and depth of color are quite poor. A recent study shows that nanosilver is released when nanosilver-treated fabric comes in contact with human perspiration and the exposure risk of nanosilver is much higher in high ionic intensity conditions than the others, which would have important implications for the risk assessment of nanosilver textiles [33]. Moreover, it was found that nanosilvers are released from nanosilver-treated textiles into environment during their washing [34]. However, Mitrano et al. found that [35] the fear of nanosilver release from treated textile is exaggerated as their study shows that textiles impregnated with traditional silver solution release more nanosilver than the textiles treated with engineered nanosilver. However, overuse of these nanosilver and nanogold-treated fabrics may pose serious threats, as released nanosilver not only affects aquatic microorganisms, [36, 37] but also there is danger of formation of silver-resistant bacteria. Therefore, it is better to avoid this kind of controversial treatment for high-end luxury textiles.

Fashion industries sometimes compromise with these unethical practices. Some silk producers use ethical practice and allow the moth to leave the cocoon by making a hole. So, continuous filaments cannot be made from these cocoons and short length filaments (staple fibers) are made from them, which are spun according to the staple fiber spinning system (e.g., cotton spinning system). As machine spinning is used, it involves use of energy, resulting in increasing the environmental footprint of the process. If one is health conscious but adamant to buy silk products, they should select products made of undyed and non-weighted muga or eri silk. Also, one needs to ask the manufacturer whether the silk garments were produced according to Fair Trade principles which protect the workers involved in all phases of producing the clothing. Somebody may suggest to buy silk dyed with natural dyes which may not be a good idea as natural does not mean that it is safe to use.

Animal fiber processing

The processing of animal fibers from alpaca, cashmere, angora, mohair, etc., is quite similar to the processing of wool fibers. The vegetable matters are removed by treating them in a strong acid solution (usually sulfuric acid) which dissolves cellulosic contaminants in the fiber. Figure 10 shows the typical steps and procedures in the chain of production of garments from various animal fibers. Animal fibers need scouring before use or dyeing, which is sometimes carried out with nonylphenolethoxylate-based non-ionic surfactants. These are moderately

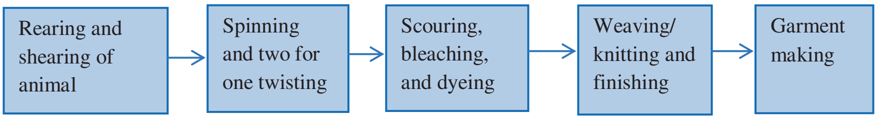


Fig. 10 Typical steps and procedures in the chain of production of garments from animal fibers (mohair, cashmere, angora, vicuña, guanaco, possum and Cervelt)

bioaccumulative, extremely toxic and endocrine disruptors for aquatic organisms and fish [38–40]. Some of the animal fibers, such as alpaca, cashmere have less fatty matters on the fiber surface and show less pilling propensity compared to wool fiber. The fibers used in luxury textiles are usually dyed in fiber form rather than in fabric form. Possum fiber is rarely used alone but is blended with other fibers, such as wool. However the possum fiber surface is smooth, which causes severe shedding of the fiber during use. Possum fiber has inherent strong backing brown or blackish gray color and is very difficult to bleach by traditional fiber bleaching processes, such as bleaching treatment with peroxides and chlorine.

Liu et al. [41], studied bleaching of alpaca fiber by ferrous mordant bleaching process. In this process, fibers are initially treated with ferrous sulfate and ascorbic acid at pH 3 and at 80 °C for 60 min and then washed at 80 °C for 20 min and then again treated with hydrogen peroxide in the presence of sodium pyrophosphate and oxalic acid at pH 6.7 and at 68 °C for 80 min which caused 5.8–7.8 % weight loss. Felting is another problem for animal fibers, as most of the animal fibers felt during laundering. The physical structure of the outer scaly surface of the animal fiber contributes to its shrinkage and felting. Under the mechanical agitation, friction, and pressure in the presence of heat and moisture, the edge of scales of one animal fiber meshes to the inter-scaling space of another fiber like a 'ratchet and wheel' mechanism. Because of this phenomenon, animal fibers interlock, preventing the fiber from returning to its original position. As a result, they bond together and the shrinkage due to felting becomes irreversible. Liu and Wang et al. [42] studied felting propensity of alpaca fiber by Aachen ball felting test method and found that alpaca fiber showed higher propensity of felting compared to wool. Chlorination followed by a treatment with a polyamide resin (Hercosett) is mainly used to make wool shrink-resistant as well as felt-resistant. The other treatment which is used by some industries is the treatment with permonosulfuric acid followed by the treatment with a silicone resin, which has better environmental credentials than the chlorine-Hercosett treatment, but not favored by the industry because of high cost of treatment. However, hardly any animal fiber used in luxury textiles are shrink-resist treated and therefore do not have issues associated with chlorination of wool fiber. Most of the animal fibers are dyed and some are printed. Dyeing of animal fiber is carried at boil, which consumes lot of energy and also at high liquor ratio which increases not only usage of water and chemical auxiliaries but also increases volume of effluent. Animal fibers are dyed with acid, reactive and also natural dyes. Some of the dyes used are metal complexed with copper and chromium which are released to environment through the decomposition of those dyes. The applied dyes are not fully absorbed by the fiber and depending on the dye classes and dye types used, the exhaustion of dye into fiber could be 50–99 %, which means that 1–50 % of applied dyes remain in the bath after dyeing and produces effluent, which needs to be treated before discharging to water courses. The environmental aspects related to mordant dyeing of silk fibers could be applicable to the dyeing of animal fibers.

3.3.3 Carbon Footprint

Carbon footprint product could be defined as the total set of the greenhouse gas emissions from cradle-to-grave. The calculation of total carbon footprint is quite complex and requires a large number of data. There are many software commercially available for the calculation of carbon footprint (e.g., Green House Gas Management, Umberto, Carbon Account, Carbon Diet, CamFor, CAMSAT, C-FIX, CO2-FIX, enVIZI, etc.). The carbon footprint of textile apparels is huge and textile industry is one of the largest contributors of greenhouse gasses on earth. According to the US Energy Information Administration, textile industry is the 5th largest contributor to carbon dioxide emission in the United States, just after the ‘chemicals industry’ in the list [43]. A study carried out by the New Zealand Merino Wool Association shows that the total energy consumed for the production of natural fiber is overwhelmingly lower, compared to the energy consumed for the production of synthetic fibers [44]. The dyeing process is the most energy hungry process in textile processing. Kalliala and Talvenmaa investigated environmental profile of textile chemical processing in Finland and opined that dyeing technologies, with the lowest possible liquor ratio, as well as recycling and chemical recovery possibilities should be encouraged to reduce carbon footprint textile production [45]. The carbon footprint and environmental impact of scouring, bleaching, dyeing, and finishing of luxury textiles will be quite similar to the carbon footprint of silk processing as discussed above, as they undergo similar processing stages and are dyed with the same class of dyes.

3.3.4 Social and Economic Impacts

The process of making silk filaments from silk cocoon (reeling) requires the killing of the moth when the cocoon is boiled, which has been heavily criticized by the animal welfare and rights activists. The mulberry silkworm has been completely domesticated and cannot live without humans for their care and feeding. There are no wild *Bombyx mori* moths living in the wild. Because of the long history of captivity, the *Bombyx mori* evolved into a blind moth that cannot fly and lives only a few days, during which it lays about 500 eggs and then dies within four or five days. The silkworm moth has even lost the ability to eat because of undeveloped structures within their mouth.

Silk for most places is not a local resource, so processing and transportation lead to pollution. To clean silk, many harsh and intensive treatments and chemicals are used, which can pollute the ground water. Producing silk uses a very large amount of resources to produce a small amount, some estimate that only thirty-five pounds of silk come from one acre of mulberry trees. The process is also highly labor-intensive, which requires more work forces than needed for other fibers.

Since 1979, vicuña have been protected by the International Convention for the Trade of Endangered Species (CITES) since 1973 and by the Vicuña Convention signed by Argentina, Bolivia, Chile, and Peru. It ensured the protection of the species in national parks and private lands for future sustainable use, by requiring animals to be sheared alive and returned to the wild. The successful partnership between Government agencies, local communities, and international conservation agencies resulted in a rapid recovery of the population of vicuña, which is now no more in the list of endangered animals [46].The Manejo De Camelidos Sudamericanos Silvestres (MACS) project has generated an important baseline of information on some of the alternative management scenarios for vicuñas and guanacos. It is clear that the use of fiber from these iconic species can make a genuinely positive contribution to sustainable rural development, including indigenous people, as well as providing an economic incentive for wildlife, ecosystem, and conservation. It is also clear that changing the management paradigm from protection to commercial use opens up many opportunities for exploitation, poaching, and inappropriate management practices that could jeopardize this initiative. Killing of animals to get their fur and fibers by unethical and cruel methods is an issue. Recently, major fashion-wear retailers (such as, Calvin Klein, Tommy Hilfiger, GAP and H&M) banned the use of Angora fiber in their products, because of unethical harvesting of fibers from live animals. Possums are poisoned, to kill them for harvesting their fiber, which is quite unethical and shows cruelty to animals.

4 Conclusion

Various animal- and insect-made fibers are used in luxury textiles. Unlike traditional textiles, most of the luxury textiles are handmade, by small cottage-type industries with minimum chemical treatments. Of the chemical treatments, dyeing is the most energy-intensive process as dyeing is carried out by boiling at high liquor ratios. Development of a low liquor ratio and low-temperature dyeing could be ideal for luxury textiles as it will not cause only environmental and economic benefits but also damage to fiber will be minimal. Application of nonyl phenol ethoxylate-based detergents could be replaced with environment-friendly, bio-based surfactants and also dyeing can be carried out without using metal complex dyes and metal salts as mordants. Sometimes production of these luxury textiles is carried out without properly trained people and therefore sometimes could be treated with banned dyes and chemicals. Moreover, sometimes animal ethics and child/forced labor situations are compromised in the case of luxury textiles processing. Implementation of various eco-credentials has a positive impact on improving the sustainability of luxury textiles manufacturing. By using dyes and auxiliaries having low environmental impacts, employing no child laborers, using low liquor ratio and low-temperature treatments, minimizing effluent, using renewable energies, etc., sustainability of processing of luxury textile can be further improved.

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Sustainability in Luxury Textile Applications: A Contradiction or a New Business Opportunity?

Claus Lütke, Ulrike Rübsam, Tobias Schlüter, Achim Schröter, Yves-Simon Gloy, Gunnar Seide and Thomas Gries

Abstract The recycling of textiles is heavily based on the material type and treatment of the fibre material. Especially materials that do not allow a recovery of the raw material in virgin material quality limit the possibilities of textile recycling significantly. This circumstance leads to great amounts of accumulating worldwide textile waste that is not yet processed into new valuable products. In this section, the authors will show two strategies for the re-use and recycling of high valuable fibre materials like polyamide and carbon used in luxury applications. Afterwards, two case studies are presented to validate the presented concepts.

Keywords Fibre recycling · Recycling concept · Carbon fibre · Polyamide carpet · Nonwoven

1 Introduction

In recent years, a growing demand for individualized products, which set the user off from the crowd could be noticed. Such products are only available to a certain group of people due to their innovative novelty, their availability or their price. Therefore, they are described as luxury goods [24]. Luxury goods are often perceived as personal pleasure, while sustainability and recycling are assigned to ethical motivations [1]. Achabou and Dekhili [1] highlights empirical studies in the French textile industry. These studies showed that the application of recycling materials in luxury clothing is affecting customer preferences negatively. This example illustrates, that recycling/sustainability and luxury goods are a perceived contradiction (Fig. 1).

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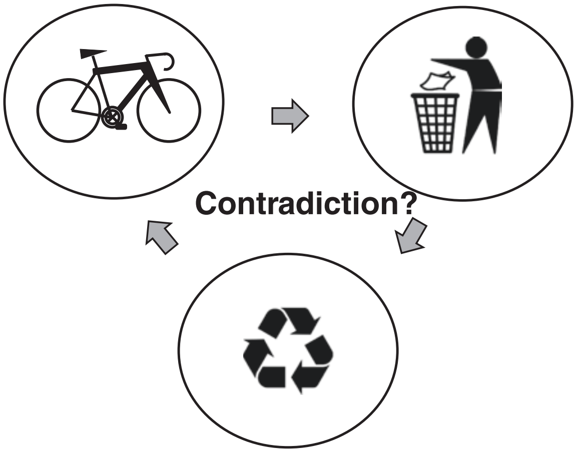

Fig. 1 Sustainability in luxury goods—a contradiction? (*Source* ITA)

However, recent research projects like the EU Framework 7 funded project EcoMeTex (see Sect. 3.1) and the BMBF funded project CAMISMA (see Sect. 3.2) revealed that novel approaches allow the efficient recycling of luxury textile materials, adding new possibilities to the end of life options and increasing the sustainability of luxury textiles. Karus [23] mentions that companies from the field of luxury products started to use the aspect of sustainability to set themselves off from competitors in the market. This strategy upgraded the company's image in the perception of the customers [23] and links luxury to "excellence". By doing this, Karus shows the important role of luxury goods as a role model in the promotion of sustainable resource and product conception.

The following section will first give an insight on the necessary requirements to recycle textiles economically and which different procedures for recycling depending on the material exist. Finally two recycling methods are explained by using practical examples of carbon and carpet recycling.

2 Sustainable Resource Use—Conditions for Successful Recycling Concepts for Luxury Textile Goods

In recent years, a higher demand for individualized products, which set themselves off from the crowd could be noticed. Such products are only available to a certain group of people because of their innovative novelty, their availability or their price. Therefore, they are described as luxury goods [24]. One example from the world of fibres, such as the availability of material, which makes this a luxury good, is the carbon fibre. Therefore, the production capacity of carbon fibres came increasingly to its limits [9]. As a result, the price of these fibres remains high. This is the reason, why the use of luxury products—e.g. Limousines—is paid with a corresponding price, mainly as a distinguishing feature to other customers [38].

Despite the differentiation to other customers, there is also a sensitivity with respect to the price of luxury goods. Because of the customers' price acceptance (i.e. max. 5 € price increase per kg saved in lightweight applications [23]), the use of luxury materials is often limited on refining elements. For this reason—especially in the automobile sector—a mixed strategy has been employed: relatively inexpensive materials, such as steel or glass fibre reinforced composites, can provide the functionality of the product. Afterwards, the product is upgraded with individual modules by the use of luxury materials—e.g. carbon fibre reinforced plastic units [38].

Recent studies have shown that fibres, which are produced with high-priced materials, dispose of high mechanical properties (tensile strength, modulus of elasticity) even after the recovery of components by thermal or mechanical methods [4, 28]. Furthermore, it was shown in these studies that recycled materials—depending on the material—can be provided more cost effective than virgin materials, since the costs for recycling are lesser than the costs for producing new filaments.

It has furthermore to be considered, using the example of Carbon- fibre-reinforced plastics (CFRP), that litigation costs (machinery and labour costs) are responsible for about 30 % of the total cost and accounts 40 % of the costs for fibre material as shown in Fig. 2. This may result in a competitive advantage due to efficient recycling. Because of certain recycling approaches, the costs for the fibre—independent from material and product costs—can be reduced by up to 50 % [4, 7].

Based on these findings from the field of carbon recycling but also from projects with other fibre materials such as thermoplastics, four criteria have been determined at the Institut für Textiltechnik of RWTH Aachen University (ITA), which are necessary for a successful recycling of fibre materials to the new fibre products. However, there is no consideration of down-cycling but of the production of equivalent products.

These criteria are:

1. *Economic or legal pressure*: The price difference between virgin and recycled materials has to be higher than the costs of recycling and the treatment process, in order to make the process economical. Alternatively, there have to be legal regulations, which prescribe recycling.

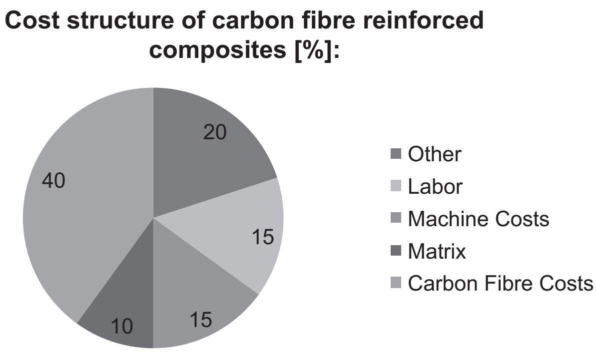

Fig. 2 Cost structure in CFK (based on [9])

2. *Energy consumption*: The energy consumption (measured in the amount of ejected $CO_2/t_{material}$) of the recycling process is lesser than the energy consumption of the production of virgin material.
3. *Material properties*: The material properties of the recycled product or raw material meet the requirements for using them in a new product.
4. *Amount available*: The material has to be available in sufficient quantity as a recyclate to pay off an industrial processing.

For an explanation of the criteria, these criteria are applied to two different fibre examples in the following. On the one hand, this is the recycling of carbon fibres and on the other hand, the recycling of BCF carpet yarns of polyamide.

2.1 Carbon-Fibres

Carbon-fibre waste generated by outtakes, production committees, destroyed components or at the end of the product life cycle of CFRP components, could not be recycled sufficiently [36]. Carbon fibres occur as waste at two different points:

- Primary waste due to cutting- and production errors
- Secondary waste due to errors in the production after applying the matrix, and after the end of the life cycle

Outtakes and production waste can be processed, usually without further treatment, since no matrix material was applied. RCF from end-of-life components and production errors (incl. matrix sheath) are currently acquired by undergoing a pyrolysis process (e.g. [29]) or the chemical dissolution of the matrix (e.g. [2]). The majority of the resulting carbon fibre waste is currently disposed of. This is induced by the fact that staple fibres can only be recycled insufficiently in typical fabrics like filament weavings due to their finite length [18, 34]. Nevertheless, the recycling of carbon fibres is lucrative due to the four criteria below.

2.1.1 Economic or Legal Pressure

With a price for virgin fibres of about 20 €/kg, the fibres are thus thirty to forty times more expensive than steel [35, 39]. According to Braun [4] and Cleff [6], the price may be reduced by up to 50 % through efficient recycling approaches. Additionally, the EU guideline 2000/53/EC demands a recycling ratio of 95 % of materials, which are used in transportation applications like automobiles and planes. This should start in 2015. Especially planes use a large amount of carbon fibres. Thus, this recycling criterion is fulfilled for carbon fibres.

Table 1 Mechanical properties of recycled carbon fibres (rCF) [32, 42]

Material value	Virgin carbon fibres	rCF (after pyrolysis)
Tensile strength (GPA/tex)	2.5–7.0	2.5–3.2
Elongation at fracture (%)	0.5–2.1	1.3–1.6

2.1.2 Energy Consumption

The energy demand for the recovery of the carbon fibres based on Polyachrylnitril (PAN) can reach up to 700 MJ/$kg_{C\text{-fibre}}$. For the recycling of CFRP—waste by up to 50 % lesser energy is required due to currently used methods. Therefore, the price reduction results in the aspect of economy and the criterion of energy consumption is also fulfilled [4, 8].

2.1.3 Material Properties

The recycled fibres (rCF) still show nearly identical mechanical properties as virgin fibres after recycling [27] (Table 1).

Based on good mechanical properties, this criterion is also fulfilled.

2.1.4 Available Amount

For the year 2020, a worldwide demand of 130,000 t/a is predicted by the 'Verein Deutscher Ingenieure' (VDI), whereat already 4000 t/a of fibre waste occur [9]. However, the full amount of the fibres used will have to include recycled fibres [9], which is why a high value in the luxury sector can be achieved through intelligent recycling approaches. For this reason, the recycling of carbon fibres was the question of many research projects, of which one project is going to be presented as case study later in the section. Subsequently, this last criterion is also fulfilled for carbon fibres.

2.2 Polyamide BCF Fibres

In the following section, the recycling of polyamide from carpets is used as an example. This application only meets the above four criteria partially to a small extent. This is revealed among other things by the fact that a large project on carpet recycling has failed in the past [21]. Thus, the Polyamide 2000 AG should sort old carpets from Germany and the EU and try to recover the polyamide [20]. Reasons for failure were, among others, the separation of the polyamide from the other materials of the carpet and the proportion of polyamide in the carpet [32]. This aspect has been considered in the EU project EcoMeTex, which will be described in the following section. With the ideas of this project, it is possible to improve the economy and the energy consumption during the recycling.

2.2.1 Economic or Legal Pressure

The recycling of carpet waste and the production of new carpets from raw materials are currently carried out only in limited scope due to the economy. Because of the new European regulation for construction products like carpeted floors, the BauPVO CPR, the aspect of the sustainable use of natural resources is emphasized [15, 46]. Thus, there is legal pressure for recycling. Moreover, there is also interest in environmentally-friendly carpets, which is reflected in the various environmental labels for carpets [6].

2.2.2 Energy Consumption

The energy consumption for reusing polyamide for new polymer fibres is less than the synthesizing of new polyamide from crude oil [14]. In the following, the exact reprocessing procedures are going to be presented. In order to keep the energy consumption for the separation of the polyamide from the other materials of the carpet low, the results of the project EcoMeTex are necessary.

2.2.3 Material Properties

For the recycling of polyamide two different ways are possible. On the one hand, the remelting and preparation of Polymer and on the other hand, the chemical breakdown of the polymer into his monomers and afterwards the new polymerisation. The material properties of the two different recycling concepts are different but both are good enough to use it for new products [40]. In the carpet section, a detailed description of the possibilities and requirements will follow.

2.2.4 Amount Available

Finally, the amount of waste of carpets is also interesting. Thus, about 1 million tons of carpet waste were available for disposal in 2005 in Europe. Of those 1 million tons, the proportion of polyamide was approximately 13 % [47].

3 Different Types of Recycling Strategies to Create Textiles Out of Textiles

3.1 Levels of Recycling

Recycling can be processed in different ways and at different stations along the production- and product life cycle. These pathways are dependent on the material and the product, which should be recycled. A total of four recycling levels are distinguished, which are described briefly below to give an overview. A detailed description of the component stages can be found in source [44] (Fig. 3):

Stage 1: Recycling of raw materials and outtakes during the production.

During the first stage, occurring raw materials and outtakes from the production process are recycled back into the process. This recycling step can mainly be used for raw materials and product residues that can be dissolved by chemical or thermal influence. Material residues that occur in the appropriate structure for further processing can also be recycled at this stage. This is, for example, the case for fibre- based products such as cotton, if not processed slivers are again introduced into the fine opening process after the carding process.

Stage 2: Recycling by re-using the products.

At this stage, products are re-used after the end of the traditional life cycle. This happens rarely in the operational area of the existing life cycle but rather by the application in another scope. At this point, the use of waste textiles as cleaning rags may be mentioned as an example.

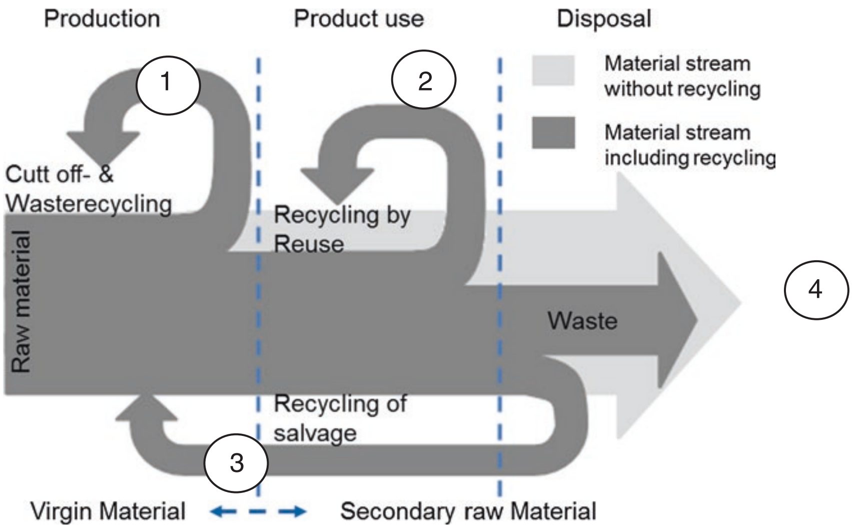

Fig. 3 Levels of recycling according to [44]

Stage 3: Recycling of secondary raw materials.

At this stage, disused components and materials are decomposed and processed mechanically, chemically or thermally to recover as many of the used materials as possible. These materials are fed back into the first stage of the process to be processed into new products. Because of the environment and influences by usage during the product life, the raw materials that have been obtained during the third stage, are often of poor quality. This can result in poorer mechanical properties (e.g., shorter fibre length in carbon fibres), or the incorporation of impurities and unknown additives.

Stage 4: Recycling due to thermal utilisation.

In the last stage, raw materials and components are combusted to use the stored energy in them. This last step should be taken into consideration as late as possible due to the complete destruction of the material.

3.2 Recycling Strategies to Create Textiles Out of Textiles Depending from the Material

There are different ways to recycle textiles. One possibility is to continue to use clothes as second-hand textiles by selling them in developing countries [17]. The limitation on recycling processes, in which it is tried to restore old luxury textiles into new luxury textiles, shows that the recycling strategies are dependent on the raw materials. For two textile examples the possibilities are presented in Fig. 4. Afterwards it is explained with the help of case studies.

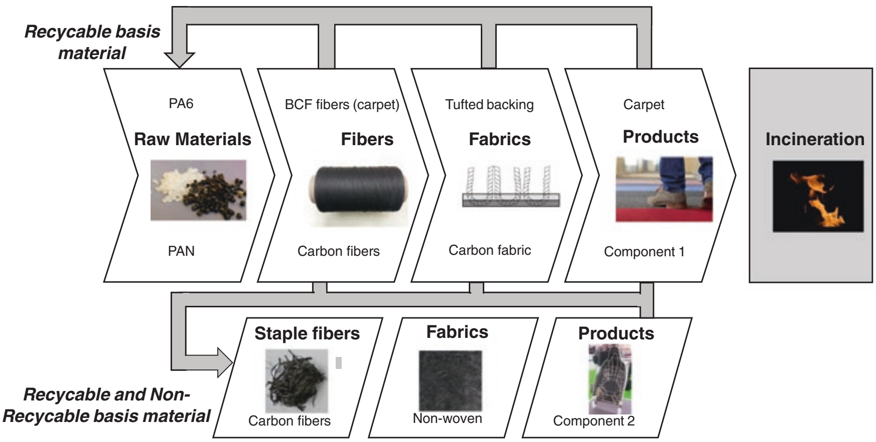

Fig. 4 Possibilities for the recycling of high-quality textile products based on two examples (*Source* ITA, David Burri/pixelio.de.)

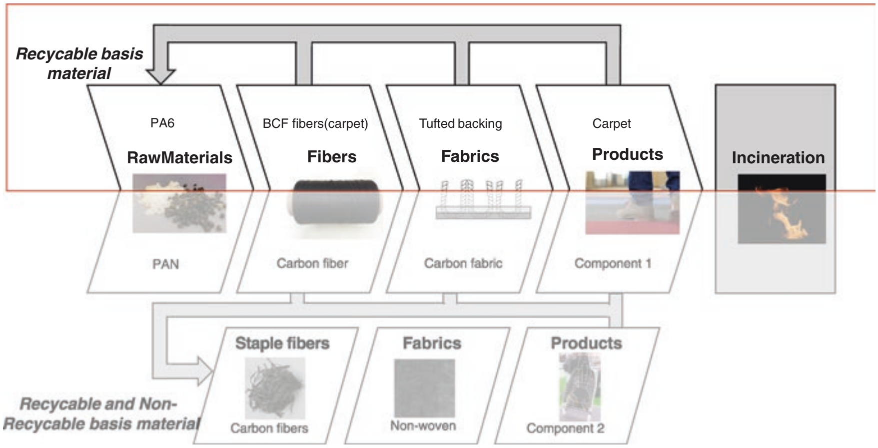

Fig. 5 Recycling of recyclable raw material (*Source* ITA, David Burri/pixelio.de.)

Significant distinction for the use of the strategies is the question, whether the fibre material can be chemically or thermally dissolved and returned to the state of the raw material, or not. In the light of this distinction, either the top or the lower track can be chosen. In the top track the material can be transferred back to the state of the raw material from any state of the product life cycle. Consequently, the entire flow of material (100 %) can theoretically be transferred into the original product (Fig. 5).

This property of returning to the raw material is usually given for polymer fibres. Therefore, the upper way of recycling can be proceeded. In Sect. 3, this strategy is demonstrated by the recycling of high quality PA6 carpets, which are used in hotels or as doormats inside the vehicle.

The lower track in Fig. 4 must be selected when the fibres can no longer be transferred into the state of the raw material. This is, for example, the case for carbon fibres, which cannot be dissolved chemically or thermally into the original state and be reused to produce carbon filaments again.

In this case, after the upper path and after a mechanical treatment (e.g. cutting of fibre residues or tearing of textile structures), the only solution left is usually the thermal utilization. As a solution to the problem of the non-recyclable raw material, a recycling can thus be carried out via the detour of the usage in alternative products (second recycling stage, see Fig. 6).

This way forms the lower track of recycling possibilities. Later in this section, corresponding applications are illustrated in a case study, in which the carbon fibre mats are used as reinforcement for car seats. Due to the transfer to an alternative application level, the fibres can be used again in an area in which they meet the material requirements. In this alternative application level, different requirements of the material, that is to be processed and used, can be demanded. Depending on the application and the used material, a recycling on a small scale is possible according to the upper track within this detour. For example, non-woven

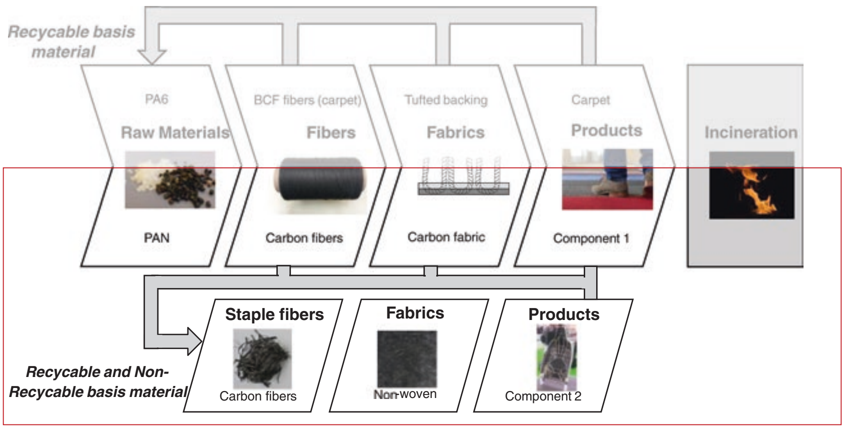

Fig. 6 Recycling in non- recyclable raw material (*Source* ITA, David Burri/pixelio.de.)

residues—depending on the material—can be dissolved and supplied to the non-woven fabric plant once more.

4 Recycling of Polymers in the Process Chain Using the Example of Carpets

4.1 Carpet in General

Most people know carpets from their everyday life. However, they are often perceived as regular commodity although they play an important role for a comfortable feeling. The luxury of carpets can be based on different aspects. One option is noble material such as animal hair or silk, which are usually processed by hand. These carpets are uninteresting for recycling processes because of their very small amounts. An alternative aspect to speak of a luxury good is the possibility of customizability. Thus, carpets can be produced from high-quality materials, such as polyamide, in industrial processes. These carpets are, for example, carpet tiles. With this type of carpet, the customer can freely combine carpet pieces with each other and thus create an individual interior design.

One way to make the carpet individually would be, for example, to use carpet tiles. It is mostly carpet pieces of 40 × 40, 50 × 50 cm or completely different forms which can be laid side by side without gluing. Therefore, these carpet tiles offer the advantage of a flexible use in a unique style [19].

Carpets can find application in various areas of our everyday life. The application area is divided into the private-, contract-, transport- and outdoor sector. Rooms such as the living room and bedroom, which are located in private homes, represent the private sector. This has to be differentiated from the contract sector. In addition to public buildings, such as offices, the contract sector includes hotel rooms. The transportation sector incorporates all carpets which are processed in cars, airplanes, trains or ships. Artificial grass surfaces usually represent carpets for the outdoor sector [11].

Depending on the application area, the requirements are very different. Thus, in the transportation sector, the requirements on the carpet in terms of weight are quite different from those in the contract sector. In the transportation sector, it is the aim to reduce weight by producing carpets, which are as light as possible, while in the contract sector, heavier carpets are preferred to fulfil requirements such as noise insulation. Based on these requirements, also the structure of the carpets is different.

Another aspect that affects the structure of a carpet is the manufacturing technique. The most common methods are tufted carpets, woven carpets and needle felt carpets. Here, the construction of a carpet is to be demonstrated with the help of a tufted carpet. The tufted carpets are the most common carpet construction in Western Europe with 480 million m^2 annually [48].

4.1.1 Construction of a Carpet

A tufted carpet is made up of several layers that are firmly connected. The top layer is the wearing surface, which consists of the pile yarn [11]. It is the only layer with which the end user comes into contact and is thus crucial for the design and pleasing haptics of the carpet. In 80 % of the carpets (in terms of the area), this layer consists of bulky continuous filaments which are referred to as BCF (bulk continuous filament) yarn [5]. For the application in the contract sector mainly PA6 is used because then the high requirements in terms of mechanical constraints can be withstood [15]. In the project EcoMeTex, carpets have been developed for the contract sector, which is why the choice of materials is limited on PA6 (Fig. 7).

In a tufted carpet, the pile yarn is embedded in a primary backing. Those tuft carriers usually consist of material combinations of PP, PES and PA. A coating is necessary to fix the pile threads in the carrier. This coating bonds the pile fibers to the carrier at the back. Usually, a latex dispersion with some filler material, such as chalk, is applied to reduce the price [12].

The last layer of a carpet is the backing. This carpet backing can be designed very differently depending on the application of the carpet. The tasks of a carpet backing are dimensional stability, elasticity, acoustics, heat insulation, and influencing the installation [45]. In the EcoMeTex project, carpet tiles by Interface, Inc. are taken as a reference. Such carpet tiles are special carpet square pieces of 50 × 50 cm [19].

Due to their small size, carpet tiles have to be relatively heavy so that they do not shift during use or vacuuming. This weight of a carpet tile is set on the back. Another important feature, which must be set on the back is the dimension stability, which is particularly important in carpet tiles. Only with absolute dimensional accuracy, carpet tiles can be installed in large numbers without problems. As a

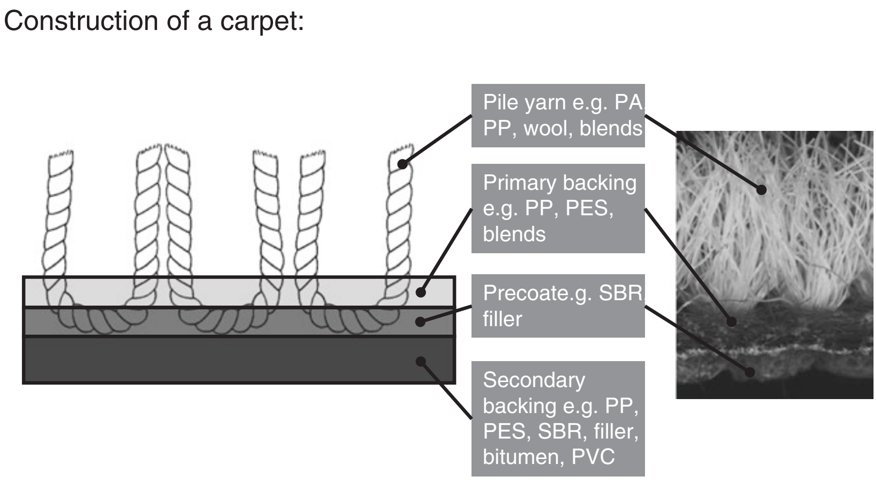

Fig. 7 construction of a tufted carpet in total (*left*) (*Source* ITA) and cross section of a precoated tufted *grey* cloth (*right*) (*Source* TFI)

reference in the project EcoMeTex, backings of bitumen and glass nonwovens of the company Interface are prepared.

4.2 Requirements for the Reuse of Polymers in Carpets and Carpet Tiles

Dependent on where the recycled material should be used in a carpet, there are different demands on the material. In the following, this is illustrated by two examples.

1. Use of recycled polymer in the carpet backing

In addition to the heavy coatings such as those found in carpet tiles, there are textile backings, which are used for wall-to-wall carpets. These textiles are knitted, woven or non-woven fabrics [45]. When using the fibers in the carpet backing, there are no requirements for the color, because after laying the carpet, the back is no longer visible. Thus, also mechanically recycled fibers can be used in fleece backings without prior modifying of the polymer.

2. Use of recycled polymer in the pile yarn

To be used in the pile yarn, it is necessary that the recycled material can be processed to BCF yarn in the chemical fiber spinning process, because a productive application in the carpet is only possible with BCF yarn. The minimum requirement for the polymer is the fact that no major impurities, due to foreign particles or other polymers, are existent in the polymer when they threaten the

Fig. 8 BCF bobbin with 100 % physical recycled material (*Source* Gneuss GmbH)

stability of the spinning process. In the EcoMeTex project, it could be shown that the waste material from the fiber production company AQUAFIL SpAItaly (Arco) can be mechanically processed with a melt filter by the company Gneuss Kunststofftechnik GmbH (Bad Oeynhausen) and then spun into new BCF filaments (Fig. 8).

At the same time, this experiment showed the limitations which exist due to the preparation of the polymer melts. Since the fundamental colour is already dark grey because of producing waste, it is not possible to selectively adjust the colour of the polymer. The requirements for a pile yarn are, however, that the colour can be set exactly and that there are no variations in the colour during production. Thus, it is necessary to recycle the polymer chemically in order to obtain new material for the pile yarn production.

4.3 Chemical Recycling of PA6

The chemical recycling of PA6 is processed by the company AQUAFIL SpAItaly (Arco). Figure 9 shows the different steps during the chemical recycling. The first step is the production of the monomer. For this, a splitting of the PA6 into the monomer, the caprolactam, is processed with the help of chemical processes. As soon as the long polymer chains have been split into short monomer pieces, it is possible to separate the caprolactam from impurities like dyes or other polymers. At the end of this cleaning process, caprolactam, which has the same purity as something comparable to crude oil, is available [10].

After the depolymerization, the re-polymerization is carried out exactly like the process with PA6-based crude oil. Part of this process is, on the one hand, the extraction of the monomer and, on the other hand, the drying of PA6. Both steps are processed to increase the purity and quality of the polymer. Subsequently, the

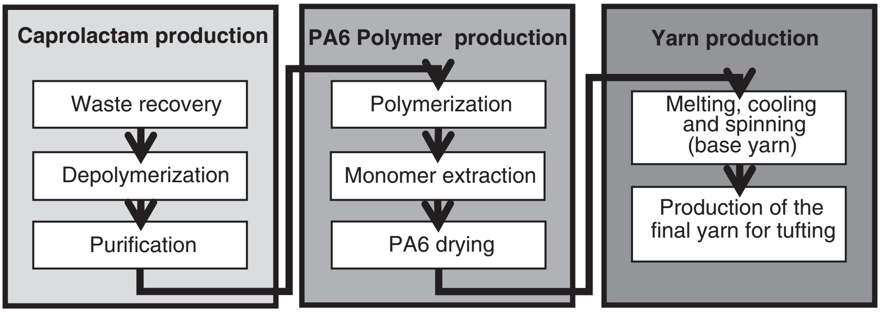

Fig. 9 sequence of process steps during the chemical recycling at Aquafil (*Source* Aquafil SpAItaly (Arco))

material can be spun into yarns again. The result of this process is a yarn which is sold under the trade name Econyl [10].

Although many impurities can be removed during the depolymerization, and thus a final product originates that is virtually indistinguishable from a new material, there are requirements on the polymer waste to perform this type of recycling. The two main requirements are [33]:

1. A high content of PA6 (min. 70 %)
2. No or a very small proportion of PET, PA6.6 and SBR Latex

When comparing the requirements for chemical recycling and the current carpets, it becomes clear that they do not fit together. Carpets are made of many different materials and particularly include PET and SBR latex, which are especially cumbersome for depolymerization. The development of recycling concepts for separating the materials during the recycling process has failed in the industrial implementation. Projects which have considered these possibilities include, among others, the RECAM Project (Recycling of Carpet Materials 01.12.95–31.05.99) and the project Polyamide 2000 AG. Therefore, the polymer from current carpets can not be won again in that way that it can be used for the production of new carpets. One possibility to avoid this problem is to adapt the carpet to the recycling process beforehand. This has been done in the EcoMeTex project.

4.4 EcoDesign of Carpet Tiles

An obvious solution would be to build a carpet with only one material, namely PA6. Consequently, there would be the possibility to recycle the entire carpet. However, when considering the requirements for the carpet tiles, such as weight and dimensional stability, it becomes clear that this mono-material solution is not possible or economical. Since PA6 is an expensive material, which cost at least

2 €/kg. To increase the weight of the carpet, it is easier and cheaper to use materials as bitumen.

Since the back is responsible for both the dimensional stability as well as the weight of the carpet tiles, the back of carpet tiles consists of bitumen and a fibreglass mat. With the assumption that this combination of materials must be retained, the only way out is a clean and simple separation of the components. The idea of the EcoMeTex project is to design the carpet in a way that the upper part of the carpet can be supplied to the chemical depolymerization and the lower part is provided for different recycling processes. Due to the fixed connection between pile yarn and tuft carrier, it makes no sense to separate them from each other. Thus, the separation layer must be below the tuft carrier. This in return has the result that also the tuft carrier has to consist for the most part of PA6 and must not contain PET.

The major challenge of the separation layer lies in the conflicting requirements that are placed on such a dividing point. Thus, the separation layer must not restrict the resistance of a carpet. These claims are very high as a carpet usually remains for 10 years in a building and is subjected to high mechanical stresses. However, other properties such as fire behavior or emission shall not be affected negatively. At the same time, it is important that the separation layer separates the layers easily and with a low energy consumption as soon as the carpet shall be re-fed into the recycling process.

4.5 Separation Layer

One possible way how to realize such a separation layer was developed in the project EcoMeTex. This is based on the calendaring technology of the company Klieverik Heli BV (Oldenzaal) which is already applied in carpeting in the automotive sector. Here, the tufted nonwoven is not coated with latex but transported and heated between two calender rolls. The pile threads on the rear side of the tuft carrier are melted and thereby form a firm connection on the back side. In addition, the layer is enhanced by hot melts or thermoplastic powders.

An interesting feature of such hot melts or thermoplastic powders is that they melt at relatively low temperatures and thus are already liquid before the pile yarn or the tuft carrier soften. Thus, they form a weak spot in the carpet structure when heated up. Exactly this feature has been utilized by EcoMeTex. Because as soon as the carpet is heated up, for instance with a calender, the individual layers can be separated cleanly from each other with little effort.

To further increase the dimensional stability of the carpet and, furthermore, to prevent that the bitumen of the backing was mixed with the hot melt, a fiberglass mat has been introduced. For future products, this fiberglass mat shall replace the glass mat in the back. Figure 10 shows the different stages of production as well as the clean separation of the different layers by simply heating.

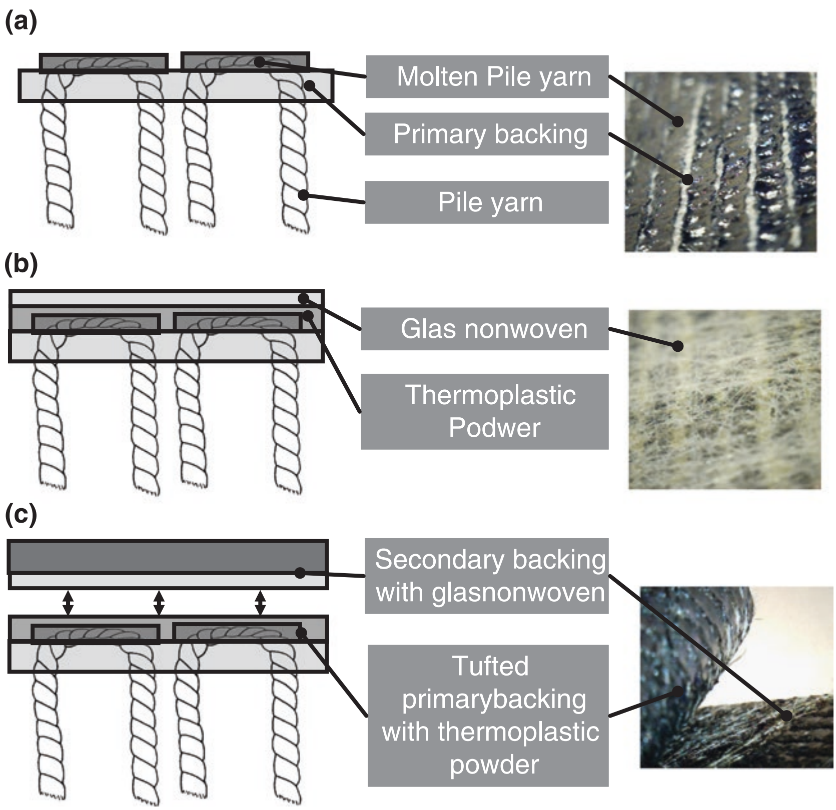

Fig. 10 **a** The bottom of a tufted and calendered fleece, **b** combination with a glass mat, **c** separation of the layers

5 Utilization of Materials in a New Part Using the Example Carbon Fibers

As already mentioned, carbon fibres cannot be returned to their state of raw material. (1st or 3rd recycling step, cf. Fig. 3). That is why the fibres are currently mostly milled and used as filler material and additive in plastics [9]. Therefore, alternative solutions of application are needed to tap the full mechanical and economical potential.

The use as a non-woven fabric seems to be obvious because of the fibre characteristics. The manufacturing processes of non-woven fabrics were developed to produce sheet material from staple fibres and are very efficient [13]. According to the process, different fibre length fractions can be used and fibrous textures can be added into the textile material. Figure 11 gives an overview of the available processing procedures.

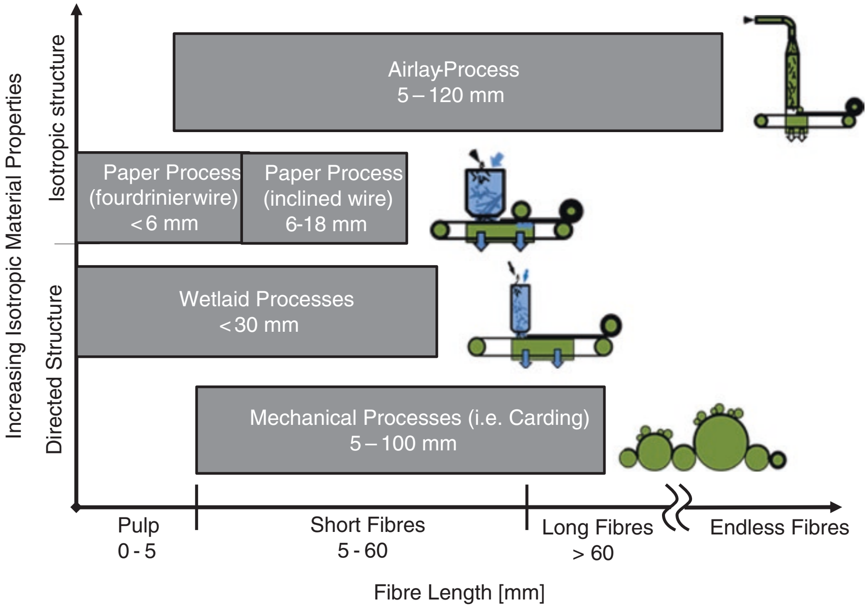

Fig. 11 Depiction of the different manufacturing processes of non-woven fabrics [27] (*Source* ITA)

Staple nonwovens can be formed by mechanical, aerodynamic or hydrodynamic processes. Besides, nonwovens can be after-treated to fit their characteristics to the future field of application [40, 43].

At the dry manufacturing of non-woven fabrics (aerodynamic, mechanical), it is necessary to take precautionary measures to protect employees and machinery. Protective clothing for employees, safety glasses and respiratory masks for the protection against carbon dust must be intended to use during the processing. Furthermore, processing as well as near machinery needs to be encapsulated so that the carbon dust does not reach machine parts with electrical elements and causes a short-circuit [16, 41].

In many cases, companies can collect primary waste and reconvert it to other products. Especially the use as reinforcing material or functional additive in composite is favoured in practice [37] (Fig. 12).

The project CAMISMA (project name deduced from "Carbonfaser/Amid/Metall-basiertes Innenstruktur-Bauteil im Multimaterial-Ansatz") serves as an example to demonstrate the added value of the use as reinforcing material. The consortium carrying it out from 2011 to 2015, consists of the RWTH Aachen [Institut für Textiltechnik (ITA), Institut für Kraftfahranwendungen (ika), Institut für Kunststoffverarbeitung (IKV), Institut für Aufbereitung und Recycling (IAR)], TohoTenax Europe GmbH, Johnson Controls INC. and HBW Gubesch Kunststoff-Engineering GmbH and is conducted by Evonik Degussa GmbH.

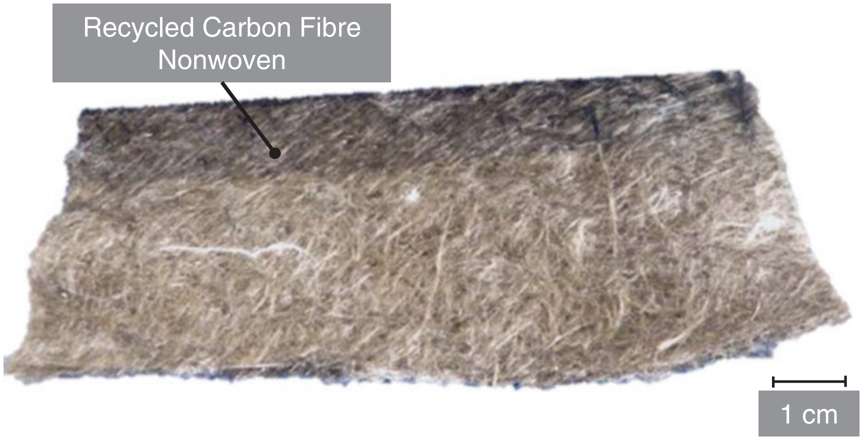

Fig. 12 Coated recycled carbon fibre nonwoven [30] (*Source* ITA)

Project aim is the economical and environmentally friendly manufacturing of components in lightweight construction. In this context, the use of recycled carbon fibre non-woven fabrics plays a vital part in the success of the project. Within the context of the project, primary waste fibres are used [31]. The aim of reaching a weight reduction >40 % with concurrent restriction of the cost increase to < 5€/ kg_{saved} was achieved by the new approach of lightweight design [23].

A fibre volume content of 32 % in the composite achieved a significant reinforcement effect of the construction element (seat back) during critical deformation testing. With this example, the project CAMISMA demonstrates well that recycling of high-quality and high-price materials does not only have to be a legally defined and economic necessity, but also a chance to solve technological problems. The exact project contents and results are presented in Fig. 13 [23, 26].

The CAMISMA-Design's idea is the intelligent combination of materials. A material is "used where it is needed". In this way, a combination of glass fibre reinforced (GRP), carbon filament reinforced (CRP) and carbon non-woven reinforced (CVK) composites with steel reinforcement in a polyamid-12-matrix is developed. In the process, the recycling carbon fibre non-woven fabrics serve as reinforcement of the injection moulding elements. They are only mechanically reinforced with tapes out of new filaments at process-related places with big material deformation. The mentioned component parts are most intensely subjected to the danger of material damage and thinning because of the high forming forces. That is why a specific reinforcement of these places is necessary. In Fig. 14, a finished CAMISMA-component with separate comments to the use of recycling material ("Non Woven CF-Tapes") is presented. The structure's biggest part was manufactured by large layers out of recycling material with reinforced injection moulding (Non Woven CF Tapes, cf. Fig. 14) [23].

Thus, by construction concepts like the CAMISMA-approach high-quality recycling materials can not only be technically and usefully integrated into new

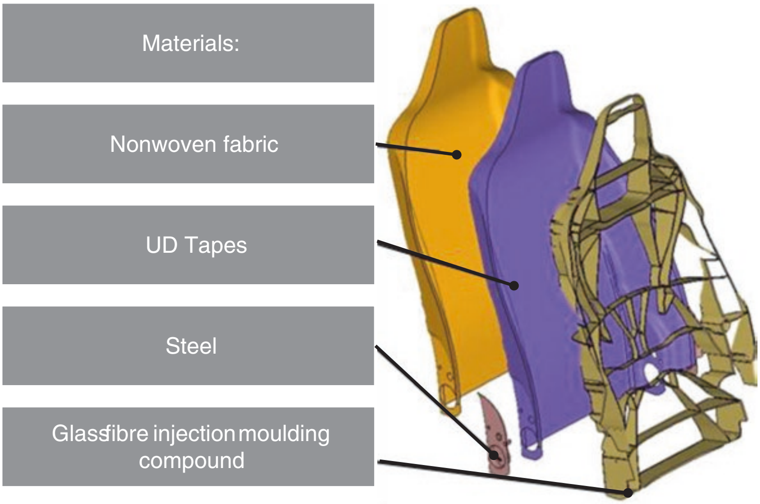

Fig. 13 Concept CAMISMA-lightweight design [25] (*Source* Evonik)

Fig. 14 Depiction of a seat back in CAMISMA's material mix approach with specific depiction of the recycling material [23] (*Source* JCI)

applications. Such approaches increase clearly the cost effectiveness as well as options after the product life cycle's end of high-quality products out of these materials. The saved costs for the disposal of carbon fibres, classified as hazardous waste, and the product costs, influenced by the material quantity, increase the cost effectiveness sustainably [29]. Besides, the construction elements can be sold to appropriate disposal companies for treatment after the product life cycle's end. Consequently, the material's economical potential can be exploited instead

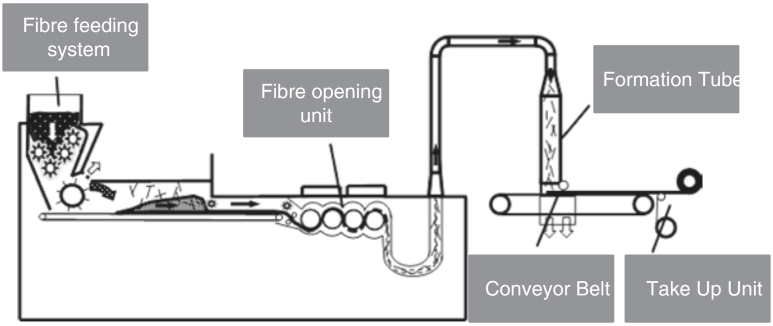

Fig. 15 ITA Airlay process [26] (*Source* ITA)

of disposing it with high costs. Therefore, CO_2 emissions are produced delayed because of the thermal utilisation, which happens years later, and increase the construction element's energy balance.

To tap the mechanical and therefore the economical potential of the fibres, it is important that staple fibres received by recycling are not shortened too much during the processing. According to examinations of the Industrievereinigung Verstärkte Kunststoffe e.V. (AFK), fibres with a minimum length of 10 mm bear the highest possible load [3].

The lowest fibre damage occurs by using the airlay procedure because the fibres are only temporary mechanically loaded during the process steps fibre opening and non-woven formation. Over the period of transporting the fibres, no essential fibre loads occur. For this reason, a continuous airlay process has been developed within the scope of the project with which economical as well as mechanical project aims shall be supported. This process is presented in Fig. 15.

By the fibre opening unit with four rolls, the carbon staple fibre flakes are opened gently to minimize fibre damage by fibre fracture. Afterwards, an aerodynamic transport of the fibres to the formation area takes place where the fibres are laid down as an isotropic non-woven. Then, the non-woven fabric is pulled off by a conveyor belt, which makes a continuous production possible. By this concept, the predetermined cost limits for the fabrication of the materials could be kept within the scope of the project [23].

The fibre orientation within the non-woven fabric is influenced by the set flow conditions in the formation area and can be modified by adapting the geometry of this area. According to the future field of application for the non-woven fabric, this variation of geometry can be interesting. Within the scope of the CAMISMA project, a geometry was chosen that generates a constant flow in the formation area. This guarantees a constant isotropic non-woven formation across the width of the conveyor belt. In Fig. 16, the flow conditions are depicted on the basis of simulation results [28].

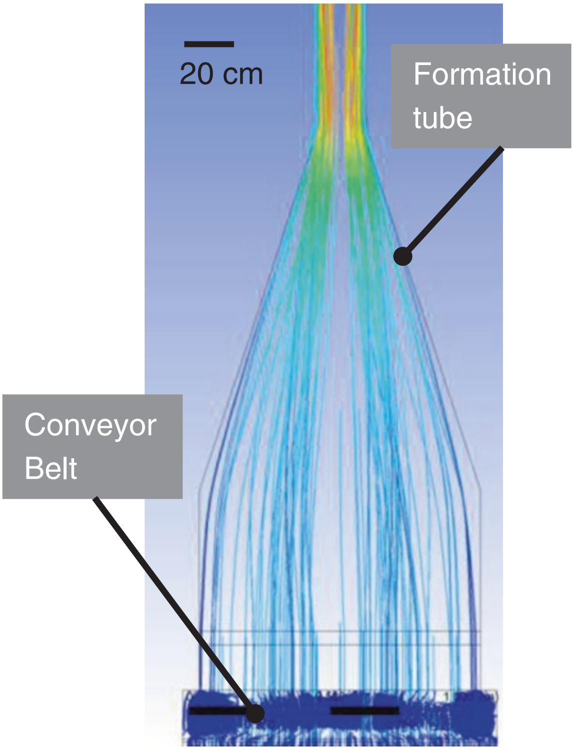

Fig. 16 Airflow in the formation tube (*Source* ITA)

6 Conclusion

The presented work showed that novel approaches in fibre recycling increase the number of available options at the product's end of life. By following the author's model of two recycling ways, product designers and users of luxury textile goods can lead the valuable materials back into the production chain of the same of alternate products. Two examples were given for high valuable carbon and PA6-fibre products from the automotive and building sectors that can serve as an example for practical application of the presented strategic approaches.

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Specialty Chemical Finishes for Sustainable Luxurious Textiles

Kartick K. Samanta, S. Basak and S.K. Chattopadhyay

Abstract In the last few decades, people have become more concerned about their health, hygiene, lifestyle, fashion, comfort, luxury, and wellbeing. Those belonging to economically well-off sections are more often choosing to buy luxurious textiles, not only to exhibit their high social and well-off strata, but also from the compulsion in health and hygienic necessity of the present day. In the production of luxurious textiles, natural fibres like cotton, silk and wool, and man-made fibres, like polyester, acrylic and regenerated rayon (viscose) play important roles. Recently, due to the rapid growth of nanoscience and technology, various organic and inorganic nanoparticles, such as silver (Ag), TiO_2, ZnO, SiO_2, lignin, and Chitosan have been applied to impart attributes needed for health and hygiene, UV protection, self-cleaned, and skin-care functionalities, both in natural and synthetic textiles. Similarly, various plant molecules, biomaterials and bio-polymers, such as banana pseudostem sap (BPS), grape and mulberry fruit extracts, natural dyes, Chitosan, tulsi, silk-sericin, aloe Vera, honey, almonds, cucumber, and mint have been applied in textiles for improvement in antimicrobial, UV-protective, anti-oxidant, skin-nourishing, and hydrophilic properties. Natural extracts of jasmine, lavender, Champa sandalwood and such others containing active ingredients like santalols, fusanol, santene, teresantol, benzyl acetate, linalool, linalyl acetate, and benzyl benzoate have also been added in textiles for their mind-refreshing fragrance and for skin nourishing, smoothening of facial lines/wrinkles and providing impetus to immune, nervous, and brain psychological system. The requirement of various attributes for professional clothing like wrinkle-resistance, comfort and self-cleaning of fabric surface have been incorporated in textiles to develop

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aristocratic, social, religious, business, and ritual party outfit. High value Cosmeto-textile and Ayurvastra have also been designed for slimming, moisturising, perfuming, healthy, fresh feeling and curing/healing of many diseases in a holistic approach by taking cue from the traditional knowledge of cosmetics, Ayurveda and clothing science. As these high value textiles are produced mostly from the natural fibres and functionalized using natural products/biomaterials, they can be effectively used for the production of sustainable luxurious textiles.

Keywords Biomaterial · Health and skin care · Luxurious textile · Natural fibres · Self-cleaned · UV protective

1 Introduction

The concept of luxury is in vogue in various states and forms since the onset of human civilisation with the clear economic distinction among the various social classes. In early civilisations, the consumption of luxurious items was limited to the elite classes. Thus, the definition of luxury was fairly clear then: whatever the poor cannot afford and the elite can, was the 'luxury'. However, in the last few centuries, as the human civilisation progressed with the democratization of the societies and with the increase in economic abilities of the common masses, an array of new affordable luxury products were created, specifically to entice the aspiring middle class. Thus, luxury is society, consumer and situation specific and in daily life, it refers to certain lifestyles. It is an offer of any higher priced product or service at any point of time.

The present society may be grouped into four categories based on their economic and financial capability, such as poor, average, rich and super-rich. Many of the rich to super-rich people prefer to possess luxurious items, including textiles as a part of their lifestyle to maintain a distinct social position. Up to 1950s, almost all the natural fibres, like cotton, silk, and wool and regenerated rayon (viscose) and cellulose acetate were used in the production of luxurious textiles. Thereafter, with the advent of synthetic fibres, mainly polyester and acrylic have also been utilized in the production of such high-value textiles. As the natural fibre based textiles get damaged more frequently due to the rapid microbial growth, causing foul smell and skin disease, various nanoparticles, biomaterials, and plant extracts such as, silver (Ag), TiO_2, ZnO, lignin, neem, silk-sericin, aloe Vera, Chitosan, tulsi, tannins, clove oil, permethrin, and napthalin have been used to make textiles antimicrobial, antibacterial, antifungal, and moth resistant and preserve them. Presently, people are quite busy in their personal and professional life, which sometimes causes physical and mental stress. In order to control such stress, they often resort to exercise, meditation, yoga, leisure, spa, and prefer to have a complete rest or a dream-sleep. In this regard, luxurious apparel and home textiles finished with a mind refreshing natural fragrance extracted from lavender, jasmine, Champa sandalwood and rose water acts as a stimulus to revitalize us, improve our senses, and rejuvenate our soul. In addition to freshness and fragrance in textiles, the aspect of health and hygiene needs to be embedded into the textile as far as the consumer satisfaction in terms of the current fashion and affordability are concerned. Now-a-days, wet-tissues or wipes for face, skin, and baby care that are finished with natural products for preventing infection, providing soothing and moisturizing of the skin, reducing the wrinkle and fine lines, keeping the skin hydrated and nourished, and removing dirt and excess oil, are also commercially available. Specifically, Cosmeto-textile has been developed by merging the knowledge of cosmetics and textiles so as to provide slimming, moisturizing, perfuming, and energizing effects to the human. Similarly, Ayurvastra, a medical textile has also been developed by utilizing the scientific knowledge of ancient medicine and clothing science for curing of several diseases in a holistic manner.

Soft and comfortable properties of textiles are important, preferred for luxurious application, and the same can be incorporated by chemical, mechanical and plasma techniques. For people to perform effectively in business, social, religious, media, personal get-together, event and party, high professional textiles have been developed by encompassing smart attributes like wrinkle-free, odour-free, self-cleaned, soft-feel, and fashion by application of silicone emulsion, cellulase enzyme, velvet finishing, poly-carboxylic acid, camouflage effect (dyes), nanomaterial for photo-catalytic activity, super-hydrophobic coating of non-Fluoro and Fluoro-chemicals. Though it has been reported that a little amount of UV exposure is beneficial for blood circulation, metabolism, synthesis of vitamin D in our body, and improvement in the body's resistance to various pathogens, but a higher dosage of radiation can cause accelerated skin ageing, sunburn, blotches, wrinkles, weak immune system, sun tanning, photo-carcinogenesis, and even skin cancer. Therefore, in the textiles meant for sports and leisure wear, it was attempted to block the transmittance of harmful UVA and UVB rays by application of organic and inorganic nanoparticles, natural dyes, grape and mulberry fruit extracts, banana pseudostem and peel saps, citrus oil, and silk sericin.

The present chapter discusses the development and role of specialty chemical finishes for production of luxurious apparel, home textiles, and smart professional, sport and leisure-wear with functional and aesthetic attributes like fragrance, healthcare, skincare, wellbeing, highly-comfortable, self-cleaned and UV protective. Emphasis has been given to recount such finishing using natural polymers, biomaterials, and plant/herbal extracts for the production of sustainable luxurious textiles from recent research and commercial product development reports.

2 Luxury and Textile

With the evolution of civilisation in the last few centuries, people have become more and more concerned about their lifestyle, health, hygiene, medicine, food and beverage, fashion, comfort, luxury, and wellbeing. Most of the rich to super-rich category of people prefer to have luxurious articles like iconic car, palace, clubhouse, cottage/flat, home-furniture, jewellery, painting, sculpture, apparels and home-textiles to be the part of their lifestyle. The very presence of such of luxurious items with them helps to maintain a distinct social status and make their life worthy the mentioning. In this context, luxurious apparel and home-furnishing textiles also play important roles as to make them at par with their other iconic items, ensuring the desired aristocracy and fashionable value with a functional touch. Natural fibres like silk, wool, cotton, linen, regenerated rayon, cellulose acetate, and to some extent polyester, the synthetic fibre are used in production of such specialty apparel, home furnishing, and interior-decorative textiles by adding extra-value during weaving, knitting, non-woven preparation and high-end chemical finishing. These kinds of royal textile products are currently being used in fashion and reality shows, and in dress materials of film actors and actresses, as high professional's casual and apparel wear, world-class luxurious interior of airport, rail and ship carriers, and for furnishing starred-hotels. Similar to the cellulosic cotton and linen textiles, since the ancient time, protein fibres like wool and silk were also used in large quantities for the production of royal apparels and home furnishing textiles for the king's family. In the ancient Byzantine time, the fabrics made of silk were considered to be the most valuable luxurious products, as it was the expression of power, wealth, and aristocracy. Such kind of luxurious fabrics were/are mostly used in making secular dress, religious vestments, and interior furnishings and till date, they are very much popular in the Italian region. In the context of luxurious products and specialty wears, textiles with the attributes of high comfort, soft feel, light to heavy weight, pleasant, skin caring/nourishing, fragranced, and with wellbeing and glittering effects, but free from solid/liquid contamination are preferred. In order to meet the demand of such high value textiles by the elite users, a few reputed companies like Bombay Dyeing, Huntsman Co., Resil Chemicals, Polygiene, Marvic Textile, W.T. Jhonson and Sons, Reliance, JOHNSON, Aditya Birla, Espirit, Philippe, Alen Solly are in the market fray and trying to increase their share in the market. High value Cosmeto-textile and Ayurvastra suitable for exercise, meditation, yoga, leisure, spa, skincare, night-dress material, and for curing/healing of many diseases in a holistic manner have been developed by encompassing the traditional knowledge of cosmetics, ancient Ayurveda and clothing science that have been discussed below in details.

3 Sustainable Luxurious Textiles

For the production of sustainable textiles, the associated chemical processing and product development should be sustainable in terms of water, energy, cost, raw material, applied chemicals, and bio-degradability. Approximately, 100 l of clean water are used to process one kg of cotton textile starting from its preparatory to finishing operation, which is finally discharged as an effluent contaminated with residual dyes, pigments, acid, alkali, size, and other auxiliaries. The discharge of such effluent in water streams has a serious impact on its flora and fauna, besides the adverse effect on fertility of agricultural land. Shortage of water in the near future will have a serious impact in the textile and allied industries. In the last few decades, due to the stringent pollution norms and the government legislation, various technologies have been developed and implemented in the textile production and processing arena, so as to reduce the consumption of water, energy, processing costs, and/or effluent load. Some of these are: (i) low material to liquor processing, (ii) spray and foam finishing, (iii) use of enzymes, (iii) natural dyes, (iv) digital printing, (v) Infrared dyeing and drying, (vi) Radio-frequency drying, and (vii) Ultrasound for dyeing and dispersion. Few more promising and emerging technologies have also been explored in laboratory to industrial scale, such as (i) super-critical carbon-di-oxide for dyeing (ii) plasma for water-free processing, and (iii) UV and laser assisted processing and finishing. All these developed technologies are either related to pre or post-processing of textiles or textile machineries. In spite of such developments, textile chemical processes till remain energy and water intensive, besides the involvement of pollution due to the usage of various non-environment friendly chemicals and auxiliaries.

The chemicals and auxiliaries used in textile processing are caustic soda, acid, hypochlorite, sizing material, stain removers (carbon tetrachloride), and unfixed dyes. Many of the textile chemicals and auxiliaries contain suspended solids and produce large quantum of effluent with high biological oxygen demand (BOD) and chemical oxygen demand (COD) values. Some of the synthetic dyes, like azo are sensitive to human skin and has a carcinogenic effect. Similarly, in polyester dyeing, toxic chlorinated compound is used as a carrier, and formaldehyde based chemicals are used in the crease-recovery finishing. In antimicrobial, rot resistance and moth-proof finishing, chlorinated compounds such as pentachlorobenzene, hexamethylene biguanide, and quaternary ammonium compounds are used. In UV protective finishing, phenyl salicylate, benzophenone and benzotriazole based chemicals are used. Some of the present day's chemicals and auxiliaries used in textile processing have the adverse effect on the environment. In the past, however, serious effort has also been made to develop various environmentally friendly synthetic dyes, chemicals, and auxiliaries, such as BTCA and DMDHEU for crease recover finishing, halogen-free flame retardant, silicate and ammonium sulphamate based flame retardant, and enzyme based desizing and bio-polishing, natural dyes, hydrogen peroxide (H_2O_2) bleaching, and so on.

Due to the global awareness of environmental pollution, climate change, carbon footprint, and health and hygiene in the last two decades, the demand for organic material is growing exponentially. Hence, organic fruits, vegetable, crops and pulses, and even organic cotton have garnered attention and in high-demand in the market places. Due to the advantages of the natural fibres being bio-degradable and produced from renewable sources with good moisture regain, soft feel, adequate to fair strength, and good appearance after the chemical treatment, they are commonly used in making apparel and home textiles. Buoyed by these advantages, the demand of natural fibre (non-organic to organic) based textile is growing profoundly, and the year 2009 was celebrated as the International year of Natural Fibres. For the sustainable development of high end textile products, specialty apparel and home furnishing application, it should be preferably made of natural fibres, and to be processed and finished with eco-friendly chemicals and auxiliaries, preferably derived from natural sources. This will incur in adding value to the natural products, while preserving the natural resources. In this regard, a number of plant extracts, biomaterials, and biopolymers, such as enzyme, natural dye, aromatic and medicinal plant, Chitosan, aloe-Vera, neem, lignin, silk-sericin, grape and mulberry fruit extract, banana pseudostem and peel sap, citrus oil, and such others have been explored in the production of sustainable health-hygiene, wellbeing, skincare, comfortable, self-cleaned, and UV protective luxurious textiles that are reported below in details.

4 Fragrance, Health-Hygiene and Wellbeing Textiles

4.1 Fragrance Textile

In the era of globalization, when people are hard-pressed in their personal and professional life to accomplish many committed and time bounded responsibilities, frequently they feel stressed out—physically and mentally. To keep the stress under control and also to live a healthier and peaceful life, they normally resort to exercise, yoga, leisure, spa, and sleep. For the same, luxurious apparel and home textiles play an important role by providing an energetic, fresh, mind-refreshing, healthy and hygienic feel to the wearer of such textiles. To fulfil the market demand of such high-value textile products, Bombay Dyeing has launched a new collection on aroma/fragrance based bed linen that provide a pleasant feeling and refreshing ambience and decoration in our living and bedroom, providing a much needed relief to our otherwise busy life. Besides, they have also come out with a luxurious bed linen made of soft cotton satin, with high thread count and fragrance of natural lavender, jasmine and rose water that revitalizes our senses and rejuvenates our soul. Further, the bed linen also helps to relax our mental stress, while ensuring a comfortable sleep. Such kinds of finishes are mostly applied in textiles by microencapsulation technique for slow release of fragrance for a longer duration. During the actual usage of such textiles in bed linen, the micro-capsules get busted either by pressure or friction and the fragrance molecules get diffused in the air, making the local atmosphere fresh and pleasant [1]. In the similar line, Scottish researchers have also developed a microencapsulated aroma therapeutic luxury textile, which is much beneficial to a cancer patient. The airtight hard shell capsules containing a particular type of aroma have also been developed as a wellbeing women wears for fighting against the side effects of chemo and radiotherapy [2]. Some of the preferred aroma for textiles and home furnishing applications are jasmine, lavender, and Champa sandalwood that contains active ingredients like santalols, fusanol, santene, teresantol, benzyl acetate, linalool, linalyl acetate, benzyl benzoate, and geraniol. Besides their mind-blowing fragrance, these materials are also helpful in revitalising immune, nervous and brain psychological system, skin-nourishing, smoothening of facial lines and wrinkles, cell regeneration, and as an anti-depressive and antiseptic agent. Absorption of such active molecules of different herbs into the blood stream improves the blood circulation and inhalation properties, and clears throat and lungs. High value Cosmeto-textiles have also been developed by encompassing the traditional knowledge of cosmetics, Ayurveda and textile science that can take care of slimming, moisturising, perfuming, energetic, and healthier feel. Textile treated with bark of Arjuna tree, rich in minerals like zinc, calcium and magnesium, flavones, and Coenzyme Q-10 helps in controlling the cardiac performance, cholesterol levels, heart stress, nervousness and weakness. Clevertex has developed wellbeing bath towels finished with sea-weed extract and ZnO, which have been incorporated directly into the inner structure of the fibres. It provides both comfort as well as relaxation from stress, and its functional attribute does not get affected by repeated washing and wearing. Additionally, such finishing possesses good antimicrobial and liquid absorbency properties that can provide comfort, and a foul-smell free product [3]. An Andrew Morgan's collection of USA has recently introduced a novel aromatherapy infused eco-friendly textile. Here, the tiny polymeric microcapsule shells provide a unique fragrance due to their diffusion in the air for a longer period [4]. In the similar line, Prince Kataria Textile has launched a luxurious soft cotton satin bed sheet with high thread count, which is lightly fragranced with the pleasant aroma of natural products. This kind of aroma embedded fabric ensures the relaxation and comfortable sleep [5]. A therapeutic eye pillow made of aroma of essential oils to ease the feelings of stress, tension, and headaches by gentle pressure on the eyes and sinuses has been marketed by the Tradekey Company in their new series of products. This kind of luxurious eye pillow is also suitable for the spa or beauty treatments [6].

4.2 Health and Hygiene Textiles Using Nano and Bio-materials

Providing customised textiles economically for addressing issues relating to health and hygiene of human beings, yet imbibing the current day fashion is a key challenge before the textile industry that need to be addressed immediately. As described above in the production of sustainable luxurious textiles, cotton, silk, wool, and to some extent polyester fibres are generally used in a large quantity for making health and hygiene textiles. The natural fibres/fabrics in a humid climate at the ambient temperature provide a favourable micro-climate for the rapid microbial growth that causes production of foul smell, skin disease, and reduce the service life of such valuable textile products. In order to arrest/prevent such damage, antimicrobial agents, which are presently available in the market for making the textile antimicrobial, antibacterial, antifungal, rot resistant, and moth-resistant are used. However, some of these agents prepared using traditional synthetic chemicals cause environment pollution. Therefore, academic and industrial research has also been intensified in the past two decades to find out the alternative chemicals along with suitable application method so as to ensure production of sustainable eco-friendly antimicrobial textiles at a lower cost for every generation of people. In the last two decades, due to the rapid growth of nano science and technology, various metal nanoparticles, such as silver (Ag), TiO_2, and ZnO have been synthesized and applied to natural as well as synthetic textiles in order to impart non-durable to durable health and hygiene functionality [7]. Similarly, various plant molecules, biomaterials and bio-polymers also have been explored for similar applications.

Nano-silver is one of the most widely accepted industrial material for its application as antimicrobial agent in textiles, air purification, water purification, and coating of household items due to its advantages of being non-poisonous and non-allergic that remain effective for a long time and over the wide range of microorganism. Nano-silver refers to the ability of silver to work at the molecular level, atom by atom to impart excellent anti-microbial property in different textile substrates, like apparel, face mask, surgical grown and medical suture. The inhibitory action of silver metal on the bacteria has been attributed due to the interaction of silver ion with the thio-groups of bacteria and also, due to the oxidative destruction of microorganism in the aqueous medium. Nano-size silver (Ag), zinc oxide (ZnO), and titanium di-oxide (TiO_2) particles demonstrate a promising, viable solution in controlling microbial infection, and their long-term efficacy has also been tested on various natural and synthetic textiles. It has been found that their intrinsic properties, such as size, shape, morphology and composition have a distinct role in determining the antimicrobial efficacy. In this context, it is mentionable that Huntsman Co, Resil Chemicals, and Polygiene have recently launched nano-silver or silver-salt based HeiQ and N9 antimicrobial agent for finishing of apparel, shocks, and active wear textiles. Miliken & Company has developed a silver based antimicrobial agent, Alphasan by forming a complex of silver with Zirconium phosphate. Another silver containing antimicrobial compound is silver substituted zeolite available from Sinanen under the trade name Zeomic. Many other companies have also marketed similar durable silver containing luxurious antimicrobial fabrics, where a silver nano-particle has been encapsulated with a fibre reactive polymer. As a result, the applied capsule can easily react with the fabric and provide a durable finish. Yang et al. has patented a process of preparing silver nanoparticle containing functional microcapsule with the intrinsic antimicrobial and therapeutic functionality of silver embedded into the fabric [8]. Similarly, Aymonier et al. found that hybrids of silver particles of 1–2 nm in size with highly branched modified polyethyleneimines adhered effectively to the polar fabric surface, while providing environmentally friendly antimicrobial coatings. Silver containing antimicrobial finish has been accepted in wound management in the modern day medical practices. In reality, silver in contact with wound, absorbs undesirable bacteria and fungi and then helps in killing them. Acticoat, a commercial wound healing textile product, is made of nano silver. It consists of three layers: (i) a layer of the polyethylene film, (ii) middle layer of rayon/polyester blended non-woven fabric, and (iii) another layer of nanocrystalline silver particles. A similar wound healing textile substrate is also available from Johnson and Johnson Company in the trade name of Actisorb. It is basically a porous–silver impregnated charcoal cloth, sandwiched in between the two nylon non-woven layers. Though this product is very much effective, it is prone to be darken in the exposure of light, which could be tackled to some extent by using a polyurethane binder with nanosilver. Recent reports suggest that bacteria skin specialists are using nano-size silver colloids at a concentration of 3 ppm on the textile fabrics for antimicrobial property.

Rajendran et al. reported to synthesize ZnO nanoparticles and developed a suitable method of their application in cotton textiles [9]. Nano-ZnO coated cotton textiles have clearly demonstrated a better antibacterial efficacy compared to its bulk (micron) particles. The results showed the maximum bacterial reduction percentage of 94.1 % for *S. aureus* and 86.5 % of *E. coli* bacteria wash durability of the imparted finish by proper choice of the particle size and its concentration. Silver-titania nano-particles were also synthesized and deposited on different textile substrates using the ultrasound irradiation in an argon gaseous environment by altering both the cavitation threshold and the intensity of ultrasound power [10]. The antibacterial activity of the Ag-titania fabric composite against Escherichia coli (gram-negative) and Staphylococcus aureus (gram-positive) cultures was also reviewed. EI-Rafie reported that as low as 54 ppm nanosilver for cotton textile was sufficient for effective antimicrobial finishing [11]. The efficiency of the antibacterial finish on such textile was 97 and 91 % for Staphylococcus aureus and Escherichia coli, respectively. As expected, the antibacterial activity was found to reduce to 53 and 48.7 % after laundering of the sample for 20 times. However, with the application of suitable binder it was possible to enhance the antimicrobial efficacy up to 94 and 85 %, even after 20 washing cycles.

Due to the global awareness of eco-friendly and sustainable product development during the last decade, various natural products and biomaterials, such as neem, nano-lignin, silk-sericin, aloe Vera, Chitosan, and tulsi have been applied for antimicrobial, UV protective, anti-oxidant, skin-nourishing, and hydrophilic finishing of textile substrates. As these materials are produced from renewable sources, they are cost-effective, easy to apply, safer to human being and environmentally friendly. Plants containing phenols and oxygen based derivatives are considered as secondary metabolites that act as antimicrobial and insecticidal agent. Similarly, the tannins, a naturally occurring polyphenols is also responsible for the antibacterial activity of natural dyes. Antimicrobial efficacy of Chitosan, aloe-Vera, neem, tea oil, eucalyptus oil and tulsi leaves on various natural and synthetic textiles have also been investigated. Chitoson derived from chitin is an effective natural antimicrobial agent due to the presence of a reactive amine group that can easily react with the negatively charged bacterial cell-wall and finally destroy it. Similarly, Chitosan citrate has also been explored for durable-press as well as antimicrobial finishing of cotton textiles. Thilagavati et.al. [12] in 2010 identified the active antimicrobial molecules in neem, pomegranate and prickly chaff flower that can control the growth of microbes. Neem leaves contain limonoids based azadirachtin, sallannin and nimbin, which are actually responsible for antimicrobial and insecticidal properties in textile substrates. The combined effect of neem and Chitosan in the form of neem-chitosan nano-composite was also utilised and applied in cotton textile for eco-friendly antimicrobial finishing [13]. A recent patent on microencapsulation of neem oil and its application on cellulosic and blended textiles showed the good antimicrobial efficacy. Joshi et al., in 2007 reported the antimicrobial property of neem seed extract on polyester/cotton blended textile that was applied on cotton with glyoxal, aluminium sulphate and tartaric acid by two-dip, two-nip method on a padding machine, and the treated fabric showed excellent antimicrobial activity against both gram positive and gram negative bacteria, that was stable up to 5 washing cycles [14]. Recently, Ahamed et al. [15] has developed a new method of preparing an antimicrobial textile, i.e. by herbal coating in nano form (neem extract nanoparticles). Nano herbal extract treated textile was found to show excellent antimicrobial activity against both gram positive and gram negative bacteria. It was interesting to note that this particular finish was durable up to 20 washing cycles, whereas the only neem-extract treated fabric was durable up to 10 washing cycles.

Tulsi (*Ocimum sanctum*) is a very popular plant in India and is used almost in all religious occasions in India. This plant is well known for its medicinal effect from the ancient time as to cure or resist many infections and diseases. The Tulasi leaf extract contains caryophyllene, phytol and germacrene antimicrobial compounds and its efficacy was studied on the cotton textile after methanol extraction. Tulasi herb dyed bed sheet (fabric) showed good antimicrobial properties, and it has been used to cure patients suffering from chest cold, cough, itchiness and mucus problems. Sathianarayanan et al. [16] in 2010 applied Tulasi leaves and pomegranate extract on cotton textile by different methods viz., direct application, cross-linking and microencapsulation. It was observed that methanol extract and pomegranate molecules showed 99.9 % reduction in bacterial growth on the cotton fabric, when these biomaterials were applied directly by the pad-dry method. However, as expected, the microencapsulation and cross-linking methods of application of such products lead to better results in terms of wash durability (15 wash durable) of the finish with a little decrease in the case of gram negative bacterial growth to 94 and 87 % for Tulasi and pomegranate extracted molecules, respectively. Recently, aloe-Vera gel, another important industrial biomaterial has been utilized on cotton textile in order to improve the antibacterial activity against staphylococcus aureus bacteria [17, 18]. The specimens treated with 5 gpl aloe-Vera gel showed the excellent antimicrobial activity in terms of high reduction in the number of colonies and clear zone of bacteria inhibition. The imparted antimicrobial finish was durable to 50 washing cycles (slightly decreased to 98 %). The findings in this study can be used for developing durable sustainable luxurious hygienic cotton textiles.

Henna and juglone obtained from the walnut contain napthaquinone that acts as an antibacterial and antifungal agent. Curcumin has been used as a natural dye as well as an antibacterial agent for woollen textiles. Similarly, the turmeric, cumin, clove oil, Karanga, cashew shell oil and onion skin treated cotton textiles have showed good antibacterial properties. These kinds of fabrics can also be used as medical textile, wellbeing and casual apparel. Gupta and Laha [19] in 2006 has investigated the antimicrobial activity of cotton fabric treated with tannin rich extract of *Quercus infectoria* (QI) plant in combination with different mordant, such as alum, copper and ferrous sulphate. Only QI extract (12 %) showed the antimicrobial activity of 40–60 % against both the gram positive and gram negative bacteria. After the application of the same plant extract in cotton textiles with 5 % alum and 1 % copper sulphate, the antimicrobial activity was found to increase profoundly to 70–90 %. However, the treated cotton fabric almost lost the antimicrobial activity, when the extract was applied with ferrous sulphate mordant. It might be due to the fact that tannin i.e., O-phenolic compounds present in the extract had a positive role in disrupting the bacterial cell integrity. On the other hand, iron can easily bind with tannin groups and damage its antimicrobial property. It was found that the samples treated with only QI losses the antimicrobial activity after 5 washing cycles, whereas the samples treated with mordant could retain it up to 5 washing cycles.

4.3 Skin Nourishing and Vitamin E Finishing

Aloe Vera (Aloe barbadensis. Miller), belonging to the family of Liliceae, has been utilized in cosmetic and medical application. It has an excellent skin care property that includes anti-inflammatory and anti-ageing attributes. Kimberley-Clark Inc. Ltd. has patented an aloe Vera application as an anti-ageing and moisturizing agent. Similarly, DyStar Auxiliaries, GmbH has also developed a textile product containing a mixture of vitamin E, aloe Vera and jojoba oil in a silicon matrix for moisturizing and UV protective finishing of different textile substrates [20, 21]. Similarly, silk sericin has the potential for biomedical applications in imparting oxygen permeability, protection of cell from ultraviolet (UV) radiation and microbe, antioxidant, moisture regulation, and wound-healing properties [20, 22–25]. Lenzing has recently launched Tencel C fibre, which is basically a Chitosan soaked Tencel fibre. Chitosan is the second most available natural polymer after cellulose and has the history of being used for long in cosmetics and pharmaceuticals for itch relieving, regulating and protecting skin, and antibacterial finishing. Chitin is extracted from the Chitosan made from the crab shells. As claimed by the company, Chitosan can add skin-soothing cosmetic benefits to Tencel. In a scientific wear study, they found that the stockings made with Tencel C could protect the skin, allowing it to retain more moisture, improving the skin elasticity and stimulating skin cell regeneration. Lenzing is promoting the fibre for use in apparels worn next to the skin and in home furnishings, like bed sheets [26].

Specialty cosmeto-textiles have been developed by merging the knowledge of cosmetics and textiles. Such kind of fabrics can provide slimming, moisturizing, perfuming, and energizing effects, in addition to healthiness and comfort to the skin [27]. Generally, synthetic organic and inorganic products are used in preparation of such cosmetic textiles. In the last two decades, various animal and plant extracts, like Chitosan and polysaccharide from the exoskeleton of shellfish and crabs, and plant based essential oils, extracts, fruits and flowers have been utilized to ensure moisturizing, revitalizing effect to the skin, and for medication of the patients with a skin ailment. Many of the cosmeto-textiles produced from the plant extract of turmeric, neem, eucalyptus oil, indigo, and sandalwood show antimicrobial functionality, in addition to a healthier skin. Further, Indigo has antiseptic properties for healing burns and wounds of skin and also, known for a good blood purifying agent. Sandalwood nourishes the skin with smoothing facial lines and wrinkles. Aloe Vera herb dyed fabrics are very pleasant to wear, energetic and also have antibacterial, antiviral, wound-healing and anti-inflammatory properties [28, 29]. Similarly, essential plant molecules, such as fruit oils of citrus, rose, pineapple, banana, cherry and flowers like Jasmine have been utilized for aroma, refreshment and relaxation effect to the skin.

In the recent years, usage of wipes has been increased noticeably for its application in skin care, cosmetics, surface cleaning, and such other applications due to their advantages of being less expensive, more hygienic, softer, and more convenient to use over the woven fabric [30]. Other benefits of wipes are: small in size, light in weight, highly flexible, easy to use, and allow quick action and drying. Wipes are used in cleaning body, wounds, skin prior to wound dressing, treat rashes or burn, and to provide a fresh feel to the skin. Wipes can be a paper, tissue or non-woven, which is subjected to mild rubbing or friction in order to remove dirt, oil and liquid, and/or release soothing fragrance, medicinal ingredient and moisturizing agent. Wipes made of tissue papers or non-woven fabrics are successively soaked with different skin care/nourishing products as discussed below. Super wipes have recently been developed from Reliance's Recron® bi-component yarn, which is specially designed to hold high quantum of water, and to provide a better cleaning capacity [31]. JOHNSON® has also marketed a skin care baby wipes to take care of the tender skin of a newly born baby. It is very much softer and contains baby lotion to provide adequate moisture to the skin [32]. In the similar line, Aditya Birla Group has marketed different categories of wipes in the brand name of "Kara", such as face-care wipes, hand-care wipes, skin care wipes, and baby-care wipes [33]. These products are engineered with various natural ingredients, like jojoba, Avocado, honey, almonds, Aloe Vera, Cucumber, Mint, and Chamomile for their outstanding effectiveness in preventing the skin from infection, and provide soothing and moisturizing effect to the skin due to the presence of essential nutrients. It softens the skin, reduces wrinkle and fine lines—the signs of ageing, strengthens the skin tissue, keeps the skin hydrated, nourished and refreshed with effective removal of dirt and excess oil, and provides antiseptic and anti-inflammatory properties. As these products are made of cellulose and finished with natural ingredients, they are fully natural, biodegradable, and sustainable.

Vitamin E is also known as "Tocopherol" and belongs to the group of fat soluble vitamins. It is available in nature from various fruit and vegetable oils. The oil has the good antioxidant and moisture binding property. Human skin generates free radicals during exposure in the Sun and UV light, which may damage the skin. These antioxidants act as radical scavengers, hence are very much beneficial for skin ailments and also, help to protect skin cells from oxidative stress [34, 35]. Similarly, the anti-oxidant property of silk sericin was also evaluated, and it was found that the radical scavenging activity is possible to enhance by 56 % in the treated sample compared to the control sample [20]. As discussed earlier, extracts like sericin, Chitosan, and aloe Vera are produced from the natural resources and hence, can be effectively used in the development of eco-friendly sustainable textiles and cosmetics, while ensuring value to the natural products.

4.4 Moth Proofing of Luxurious Woollen Product

Similar to cellulosic cotton fibre, protein fibres, like wool and silk were also used in a large quantity in the ancient times for the production of apparels and home furnishing textiles for the king and the royal family. These sorts of royal textile products are also being used currently in fashion and reality shows, dresses for film actors and actresses and as the high society, professional casual and apparel wear, world class airport interior, luxurious flight and train interior furnishing, and so on. In the ancient Byzantine period, the fabrics made of silk were considered to be the most valuable luxurious products, as it was the expression of power, wealth and aristocracy. Such kind of luxurious fabrics were/are mostly used in making secular dresses, religious vestments and interior furnishings and they are very much popular in Italy, even today. Wool fibres are mostly used in imperial garments, warm clothes, and carpets to offer luxurious aesthetic feel, elegance, and comfort over a period of time. However, most often, the woollen products get attacked by moths and other microbes in the hot, humid, and closed-room environment. These microbes or moths generally eat the protein material of the wool fibre and release amine that produces foul smell. The process reduces the service life of the product in addition to lowering the elegant feel and look altogether of the textile sample. Therefore, to preserve the aristocracy of such luxurious woollen products, several moth-proof and/or antimicrobial finishing formulations have been developed over the period of time. Some of them are permethrin, naphthalene, and dieldrin based chemicals. Though they are quite effective in preventing the growth of moth in woollen products, they are not environmentally friendly, and also, adversely affect the elegance of such products [36]. For example, as dieldrin is a chlorine based compound, permithrin causes nausea, headache and immunotoxic problem. As discussed earlier, due to the increased global awareness on sustainability and demand for green textiles, recently, silver nanoparticles along with Chitosan, a bio-polymer has been found to be quite effective in moth-proof finishing of woollen products. Here, Chitosan helps to absorb the microbe induced bad smell, and the silver nanoparticles kill the bacteria and moths by cell-wall destruction. Nano-titanium dioxide particles in combination with citric acid were also found to be effective in moth-proofing and the same has been evaluated by measuring the weight loss of the treated fabric by feeding it to the larvae beetle [37]. In the same way, cyclodextrin has also been explored in the industry, primarily due to its advantages of absorbing the bad smell of amines by many available cavities, besides, it can provide suitable aroma to the woollen products [38]. Similar to cyclodextrin, butane-tetra-carboxylic-acid (BTCA) in combination with zinc oxide (ZnO) nanoparticles has also been investigated for similar end applications [39]. The Defence Research & Development Organisation (DRDO), of India has developed a fine environmentally friendly aerosol spray mechanism for enhancing the storage life of the woollen military products [40].

4.5 Wellbeing Textile for Yoga and Other Applications

In today's globalised society, people frequently face stress due to increased professional responsibility. To keep such physical and mental stress in control, and also to live a healthy and peaceful life, people tend to take optimum diet as prescribed by the physician, and do exercise and yoga regularly. Most people are also actively engaged in sport profession. Hence, specialty textiles for sports, leisure, exercise, and yoga are important. Functional sports and active wear with high moisture management assist a quick drying of the garment, reduce post-exercise chill, and provide the adequate thermal insulation. Textiles in different forms are being used by the mankind from its early existence for protection against heat, cold, rain, foul weather, and such on. With the evolution of the society, natural fibres based assemblies have been utilized in the form of ropes, twine, clothes, nets, and such other highly engineered goods. Ayurveda—an ancient, intricate, hygienic, eco-friendly and wholesome medical science practice, was developed in India thousands of years ago to prevent and/or to cure many diseases using various medicinal plants. Coinciding almost the same period, during the Vedic era, Ayurvastra, a medical textile was also developed by utilizing the scientific knowledge of ancient medicine and clothing science for curing of several diseases in a holistic manner. The Ayurvastra could be produced by dyeing of clothing using natural dyes, and finishing with medicinal and aromatic plants/herbs. During wearing of such textiles as a Yoga, or a sleeping dress, it has been reported that many diseases, like Arthritis, Osteo Arthritis, Arthritis rheumatism, Dermatitis atopica, Dermatitis from contact, Allergies, Hypertension, Tunnel carpal, Rheumatics, Diabetic, and Psoriasis can be healed. Additionally, the diseases like Asthma, Blood Pressure, and even some forms of cancer can also be cured by wearing such textiles [41–43]. Several wellnesses that have been possible to achieve due to wearing of such medicinal textiles are: immune boosting, weight-loss, energy giver, blood purifier, skin shining, inflammation, and respiratory disorders reducers [41, 44–46]. Medicinal plants and herbs like indigo, Arjuna bark, Alpinia (*Alpinia Galanga*), Accasia (*Acacia confuse*), Vetivert (*Vetiveria zizanoides*), Strychnos (*Srychnos spinosa*), Dadima (*Punica granatum*), Amalaki (*Emblika officinalis*), Haldi (*Curcuma longa*), Harda (Terminalia Chebula), Tulsi (*Ocimum sanctum*), Manjistha (*Rubia cordifolia*),

Fig. 1 Speciality fabrics for yoga and home textiles [48]

Sappan (*Caesalpinia sappan*), and such on have been explored in developing such medical textiles. As Ayurvastra is produced from natural fibres and plant/herb molecules, it is eco-friendly and sustainable, hence, has made its own importance and again, is being demanded by the eco-concerned user for curing of many diseases, holistically. Physicians normally advise to use medicinal cloths during sleeping, meditating, exercising, or at rest so that the medicine embedded fabric can restore the balance in the body and strengthen the immune system [41]. Considering all these points, the medicinal textiles are also often recommended for a bed cover, undergarment, towel, sleepwear, and all other garments that remain in contact with human skin so that the medicinal molecules can be absorbed easily through the skin [47] (Fig. 1).**Fig. 1** Speciality fabrics for yoga and home textiles [48]

5 Improvement in Fabric Comfort, Softness and Aesthetic Feel

Textiles with soft feel are the most preferred and commonly desired luxurious items to the consumers. The high comfort attributes in a textile can be incorporated mainly by two methods, viz: (i) chemical and (ii) mechanical, which are discussed below.

5.1 Chemical Methods

In chemical methods, such attribute has been incorporated by application of macro, micro, and nano silicone emulsion, where the penetration of such molecules into the textile structure provides a soft and lofty feel. Here, the bouncy nature of the siloxane (Si–O) group present in the chemical helps to get the desired soft-effect of the treated fabric. Recently, Marvic Textile launched a product named "Diluso–coral", a super-soft, linen-viscose based chenille, which has been surface engineered with silicon emulsion for luxurious application. The US researchers have also tried to prepare a soft fabric with combined polypoxide silicon resin mixture in a ratio of 0.05:1 to 1:1 by weight [49]. High IQ cool, a comfortable textile is also being demanded by a specific category of people to ensure the transportation of moisture away from the body, to reduce post exercise chill, and to provide a pleasant feel. This is done by engineering the design of the fabric and/or by finishing of it with glycerol or glycol based chemicals. The product has been reported to be highly successful for polyester and blended textiles. Fatty acid polyethylene based softeners are also used in textiles, but their effects are not durable. They act as a perfect lubricant and enhance the tear strength and sewability of the treated fabric by assisting the yarn mobilisation. Similar to a fatty acid, textile industries are also using anionic based softener to enhance fabric comfort and antistatic property, though such application has reported to downgrade the durability of the textiles. In this context, it is mentionable that 2–10 % of anionic polyurethane has been found to be quite effective before or after dyeing to ensure excellent softening property in polyester and its blended textiles [50]. Cationic softeners based on quaternary compound provide a good soft-touch, smooth-feel, fluffy, and non-yellowing tendency along with reasonable durability in cellulosic textile due to its affinity towards the cellulose polymer [51]. In this regard, Finotex Chemical Ltd. has developed Finox LFNY, which is a modified cationic softener, on being applied to the fabric provides elegant softness, handle and least yellowness [52]. Similarly, amphoteric softener (non-ionic) based on poly-oxyethylene have been reported successful for polyester, nylon, PVA, urethane elastic fibres and other synthetic products, where there is a chance of static charge generation. Additionally, it improves the fabric hydrophilicity, fluffy and bouncy, antistatic, softness, and soil release properties [53]. The W.T Jhonson and Sons of England has marketed innovative ranges of specialty cool finishes, especially for the woollen products that are exceptionally light in weight, cool and comfortable making them ideal for summer application. Sometimes various enzymes have also been used in textile processing and finishing due to their advantages of soft and gentle action on cotton cellulose, apart from being environmentally friendly. Concerning this, Cellulase enzyme is the most popular and widely used enzyme in bio-polishing of cotton textiles to impart luxury, soft-feel, elegance and aristocracy look with smooth touch. It is also effective in the removal of fuzz and pills from the fabric surface, making it more lustrous, cleaner and smarter. A group of researchers has also developed a new cool-comfort technology for incorporating cooling effect into textiles without using any chemical and polymer treatment. The fabric has exhibited its cooling function due to its unique construction that consisted of multiple fibre series, including hydrophobic polyester, hydrophilic nylon and a hollow-core polyester fibre. Like in the case of moisture management finishes, this fabric can wither away moisture from the skin or human body, where it has been applied. But, unlike the conventional moisture management finish, the fabric absorbs moisture from the outer environment, instead of allowing evaporation of moisture into the outer surfaces. It stores the absorbed moisture in the hollow core of the polyester fibre, which has been used as a hose between the back and the face of the fabric to siphon-off the water molecules, so that the moisture remains largely inside the fabric without escaping to outside. Here, the moisture evaporation could be controlled by manipulating the nylon and the polyester fibre. Such kind of technologically superior, comfortable textile has a promising market in luxurious sportswear, towels, blankets, and hats [54]. Cotton fabrics made of voluminous carded yarn and weave like denim, satin, herringbone twill have also been used to make softer, lustrous and supple garments. The fabrics are coloured by dyeing or printing with attractive shades with good fastness property coupled with glittering and colouring effects. Similarly, the fabric made of soybean protein fibre had many attractive qualities, such as silk-like lustre, good drape, elegant look, and health nourishing quality due to the presence of amino acid. Hence, it is suitable for making high quality apparels. Additionally, when the soybean fibres were used to make knitted fabric, it offered many positive attributes to the fabric like softness, smooth handle, and good texture. It has the moisture absorption capacity almost equal to the cotton fabric and a better strength compared to wool, silk and cotton fibres [55].

In order to develop sustainable luxurious textiles, many natural products have also been attempted. For example, silk sericin has been explored for multifunctional applications like imparting properties like oxygen permeability, antioxidant, moisture regulating, wound-healing, anti-cancer, anticoagulant, cell and UV protection [20, 22, 23]. The sericin generated in the degumming process of silk and discharged as an effluent has been used for hydrophilic finishing of polyester textiles. On application of silk sericin in the polyester sample, the moisture regain of the fabric was found to improve to 2.3 from 0.6 % in the untreated sample.

Angora rabbit fibre is considered as one of the world's finest luxury fibre due to its advantages of extremely warmth, soft, silky touch, and lightness properties. It is the third largest available animal fibre in the world after wool and mohair [56]. The fibre with 10–20 micron in diameter and 40–70 mm in length has air occluded cavities that ensure high thermal insulation. Scanning electron micrographs of the longitudinal and cross-sectional surfaces of Angora rabbit hair is reproduced from reference [57], which showed its somewhat scaly but smoother surface structure with prominent medulla. Similarly, the lower density of 1.15 g/cm^3 makes it a much better choice than wool (1.33 g/cm^3) and cotton (1.54 g/cm^3) fibres for making light weight fabrics. In spite of many positive attributes, this fibre has not been used to its full potential, as the outer surface of it is very much slippery, thus making it unsuitable for spinning. Hence, it is most often blended with wool, mohair, cotton, or silk fibre for spinning followed by production of fashionable garments, winter cloth, and underwear. Besides, production of cotton/polyester and Indian fine, yet short angora rabbit hair (11.1 μm, 32.3 mm) blended (30:70) yarn has been optimised to produce low-shrink yarn [58], and softness coupled with elastomeric feel has been created by microderm softening treatment [59] (Fig. 2).

In order to overcome the fibre spinning problem, emerging plasma technology has been used for 1–10 min at an atmospheric pressure. Plasma, an ionized gas composed of ion, electron, UV light, electron, protons, and ions, was used to increase the co-efficient of friction from 0.10 in the untreated sample to 0.30 in the

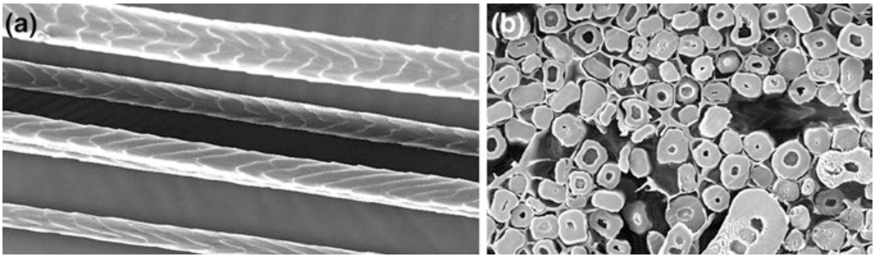


Fig. 2 Scanning electron micrographs depicting **a** longitudinal and **b** cross-sectional view of Angora rabbit hair fibres [57]

1 min air plasma treated sample. This process helped to produce yarn from 100 % angora fibres and it was used to produce Stole, Shawl, Scarf, Cap, Sweater and multilayer products for soldiers. Similarly, wool top (fibres) was plasma treated to make woollen products itch-free and making it suitable to be worn next to the skin. The adverse itching effect in wool fibres arises from the prickling due to protruding coarse fibres and friction with the skin due to the presence of sharp scales. The plasma treatment was used to remove/reduce the scale followed by proteolytic enzyme treatment. Finally, yarns and knitwear products were developed that were coated with suitable polymer in order to cover up the scale of wool fibres. From the various fabric characterizations, it was found that these products were completely itch-free and could easily be worn next to the skin as an inner garment [60].

5.2 *Physical Methods*

Similar to the chemical method, the fabric comfort and aesthetic feel can also be enhanced by physical methods, such as Velvet finishing. Velvet is a woven, tufted fabric in which cut threads are evenly distributed over the entire or specified location of the fabric with a short dense of the pile. These kinds of specialty textiles are mostly used in ladies garment, home furnishing items, and warm garment. Some of the Indian industries are using lafer/sueding machines for imparting the velvety touch to the cotton fabric. In this machine, there are piles and counter piles that rotate at a particular speed, tension, and cycle for raising the piles, so as to ensure the velvet effect on the cotton fabric. Luxurious velvet fabrics are very much popular in Egypt and China. Fabrics are woven with different colours of warp threads to enhance their appearance due to the reflection of light at various angles during draping and folding. Such kind of specialty fabrics can also be made by choosing the pile silk thread, right quality of dye, and resorting to specialty weaving so as to ensure the desire pile density and pile height. The velvet fabrics have also appeared in contemporary painting and secular portraits as a part of fashionable dress, sleeves or skirt. Some companies also have stretch silk velvet product range, which is made of 82 % rayon, 9 % silk and 9 % polyester, and it shrinks 13 and 24 % in length and width wise, respectively.

6 Luxurious Party Wear and Textile

With the evolution of human society in the last few decades, people are now more connected to each other, personally and professionally, specially due to the development of internet and mobile technology, computer science, transportation, and due to job mobility anywhere in the world. They do form many communities and/or group like, social, academic, personal, and professional to exchange their knowledge, thoughts, and emotion. In this regards, business, social, religious, and personal get-together party have become the part and parcel of their life. Professional people expect their apparel and party wear textile should be at par with the personality of the person. It should have some professional smart attributes like wrinkle-free, odour free with freshness and fragrance, self-cleaned, softer and with comfortable feel. Luxurious, comfortable active party wears are also very much popular among the children and young generation, as they frequently participate in many reality TV shows. In such a party, the textile gets contaminated with the soil (solid), semi-solid or liquid, such as food, beverage and drink in addition to the formation of crease marks. Therefore, soil release/repellent, liquid repellent and colour removal finishes have become popular to maintain the elegance of such textile products. The different types of luxurious party wears are discussed below.

6.1 Professional (Luxurious) Party Wear Textile

In general, people prefer to wear attractive, aristocrat, comfortable and lustrous textiles during religious, social, and business meet/get-together. Accordingly, fabric design, weave structure, colour, and imparted finish play an important role—individually and collectively. Today's child to pre-young generation is very much fashion conscious to make sure to register their presence and their active participation in front of media, TV, cinema, and public show. Additionally, they themselves are a lot choosy customers for different fashionable textiles with functional attributes. Hence, a textile designer has to concentrate more on the simplicity, comfort, new look, and new fashion with functional attributes, while designing a party wear for children [61]. The ideal baby clothing for a party should be attractive, soft, comfortable, fit for play and rest, comparatively loose, and easy to wear on and take-off [62]. At the same time, it should be lustrous, light in weight, non-irritating, allowing quick transmission of sweat from the skin, and with good oil and stain release properties. The party wear fabric has also been prepared from carded

Table 1 Technical details of the yarn and fabric quality for party wear [63, 64]

Warp and weft count	GSM	EPI and PPI	Design	Cover factor
30 K × 30 K	160	136 × 60	4/1	26.0
32 K × 30 K	162	144 × 60	3/1 (s)	26.5
50/2R × 30 K	195	118 × 96	3/1 (z)	26.4
30 K × 30 K	135	76 × 78	2/2 HBT	21.1
30 K × 30 K	210	146 × 96	Dobby	27.5

and Siro spun cotton yarn, as it is bulkier and spacious in nature due to high specific volume compared to a similar combed yarn. Such fabrics have been designed with herringbone twill, denim, and satin. These kinds of weave structures, when constructed with suitable yarn quality, generally provide a lustrous look and comfortable feel. Table 1 shows the technical details of the yarn and fabric quality suitable for making a party wear.

The fabric has been dyed with attractive reactive colours, like baby yellow, parrot green, turquoise and purple with good fastness properties. Successively, the samples were then finished with modified hydrophilic silicon emulsion and silicon macro emulsion, followed by drying at 150 °C for 1 min. The performance properties of the finished fabrics were evaluated in terms of wetting time, wicking time, strength, colour fastness, and soil release properties. All the treated fabrics showed a very good hydrophilic property in terms of usability and vertical wicking. The satin design of the fabric showed comparatively a better moisture management property. Soil release property, an important parameter of the party wear, has also been evaluated in all the treated samples. It can be observed from Fig. 3 that all the treated fabrics showed good soil release properties. This may be because of hydrophilicity of silicon emulsion that reduces the interfacial surface tension between fibres and the wash liquid, and helps to roll-off the soil particles.

6.2 Wrinkle Resistant Elegant Textile

In order to improve fabric elegance and to incorporate the aristocrat look, particularly in the cellulosic cotton textiles like shirting and suiting apparels, they are normally imparted with wrinkle resistant, i.e., the durable press finish property. For the same, formaldehyde based resin (DMDHEU) along with suitable catalyst is frequently used. However, the treatment reduces the fabric tensile property. Additionally, some other softeners are also added in the finish bath formulation in order to enhance or maintain the fabric handle and/or the comfort property. As the high concentrations of formaldehyde during the application have reported to cause teary eyes, cough, headache, difficulties in breathing, and even cancer, its use is highly objectionable in textile processing. This has led to the development of nano

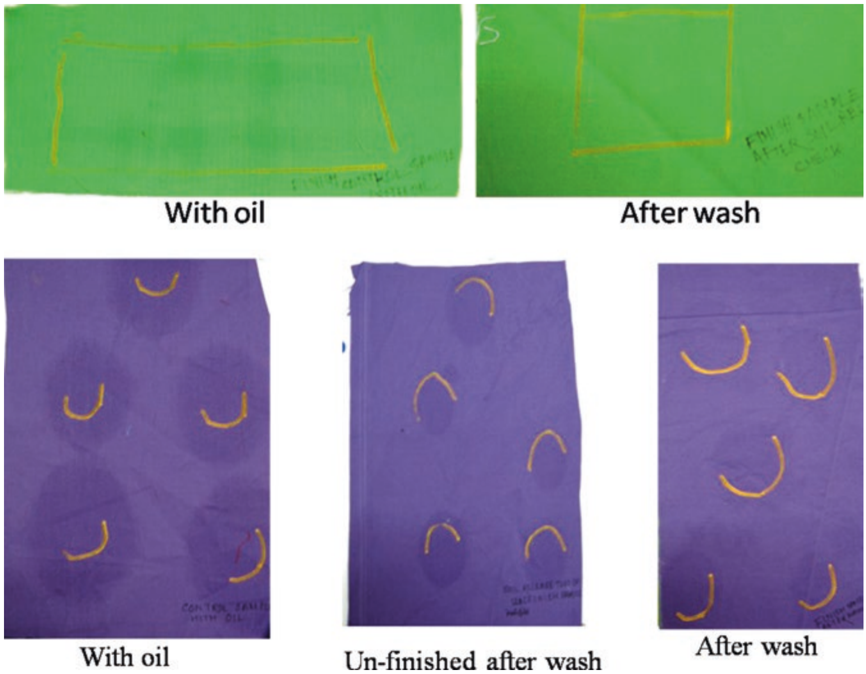


Fig. 3 Soil release properties of the control and treated party wear fabrics [63–65]

and polycarboxylic acids based environmentally friendly chemicals and processes in the recent years. Some of the explored poly-carboxylic acids are 1,2,3,4-butanetetracarboxylic acid (BTCA), citric acid (CA), succinic acid (SUA), malic acid (MLA), maleic acid (MA), and itaconic acid (ITA). Among these, only the BTCA has met with reasonable commercial success. The first application of nanomaterial in durable press (DP) wrinkle-resistant finishing of silk fabric was the use of titanium dioxide (TiO_2) nanoparticles as a catalyst in the presence of maleic anhydride (crosslinking agent) [66]. Nano-TiO_2 was employed as a photo-catalyst for finishing of cotton using polycarboxylic acids: BTCA, MA, SUA and CAs. The water molecules and hydroxyl ions could be reduced by the photo-reduction process. As a result, the carboxylic acid groups and vinyl double bond of the acid cross-linking agents reacted with the cellulose molecules. Similarly, nano-titanium-dioxide and nano-silica was used to improve the crease resistant property of silk and cotton [67]. These two nanoparticles with carboxylic acid in the presence of maleic anhydride catalyst under UV radiation can catalyse the cross-linking process. Espirit has developed a latest fashion in wrinkle-free trousers by adding more comfort and style attributes to it. These trousers are adaptable to different body types and its wrinkle-free property makes it suitable for elegant office, travel and long-journey wears [68]. Mob Stub Company of America has marketed a wrinkle-free product by the trade name “stay trendy”, which is made of soft 90

GSM microfibre. The products are very soft and comfortable due to the positive attributes of microfibre fabrics, such as light-weight, resilient, wrinkle resistant, luxurious drape, body shape retaining, and pilling resistant, and hence, can be used for making wrinkle-free bed sheets, pillow cases, and fitted sheets [69]. In this fabric, the heat penetrates faster compared to the other type of fabrics, making it suitable for cool ironing to resist the creasing. In the ninetieth century, British researchers have reported to develop 100 % wrinkle free woollen fabric made of high twisted worsted yarn with a porous plain weave structure suitable as travel wear by the trade name "Fresco". Additionally, it was crisp, cool, crease resistant and suitable for summer and the hottest climates [70]. The Van Heusen Company has also marketed wrinkle-free shirts treated with moisture cure technology. The fabric resists creasing and provides a comfortable feel like cotton to its user [71]. Louis Philippe has developed a creamy collection of easy care shirting fabric from the finest single yarn with silk protein finish. The yarn is treated with liquid ammonia before being converted to fabric so as to introduce softness and durable press, like in the silk fabric [72]. Park Avenue and Alen Solly have also introduced luxurious soft and wrinkle-free fabric with high durable press ratings [73].

6.3 Camouflaged Fashionable Textiles

An active camouflage provides a perfect copy of the visual surroundings that is present in nature in several groups of animals, including cephalopod molluscs, fish and reptiles. Mainly two different mechanisms are responsible for such an active camouflage effect in animal body. One is counter illumination and the other one is colour change [74]. Researchers have tried to mimic such a camouflage effect on the textile substrate also, in order to produce fashionable textiles. It is also commonly used in the defence applications such as military dress, vehicle, and copter painting. In this regard it is mentionable that CSIRO scientists have developed camouflage military fabrics by mixing different dyes. It reflects the visible, UV and also the infrared light in such a way as to mimic the reflectance spectrum of the background like plant, soil, and buildings. It works perfectly when the reflected light from the fabric matches with the background reflection [74]. Zhang et al. in 2007 has studied the effect of four different vat dyes for camouflage in the fabric. Application of 1–2 % Vat Blue 13 dye plays an important role in green camouflage, as the fabric reflectance matches with the reflection of greenish leaves [75]. The visual effect of the camouflage was possible to change by altering the cotton fabric construction. Recently, Goudarzi et al. [76] reported camouflage effects on cotton fabric in the visible and NIR region using three different vat dyes, namely C.I. Vat blue 6, C.I. Vat yellow 2, and C.I. Vat red 13 to get the reflectance curve similar to the greenish forest leaves and NATO green shades. Tulip Company provided a tie-dye T shirt in camouflage colours to provide a stylish fashionable look. The flat work surface of the fabric was covered with a surface cover and then, applied with a suitable mixture of kit colours till it got saturated, followed by colour fixation on the fabric in moist condition for 6–8 h [77]. It is also possible to make a person invisible by finishing the garment with a highly reflective material. In this area, the first research was initiated in the1960 s by the Harvard and the University of Utah [78].

6.4 Liquid Repellent Self-cleaned Textile

The technology of self-cleaning coating or finishing has been intensified in the recent years because of its smart application in textile, painting and such industry. The main attractions of self-cleaning coating/finishing are saving of labour, water and energy, new and aristocrat look for longer duration, detergent saving, and improved product service-life. Self-cleaned textile substrates can be developed by two methods: (a) super-hydrophobic coating and (b) hydrophilic finishing/coating. In both the methods, the coating helps to clean itself by the action of water. In the former case, water droplets roll-off on the surface and carry away the dust/dirt particles as shown in Fig. 4. And in the latter case, the active smart material breakdowns the absorbed colour contamination in the presence of sunlight and the process is known as 'photocatalysis'. In both the methods, it is possible to keep the textile clean from physical and/or chemical contamination without usage of water and detergent/wetting agent, and hence, suitable for making luxury party wear. However, in the first case, a small amount of water may be needed to allow the solid contamination to roll-off with water. Self-cleaning finishing of textile by

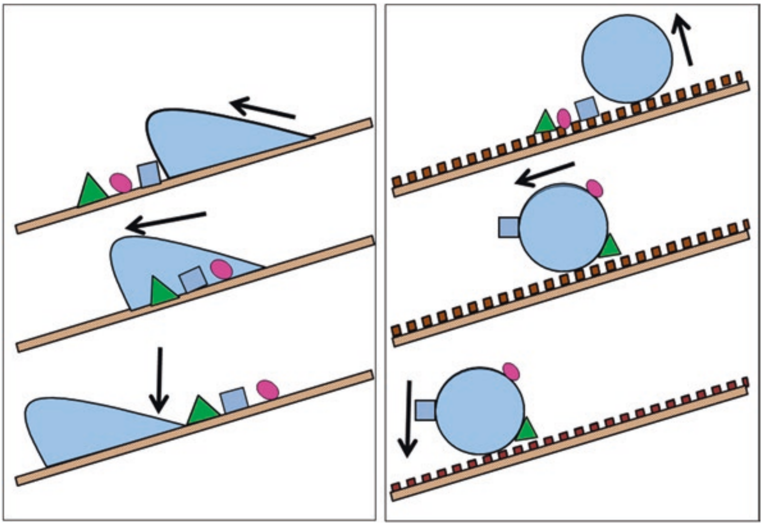


Fig. 4 Removal of dirt and dust from the **a** smooth hydrophobic and **b** rough super-hydrophobic surfaces [79]

'photocatalysis' mechanism using TiO_2 and ZnO nanoparticles has been discussed in the next section.

The research on super-hydrophobic or lotus effect on textile substrates has been intensified for developing elegant apparel textile to protect its user from the unwanted wetting, staining or chemical contamination, when in touch with rain-water, food, beverages, chemicals and pesticides. This kind of textile does not allow the liquid droplet to get absorbed by the fabric by enabling the liquid droplets to roll-off and leaving the underlying material un-wetted. When the water contact angle (CA) in a hydrophobic substrate becomes more than 150° with water rolling angle <10°, the surface is called super-hydrophobic surface. To produce such a surface, a combination of two fundamental properties, such as surface roughness and hydrophobic chemical are required. Unlike in a smooth surface, the dust particles do adhere to the water droplet and finally, are removed by rolling-off from the rough super-hydrophobic surface.

Fluorocarbon finishes constitute an important class of hydrophobic self-cleaned textile since 1960s. The treated fabric helps to repel water as well as oil from the surface. It contains a perfluoroalkyl residue in which all the hydrogen atoms are replaced by the fluorine atom; thus helps in reducing the surface tension to a value as low as 6 Mn/m. You et al. 2004, has prepared a self-cleaned dirt and water-repellent luxurious textile using nanoparticles of hydroxyapatite, titanium dioxide, zinc oxide and Fe_2O_3 [80]. The cotton fabric was finished with plasma deposition, and the treated fabric could maintain the required breathability, soft-feel and comfort properties [81]. Similarly Hang Ji and associates has developed a self-cleaned fabric using poly-dimethyl-siloxane (PDMS). In the sample, an anti-stick layer was added to the PDMS, which was then used as a negative template for the second PDMS casting step [82]. The second PDMS layer was the positive image of the lotus leaf. Similar to cotton, the inherent hydrophobic characteristic of polyester fabric was also further enhanced to impart lotus leaf like effect. It is claimed that the triglyceride in the emulsion copolymer melts and gets dynamically oriented in the film to provide a unique structure during the curing. Nakajima et al. proposed the mechanism to make a super-hydrophobic fabric by using TiO_2 and a sublimeable material, followed by a subsequent coating of a fluoroalkyl silane compound [83]. The treated fabric was found to be a good resistance against ketchup, charcoal dust, vegetable oil, turmeric solution, motor oil, and creamed spinach. A similar super-hydrophobic surface has also been prepared by using aluminium oxide, a gel like isotactic polypropylene, carbon nanotubes, aligned carbon nanotubes, silica, ZnO nanoparticles, ZnO treated carbon nanotubes, and similar other nanoparticles. However, all the chemicals mentioned above do not render to a durable finish to soap washing. Similar to the above, i.e., the creation of surface roughness by nanomaterials to produce a super-hydrophobic textile, surface roughness has also been created by mechanical methods like calendaring, embossing, etching, sueding or sanding, followed by treatment with nanoparticles of cross-linkable fluorocarbon having nanoparticles of silica, alumina, zirconia, titania, and zinc oxide. This process significantly improves the hydrophobicity of the sample, besides decreasing the water rolling angle. Similarly, micro-denier polyester fabric was initially abraded with a diamond coated roller with 30 psi pressure for 12 cycles, followed by application of chemical finish consisting of 1 % hydrophilic silica particles, 4 % fluorocarbon stain repellent, and 1 % cross-linking agent at a wet-pickup of 50 %. The sample after drying and curing showed super-hydrophobic behaviour, which was durable to 20 home washing cycles. In 2011, Havard scientists have created a slippery liquid infused porous surface that repels many substances like water, oil, ice, wax, etc. This kind of textile surface can also withstand a wide range of pH and temperature. The coating anchors a slippery lubricated film infused to a nano-porous solid surface [83]. NanoSphere® has also developed dust, oil, water, honey, coffee, and red wine repellent textiles, which are very much suitable for the party-wear [84] textiles. Similarly, Luna Innovations has announced an agreement granting UltraTech International an exclusive license to commercialise Luna's new textile repellent technology that can protect its user from pathogens and industrial contaminants [85].

Similar to the mechanical method of creating surface roughness, cold-plasma treatment has also been utilized in making rough surface followed by in situ or post plasma reaction of hydrocarbon, silicone, or fluorocarbon compound to achieve a super-hydrophobic surface. Samanta et al. has reported super-hydrophobic finishing of regenerated cellulose using helium/tetrafluoroethane plasma at an atmospheric pressure. The sample after plasma reaction for 8 min, showed a water contact angle of 153° and water rolling angle of $<10°$ as shown in Fig. 5. From the scanning electron microscope images, though both the untreated and the treated samples looked similar, they were distinctly different chemically, as one is hydrophilic and other one is super-hydrophobic [86]. The plasma treatment with oxygen gas in the presence of hexafluoroethane was carried out on cotton fabric to impart the hydrophobic finish [87]. When polyester (PET) fabric was treated with radio frequency (RF) plasma in a mixture of argon gas and gas-phase hexamethyldisiloxane (HMDSO), the water repellence rating was found to improve greatly. The atmospheric pressure plasma treatment with Ar/fluorocarbon gaseous mixture on technical textiles resulted in polymeric film deposition composed of super-hydrophobic PTFE (poly-tetrafluoroethylene), when F/C ratio was kept ≤ 3 in the gas mixture [88]. Super-hydrophobic finish was possible to achieve within 30 s, when fluorocarbon plasma was applied on to cotton fabric, due to the deposition of a nanoparticulate hydrophobic film [81].

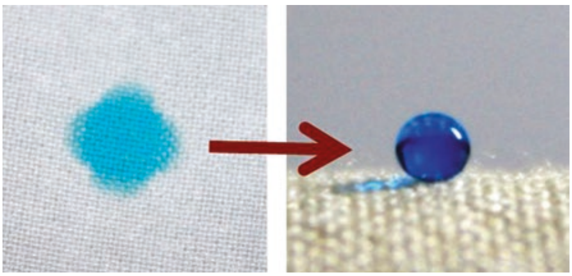


Fig. 5 Super-hydrophobic textile produced by plasma treatment [86]

6.5 Photo-Induced Self-cleaned Textile

As discussed above, the self-cleaned finishing of textile is important to keep the textile clean by the photocatalysis action of semiconductor metal oxide nano-particles and also, for saving a large quantity of water and wetting agent required for washing of textile to remove any colour and other solid contamination. Titanium dioxide (TiO_2) nanoparticles, a wide band gap semiconductor, have been extensively studied in the last decade for scientific and industrial research for self-cleaning finishing of textile, air and water purification, sterilization/disinfection, and degradation of organic colour in liquid [89]. The TiO_2 or ZnO nanoparticles loaded textile can clean the colour spot automatically in the presence of sunlight. The photocatalytic activity of such nanoparticle depends on their size and shape; the catalytic activity increased as the particles size decreased, preferably below 10 nm. Gupta et al. [90] synthesized and applied TiO_2 nanoparticles on cotton textile by sol-gel technique without using of any binder and evaluated the photocatalysis activity. The TiO_2 nanoparticles of size <10 nm were synthesized that demonstrated better photocatalytic activity than the similar size commercially available TiO_2 nanoparticles (P25). The highest reduction of 76.5 % in K/S value was possible to achieve after 48 h of sun light exposure. Khataee et al. [91] studied the discolouration of C.I. Acid Blue colour commonly used in textile industries using TiO_2 nanoparticles. It was found that TiO_2 nanoparticles were quite effective in degradation of organic colour. Dye discolouration depends on the initial pH and the amount of TiO_2 present in the solution. Doh et al. [92] developed photocatalytic TiO_2 nanofibers for the treatment of organic pollutants by electrospinning method. Photocatalytic activity was enhanced by coating of TiO_2 nanoparticles on the surface of the TiO_2 nanofibers. Samanta et al. synthesized TiO_2 nanoparticles on cotton textile by sol-gel method for degradation of organic colour contamination of manjishtha natural dye. It was possible to decrease the K/S value from 5.2 in the unexposed sample to 0.3 after 40 h of Xenon lamp exposure as shown in Fig. 6 [93]. The same fabric additionally showed excellent UV protective functionality with UPF rating of 50+ and the finish was durable to more than 30 washing cycles.

Hong Kong Polytechnic University researchers have also developed a process technology for self-clean finishing of cotton textile by titanium dioxide

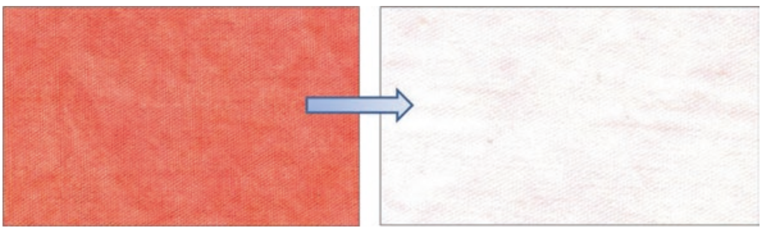


Fig. 6 Self-cleaned cotton textile using TiO_2 nanoparticles

nanoparticles coating at low temperature. Recently, Torey of Japan has also developed an innovative technology to improve the durability of photocatalytic coating agents using fullerene, an allotrope of carbon. Durable self-cleaning finishing of cotton textile has been reported using Titania aqueous nano-sol and the colour stain was possible to remove after 12 h of UV light exposure. A comparison of TiO_2 (35 nm) and ZnO (9 nm) nanoparticles on UV protection and self-cleaned finishing of cotton textile was investigated using an acrylic binder. In this process, the colour degradation experiment was carried out under visible light. ZnO nanoparticles showed a better self-cleaning performance compared to the TiO_2 nanoparticle. After 48 h of exposure, the decreases in K/S percentages were 50 and 70 % in the 2 % TiO_2 and ZnO nanoparticles treated samples, respectively [94]. A self-cleaned cotton textile exhibiting water repellence and photocatalytic activity under visible light was prepared by step-wise deposition of anatase TiO_2, *meso*-tetra(4-carboxyphenyl)porphyrin (TCPP) and trimethoxy (octadecyl)silane (OTMS). The sample showed the water contact angle as high as 156° and could able to degrade methylene blue colour [95]. International Advanced Research Centre for Powder Metallurgy and New Products (ARCI), India has developed nano-titania for self-cleaning of textile, by tailoring its band-gap. They have also developed a co-catalyst (Cu, Pt) modified semiconductors for visible light, and for efficient photocatalysis action by interfacial charge transfer [96].

7 Luxurious UV Protective Sports and Leisure Wears

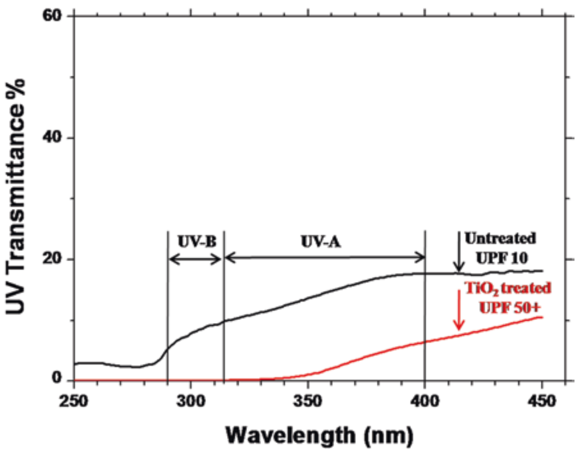
In recent years, people, particularly from rich to super-rich category are more keen on yoga and leisure activities to keep them physically and mentally healthy and active. During such activities, they frequently come in contact with excessive sunlight and UV rays that may cause several skin damages. Also, nowadays the children as well as the younger generation actively participate in various personal and professional indoor and outdoor activities—including sports, reality shows, recreational, educational and business meets that are the sources of their excessive sunlight exposure. In this context, the UV protective textile is important in our daily life, as about 6.1 % of the total solar emission reaching to the earth is composed of UV radiation, which causes radiation induced skin diseases. The remaining portions of the solar emission spectrum are visible light (51.8 %) and infrared radiation (42.1 %). Some amounts of UV exposure are considered to be appropriate as to promote the circulation of blood, invigorate the metabolism, synthesize vitamin D and improve resistance to various pathogens present in the human body. However, due to lower wavelength and higher photon energy of the UV rays compared to the visible light and infrared, it has the more ability to penetrate the top layer of the skin. This may lead to the onset of acute and chronic diseases, such as accelerated skin ageing, sunburn, blotches, wrinkles, weak immune system, sun tanning, photo-carcinogenesis, skin cancer, eye and DNA damage. Hence, it is desirable to ensure that an individual is subjected to an optimum exposure to sunlight. The UV radiation is categorized into three zones based on their wavelength, namely (i) UVC (200–280 nm), which mostly get absorbed in the ozone layer of the upper atmosphere (ii) UVB (280–320 nm), that penetrates the top layer of the skin and more likely to cause skin ageing, sunburn etc., and (iii) UVA (320–400 nm), which penetrates through the skin and may cause skin ageing [97]. Therefore, to design and develop an effective UV skin care textile, one has to ensure that the textile effectively block the transmission of both UVA and UVB rays. The UV protective performance of a textile is defined by the Ultraviolet Protection Factor (UPF). Its numerical value indicates that how long a person wearing the textile can stay in the sun before skin reddening starts, compared to a person without the said textile as a cover. The UPF value is meant to create an awareness of the negative impact of UV-radiation among the end-users. The UPF value of $\leq$10 in a textile is considered as providing almost no protection from the UV radiation. On the other hand, a fabric with UPF value of $\geq$50 is considered to be an excellent UV protective textile. The fabric's ability to absorb and/or restrict the penetration of the UV light through the fabric depends on several parameters, such as fibre type and its chemical composition, fabric structural parameters (e.g., weave, threads/cm, thread count, cover factor, etc.), the nature and depth of the dyes and pigment, presence of optical brightening agent (OBA), applied finish, stretch, moisture, and relative humidity, and such on. As the natural fibres based woven and non-woven textiles like cotton, linen, silk and wool have a lower capacity of UV absorption than those made from synthetic fibres, they do require to be finished with UV absorbing chemicals or agents to enhance their service life, while ensuring protection to its user. In the past, during development of UV protective traditional to high-end, luxurious textiles, mostly chemicals like silicate, Triazine class-hindered amine, derivatives of o-hydroxyphenyl diphenyl triazine and OBA were used [93, 98–100]. However, in the last two decades due to the rapid growth of nano-science and technology, the nano-size metal particles have been playing a promising role in commercial applications of multifunctional finishing of textiles, including UV protection. These nano materials are getting accepted because of their advantages of being nontoxic, environmentally friendly, and stable even under high temperature and pressure processing conditions, and unlike traditional chemicals, they required to be applied in a minimal quantity that does not hinder impartment the desirable textile properties to an apparel [89]. It has been also reported that the nanoparticle of natural polymer, such as nano-lignin act as a good UV absorber. Natural polymers, such as silk sericin and aloe Vera have also been recently attempted for high-end biomedical applications, to impart functional properties like oxygen permeability, cell protection, antioxidant action, moisture regulation, UV protection, and skin nourishing [20]. Also, in the context of global demand of green/eco-textile/organic textile products, researches on sustainable UV protective textiles using plant molecules have been intensified as reported below.

7.1 Using Inorganic and Organic Nanoparticles

Nanotechnology, a rapidly growing emerging interdisciplinary science, is gaining much attention in both academic research and industrial product development for applications in textile, medicine, electronics, optics, plastics, polymer, energy, aerospace, and agriculture [89]. It is no wonder that the textile sector has also embraced and adopted benefit of nanotechnology for novel product development by using significantly small amount of chemicals. Nanotechnology aims at manipulating atoms, molecules and development of nano-sized material in a precise manner in order to build up a new material that can be effectively used to produce functional, smart, intelligent, and luxury textiles, such as water and oil repellent, hydrophilic, hydrophobic, UV protective and with glittering effect, and health and hygienic concerns [89]. Nanoparticles, due to their large surface area-to-volume ratio, high surface energy, and better affinity towards textile substrates though applied in small quantity, can increase the durability of the imparted finish, while preserving the physical and mechanical properties of the fabric. Mainly the metal and metal- oxide nanoparticles, such as TiO_2, ZnO, SiO_2, Al_2O_3, MgO, CaO and silver (Ag) have been explored, as they are stable under harsh process conditions and quite safer to human beings and animals [7, 101, 102]. The application of small amounts of such nanomaterials helps to achieve a good UV protective performance, making them a preferred choice over the organic UV blocker. It has been established that the nano-sized titanium dioxide and zinc oxide are the two most-efficient and well explored compounds for UV absorbing and scattering, thus providing excellent UV protection compared to their micron size particles [22]. In addition to UV-protective finishing of textiles, the ZnO nanoparticles can also be used for making antibacterial products, solar cells, sensors, electro-acoustic transducers, photo-diodes, light emitting devices, sunscreens, gas sensors, and anti-reflection coatings [103]. Nano-ZnO has been characterized and applied on cotton and polyester/cotton blended textiles for UV protective finishing by Kathirvelu et al. [101]. The 2 % nano-ZnO coated cotton fabric was found to exhibit about 75 % blockage of the incident UV rays and there was no significant change in fabric strength and whiteness value [41]. A similar finish was found to be durable up to 55 home laundering cycles [104, 105]. The ZnO nanoparticles of 40 nm were synthesized using zinc nitrate and sodium hydroxide as precursors, and a soluble starch as the stabilizing agent to improve UV protective performance of a 75 GSM cotton fabric [100]. An acrylic binder of 1 % was used for anchoring the 2 % ZnO nanoparticles on the surface of the cotton fabric. It was found that about 80 % of the UV light can easily pass through the untreated fabric, whereas only 50 and 25 % could pass through the bulk ZnO and nano-ZnO particles treated samples, respectively. This result is a clear indication of the ability of nano-ZnO particle in blocking ability more of the amount incident UV light compared to their micro sized particles. Besides, the nano-Zno particle treated sample showed an improvement in air permeability without affecting the mechanical properties. On the other hand, as expected, the fabric to fabric and fabric to metal co-efficient of friction were found to be more in the treated fabric. In another study by the same research group, the size of the particles was measured to be 38 ± 3 nm under a Transmission Electron Microscope (TEM) [106]. The starch content in the nano-ZnO-starch composite was 37.7 %. The UV–visible transmission spectra of the fabrics showed the blockage of UVA (315–400 nm) and UVB (280–315 nm) were 19 and 32 % in the control sample, as against 42 and 59 %, respectively, for the bulk ZnO (2.0 %) treated, and 65 and 68 %, respectively for the nano-ZnO (1.0 %) treated samples. The UPF value of the control cotton fabric was calculated to be 1.54 and it was 2.48 and 3.71 for the bulk ZnO and nano-ZnO coated fabrics, respectively [106]. Both these ZnO treated samples were found to possess anti-microbial efficacy of >90 % against *Klebsiella pneumoniae* (Gram negative) and *Staphylococcus aureus* (Gram positive) bacteria with slightly better result in the case of nano-ZnO treated sample.

Similar to ZnO nanoparticles, titanium dioxide (TiO_2) nanoparticles also possess a good UV blocking property and the same has been explored for cotton and polyester woven textiles. Titania nano-sol was produced from titanium iso-propoxide by sol-gel technique using water (T_1) or ethanol (T_2) as a medium, and then applied in the fabric sample by pad-dry-cure method [93, 107]. The UV reflectance spectrum of nano-TiO_2 treated PET fabrics profoundly decreased the reflectance of the irradiated UV ray compared to the unmodified sample, implying higher blockage of incident UV rays. In an another study, the particles of 10–300 nm were synthesized in cotton textile in situ as measured by TEM, AFM and the particle size analyzer. After application of such nano-finish, the UPF was found to increase significantly from 10 in the untreated sample to 50+ in the nano-particle treated sample, as measured according to AATCC 183:2000 method on a Labsphere UV transmittance analyzer [108]. As a result, the UVA and the UVB transmittance values were reduced from 15 and 8 % in the untreated sample to 6.2 and 0.1 % in the TiO_2 treated sample, respectively as shown in Fig. 7.

Fig. 7 UVA and UVB transmittance percentage in untreated and TiO_2 nanoparticle treated cotton textiles [108]



It was estimated that a minimum 0.24 % TiO_2 loading was sufficient to enhance the UPF rating of cotton fabric from 10 to 50+. Similar to ZnO nanoparticle finish, this particular finish was also found durable up to 30 wash cycles as per the AATCC-61-2A method, without usage of any binder/cross-linking agent. This indicates that the TiO_2 nanoparticles are firmly present in the structure of the cotton textile and do not come out during the washing of the sample with soap solution, hence can be used for the development of durable sustainable UV protective healthcare textiles. The UV protection, antimicrobial, and self-cleaning finishing of a cotton textile (118 GSM) by sol-gel synthesis of TiO_2 nanoparticles and 1 % acrylic binder has also been reported [102]. When water was used for nanoparticle synthesis, it led to the formation of smaller particles (7 nm) compared to 12 nm formed in the ethanol based preparation. As expected, the UPF value was found to reduce from 44.8 to 18.8 in the unwashed to wash sample in 18 washing cycles [102]. Smaller size particles exhibited a better antimicrobial and self-cleaning properties than the bigger ones. In a similar research on UV-blocking treatment of cotton fabrics, titanium dioxide nanoparticles of 6 nm was produced by the sol-gel chemistry and the finish was found to be durable to several washings (maximum up to 50).

Similar to synthesis and application of inorganic metal oxide nanoparticles in textile, the organic polymeric nano-material, i.e., nano-lignin has also been attempted in the last decade for UV protection, antimicrobial, and anti-static finishing of cellulosic textiles in an environment friendly manner [109]. Pigments and lignin in the natural fibres like hemp, flax, jute, and such on act as a UV absorber and ensure a good protection. Nano-lignin was obtained from kraft lignin by ultrasound treatment, and the particle size was measured to be in the range of 5–170 nm [98]. The nano-lignin was applied by padding method in the presence of silicone emulsion (5–25 g/l) that ensured insignificant change in the fabric stiffness and air permeability. The highest achievable UPF was 25 in the treated linen sample compared to 5 in the untreated sample. The presence of silicone emulsion along with lignin helped in providing better UPF (>45) and fixation of particles in the fabric structure. However, the improvement was not so promising in the case of fabric made from hemp. It was observed that the plasma treatment for 5 min in oxygen mixture was useful for surface activation, prior to application of nano-lignin in the linen fabric [80, 81]. In case of flax non-woven fabric, the lignin treated sample showed almost double the UPF value (50) compared to the unmodified sample [110, 111].

7.2 Using Plant Molecule and Natural Polymer

Similar to the application of organic and inorganic nano-materials, in recent years a number of plant molecules (extract) and natural or bio-polymers have also been utilized for the development of sustainable UV protective textiles. Recent studies have reported the presence of active molecules in some of the natural dyes that can absorb UV light and impede its passage through the fabric. A European research group has reported UV protective property of linen, hemp and silk fabrics due to application of dyes extracted from madder woods, knotgrass, fenugreek, and marigold. The achievable UPF value was as high as 50 in the linen fabric with India madder [112]. Sarkar [113] has also reported that the madder (*Rubia tinctorium*) and Indigo (*Indigofera tinctorial*) extracts have good UV protective property. To understand the mechanism of action of UV protection, these extracts were applied to the alum pre-mordanted plain and twill woven cotton textiles with an initial UPF of 3.8 and 19.2, respectively. It was observed that 6 % madder extract and indigo dyed plain woven cotton fabric exhibited the UPF of 16.6 and >50, respectively. The improvement in UPF value was due to the dark blue colour of indigo dye. Similarly, pomegranate and alum mordanted ligno-cellulosic UV protective bleached jute fabrics were possible to develop after dyeing with the extracts of babool, manjistha, annatto and ratanjot [114]. In a few recent studies reported from India, the UV protective property of bamboo, Tencel fiber, and blended fabrics from regenerated fibres was enhanced using grapefruit oil. The extracted honeysuckle molecules also provide a good UV protective attribute to the wool fabric. Similarly, Subramaniyan et al. [115] has reported that anthocyanin extracted from the mulberry fruit could improve the ultraviolet protection property of cotton fabrics. As expected, the higher concentration of anthocyanin at lower pH of 4.5 had helped to provide a better UPF in the study. They have also observed that the crude mulberry extract could provide the same degree of UV protection, when applied at an acidic pH with the same concentrations. Recently, Vijayalakshmi and Ramachandran [116] reported the use of sweet spring citrus oil for its application in antimicrobial, antifungal, and UV protective finishing of light weight denim fabrics, such as 100 % cotton, 100 % tencel, cotton/polyester blend, and tencel/polyester blend. It was observed that the plain woven bleached cotton fabric showed a poor UPF value of 10 and after mordanting with tannic acid and alum, the UPF value did not improve much. However, when the mordanted fabric was treated with the alkaline BPS, an agricultural waste material available in India and others countries in plenty, the UPF value was found to improve to over 100 (i.e., a 50+ rating). Consequently the UVA and the UVB transmittance percentages get reduced drastically from 9.5 and 7.2 % in the untreated samples to 1.2 and 1 % in the BPS treated samples, respectively. The UV protection of BPS treated sample is arising possibly due to the presence of *N*,*N* alkyl benzeneamine as confirmed by a GC-MS analysis of the BPS [117, 118]. It was found that the UPF value remained at 70 and 55 after 1st and 2nd washes, respectively. Salah [119] reported the utilization of banana peel saps, an agro-waste for improving the UV protection and antimicrobial property, and natural dyeing of cotton fabric. Cotton fabric made of Egyptian fibre showed a UPF of around 19.8, whereas the same fabrics after mercerization and sap dyeing, exhibited a UPF of around 60. The reduction in UV transmittance through the fabric might be due to the combined effect of reduction in fabric porosity due to the alkaline swelling after mercerization, mordant-fabric complex formation, and the presence of Luteolin in the banana peel saps. The bleached, mordanted, and banana peel saps treated cotton fabric showed more than

90 % bacterial reduction against both gram positive and gram negative bacteria. Similarly, the spinach juice (SJ) treated, bleached cotton fabric in alkaline condition had the UPF value of 50+ (125) and the UVA and UVB transmission percentages get reduced to 2 and 1.8 %, respectively. In this case, the improvement in UV protection was due to the presence of organic colour and silicate molecules in the spinach extract [120].

The silk sericin, a bio-polymer has also been explored for multifunctional finishing of natural and synthetic textiles, including UV protection. Silk derived from the silkworm is composed of two major proteins: fibroin and sericin. Sericin or silk glue is a globular protein, which has around 25–30 % of silk proteins. The silk sericin is a well-known biomaterial for biomedical applications including protection from UV rays [23]. Sericin generated in the degumming process of silk and discharged as an effluent, is a by-product that can be recycled and re-used for the development of high value textiles and cosmetics. The polyester fabric after treating with Lissapol N was placed under UV excimer lamp for 1–15 min prior to functionalization with silk sericin. The UPF value was found to increase from 55 ± 5 in the untreated sample to 125 ± 6 in the treated sample [23]. As the sericin acts as a UV absorber, it helps to convert the electronic excitation energy into thermal energy.

8 Challenges and Prospectus of Chemical Finishes in Sustainable Luxury Textiles

In the early phases of human civilisations, the consumption of luxury items including textiles, was confined to the elite classes of people of the society. However, in the last few centuries, with the rapid growth of economic abilities of majority of the masses, an array of new affordable luxury products has been introduced and marketed, specifically to entice the aspiring middle class. The luxury textile now broadly refers to those textiles specially engineered with highly functional, aesthetic, comfortable and fashionable attributes that are available at a higher price. Till 1950s, mostly cotton, silk, wool, linen, and regenerated rayon fibres were used in making luxurious textiles. Later on, till the end of the twentieth century, due to several technological advancements of man-made fibres including the synthetics and for the specialty polymers, these fibres are also being utilized, either alone or in blends with natural fibres for the production of luxury apparel, home and other utility textiles. Of late, natural fibre based textiles are once again in demand by the eco-conscious elite buyers.

Textile processing chemicals and auxiliaries, such as caustic soda, acid, hypochlorite, hydrogen peroxide, carbon tetrachloride, synthetic dyes (azo based), chlorinated compound, formaldehyde based chemicals, pentachlorobenzene, hexamethylenebiguanide, quaternary ammonium compounds, silicon emulsion, permethrin, naphthalene, phenyl salicylate, benzophenone, benzotriazole, and such on are used in processing and finishing of natural as well as synthetic fibres in order to improve their functional and aesthetic values. Some of the present day textile chemicals have the adverse effect on environment, plant and animal bodies. Therefore, for the development of sustainable luxurious textiles, the associated chemicals and technology, and the final product should also be sustainable in terms of water, energy, cost, effluent-generation, and their bio-degradability. Due to the rapid growth of nano-science and technology in the last two decades, various organic and inorganic nanoparticles, such as silver (Ag), TiO_2, ZnO, SiO_2, lignin, neem and Chitosan have been examined for their commercial exploitation for the production of high-end textiles by application of minimal quantity. More recently, due to the increased global awareness on issues like sustainability, global warming, carbon foot-print, and eco-textile, the focus on current research and development has been intensified in the field of green-chemistry, material science, biomaterials, bio-polymers, bio-molecules, and bio-technology. As upshots of such cutting-edge technologies, and due to constant R&D endeavours a number of new bio-materials like BPS, grape and mulberry fruit extracts, numerous natural dyes, Chitosan, tulsi, silk-sericin, aloe Vera, lignin, neem, honey, almonds, cucumber, and mint have proven useful for antimicrobial, UV-protective, anti-oxidant, skin-nourishing, and hydrophilic finishing of textiles. These kinds of green and/or bioactive agents/molecules have the highest potential for application in the production of sustainable luxurious textiles. As reported earlier, the luxurious textiles being the high valued textiles, are recommended to be washed with solvent (dry cleaning) or alkali-free detergent. This is because, as many detergents contain trace amount of alkali that may prove detrimental to fabric colour, look, and feel, especially, if they are wool and silk products. To cite an example, take the case of Godrej made soda-free Ezee liquid detergent for silk and woollen products, approved by the Woolmarkis being claimed to be five-time safer than the normal detergents, as far as prevention of shrinkage, maintaining the shine and softening of clothes is concerned [121]. However, there is a dire need to develop suitable standards for characterising and certifying the high-value textiles. Though it is a bit difficult task, as it will vary from product to product, however, once achieved will help in establishing an authentic and steady production lines and marketing channels for the luxurious textiles.

9 Summery

With the constant evolution of the society, particularly in the past few decades, people have been more connected with each other personally and professionally due to the advancement in internet, mobile, computer science, transportation and related technologies. They do form many social, academic, personal, and professional community/groups for exchanging their knowledge, thoughts, and emotion. In order to successful deliberation of their knowledge, performance, and effort in such places their textiles should also reflect the personality of the person. In the 21st century, people are too busy as to execute many times-bound personal and professional responsibilities causing frequent physical and mental stress in them. To have a control on such stress, and also to live a healthier and luxurious lifestyle—exercise, yoga, leisure, spa, and dream sleeps have become a part and parcel of their life. This has boosted the increased applications of luxury apparel and home textiles. They now play important roles as to provide an energetic, fresh and mind-blowing fragrance with due consideration of health and hygiene attributes of the human being. In this regard, various organic and inorganic nanoparticles, like silver (Ag), TiO_2, ZnO, SiO_2, lignin, Chitosan, and neem-chitosan are being increasingly applied on natural as well as synthetic textiles for development of health and hygiene, UV protective, self-cleaned, and skin care textiles. Similarly, a number of plant molecules, biomaterials and biopolymers, like BPS, grape and mulberry fruit extract, natural dyes, Chitosan, tulsi, silk-sericin, aloe Vera, honey, almonds, cucumber, and mint have been applied in textiles mainly for skin care and infection control. In order to ensure a pleasant and fresh feel to the ambience and in our living room, the extracts of jasmine, lavender, Champa sandalwood, etc., have been applied in textiles by direct and micro-encapsulation technique. High value Cosmeto-textile and Ayurvastra have been developed by coupling the traditional knowledge on cosmetics, ancient Ayurveda and clothing science. After the application of plant and herbal extracts, like neem, eucalyptus oil, sandalwood, indigo, Arjuna bark, Alpinia, Vetivert, Dadima, Amalaki, Haldi, and Tulsi on textiles, they could exhibit antimicrobial, skin nourishing, slimming, moisturizing, perfuming, and energizing functionalities along with attributes of curing/healing of many diseases in a holistic approach. Emerging water-free plasma and UV-excimer technologies were utilized for improvement in hydrophilicity, durability of applied finish, and removal of a surface scale present in wool and Angora fibres that ultimately helps to produce super-soft luxurious textiles. Professional smart attributes, like wrinkle-free, order free, fresh, self-cleaned, soft and comfortable feel was incorporated in aristocrat, professional and active party wear by application of macro, micro, and nano silicone emulsion, cellulose enzyme, velvet finishing, polycarboxylic acid, camouflage dyeing effect, nano-material for photo-catalytic activity, and super-hydrophobic coating of non-fluoro and fluoro chemicals. Similarly, in sports and leisure wear textiles, the harmful UVA and UVB rays can be blocked by application of organic and inorganic nanoparticles, natural dyes, grape and mulberry fruit extract, banana pseudostem and peel sap, citrus oil, and silk sericin. Therefore, the various organic and inorganic nano-materials, biomaterials, and plant/herbal extracts can be effectively used for the production of sustainable health-hygiene, well-being, skin caring, comfortable, self-cleaned, and UV protective luxurious textiles.

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Part III
Sustainability and Business Management

Sustainable Practices in Luxury Apparel Industry

Shams Rahman and Aswini Yadlapalli

Abstract Although the market share for the luxury apparel has increased considerably, the industry, however, is perceived to be lagging behind in sustainable practices. This chapter identifies sustainable practices within luxury apparel brands against Global Reporting Indicators (GRI) and extends the 'Greening Goliaths versus Emerging Davids' conceptual framework for classifying the luxury brands. Using the case study approach, this chapter analyzes sustainable practices of nine global luxury brands and classifies them into four clusters: Ecopreneurs, Greening Goliaths, Emerging Davids, and Sustainable Entrepreneurs. Results indicate that true artisanal brands with third party accreditation in sustainable reporting such as Prada and Gucci emerged as sustainable entrepreneurs. On the other hand, Ralph Lauren a ready-to-wear luxury brand with emphasis on economic values emerged as an ecopreneurs.

Keywords Global reporting indicators · Luxury apparel · Sustainable practices · Global brands

1 Introduction

Over the past 20 years, the number of luxury consumers worldwide has almost tripled from 90 million in 1995 to 330 million in 2013 [3]. It has been projected that in 2015 revenues for luxury goods worldwide will grow approximately 5–6 % of annual average [3]. This phenomenal growth in this sector is due mainly to the creation of 'new rich' in South-East Asia and the increasing social relevance of

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M.A. Gardetti and S.S. Muthu (eds.), *Handbook of Sustainable Luxury Textiles and Fashion*, Environmental Footprints and Eco-design of Products and Processes,
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owning luxury goods [2]. Among all categories of luxury products, fashion items manifest the prestige of the owner and communicate the identity of the user.

In the literature, it is argued that luxury and sustainability are incompatible terms—both cannot be achieved at the same time. Consumption of anything more than basic needs jeopardizes the life of next generations and is regarded as unsustainable. Luxury products are known for the waste of resources for the pleasure of few and symbolize social inequality. This could be one of the reasons why the industry has been under continuous scrutiny for unethical practices [23] and recently been targeted by the media for lagging behind in social and environmental sustainability aspects [26].

Luxury industry relies heavily on communications for branding and marketing. To build a sustainable brand image, luxury brands need to emphasize on social and environmental values while marketing. A common practice in advertising sustainable aspects of business is to use sustainable images and videos in media. The other form would be to disclose social and environmental aspects of businesses in corporate reports and websites following international standards. Unlike ready-to-wear garment brands, advertising sustainability through organizational disclosure is not a very common practice in the luxury apparel industry. Are these firms trying to hide their weaknesses when it comes to sustainability? Does this mean that the luxury apparel industry is lagging behind when it comes to the sustainable question? Using the case study approach, this chapter analyzes sustainable practices of nine global luxury brands (companies) and categorizes them using 'Davids and Goliaths' type matrix analysis.

Reminder of this chapter is organized as follows: Sect. 2 provides an overview of apparel industry. Concept of luxury and luxury apparel industry in global context is detailed in Sect. 3. Section 4 summarizes sustainable reporting practices in apparel industry and extends 'Emerging Davids versus Greening Goliaths' framework to luxury apparel industry. A case study on world's famous luxury apparel brands and their sustainability aspects is discussed in Sect. 5. Section 5 also examines the classification of case firms based on sustainable reporting practices. Lastly, Sect. 6 provides the summary of the chapter.

2 Apparel Industry

Apparel industry reshaped the Western economies during the industrial revolution and later contributed immensely to the economy of many East Asian nations. More recently, this industry is driving the economic growth of many South and South-East Asian nations. The main reason for the trade shifts from developed nations to developing nations is the adoption of low-cost country sourcing strategy, which transformed the global supply chains more complex. Hence, the industry is characterized by complex global supply chains, speed to market, shortened product life cycle, and increased number of fashion seasons [6].

Over the past 50 years, export of clothing and textiles globally has increased by 100-fold, i.e., in dollar term it has increased from under $6 billion in 1962 to $706 billion in 2011 and is expected to grow by 5 % each year [34]. Approximately, 70 % of these exports are from developing nations. Recently, the textile and garment industry has been rated as the single largest source of manufactured export goods from developing nations.

The global expansion of apparel industry raised issues related to transparency with complex and at times fragmented supplier networks. Low tech, labor intensive, and pressure for competitive prices have led to the human exploitation in the apparel industry. There are tens of millions of people working under sweatshop conditions in developing nations. Several fatal incidents in the past, such as collapse of Rana plaza in 2013 that killed 1133 garment workers and fire in Ali garment factory with a death toll of 300 people, raised concerns about social and environmental aspect in garment industry. Likewise, most of the luxury fashion brands do not own production facilities and they are outsourced to the production facilities across the globe [12]. This has increased the luxury apparel supply chain complexity and raised concerns regarding social and environmental aspects of luxury apparel business. In order to investigate social responsible practices in luxury fashion, it is important to understand the concept of luxury and characteristics of luxury fashion.

3 Luxury Apparel

3.1 Concept of Luxury

The concept of luxury can be traced back to the great civilizations as the products associated with wealth, exclusivity, and power. Luxury reflects social norms and aspirations of the society at a given time [12]. Heine [20, p. 2] highlights that "luxury is a relative term that could refer to almost anything or nothing depending on whom you ask." Likewise, Gardetti [15] proposes that luxury is an ambiguous concept and the definition depends upon the culture, economic, and legal aspects, whereas Chevalier and Mazzalovo [12, p. ii] states that "There is no single definitive meaning, but rather a large number of alternatives from which to choose" and "It is probably unrealistic to seek a universal definition of luxury" (p. 1).

The concept of luxury is viewed from either a consumption perspective or from product branding perspective. The opulent research on luxury fashion focused on explaining luxury consumption as a symbolic function at both individual and collective levels. Luxury is referred as seeing and being seen. From product perspective, luxury brands are defined in terms of high quality, transaction value, exclusivity, craftsmanship, authenticity, and uniqueness [14]. In the literature, luxury has been characterized and categorized in different ways. For example, Chevalier and Mazzalovo [12] broadly clustered luxury into two categories. The first category is related to the supply of products and services, and the second category is related to the psychological and social implications of these products or services. Reddy and Terblanche [28] classified luxury into two broad categories based on technical features and customer perceptions. Silverstein and Fiske [30] referred 'old luxury' from product characteristics perspective and new luxury from the point of view of the customers [8]. The most common four dimensions that consumers perceive as luxury are elitism (distinction), product quality along with high prices, personal emotional elements, and power of the brand. Although there is no unique definition for luxury, it is largely perceived as a symbolic dimension reflecting values related to the culture of the society [8].

Over the last half a century, the luxury market has undergone dramatic changes. Globalization led to an increase in competition and low entry barriers. This has led to an expansion of consumer markets not only from high worth individuals but also the middle-class [19]. The broad customer base created a concept of luxury for the masses [10]. Following the trend, less luxury brands shifted from "mass" to "premium" brands offering luxury products at better price-value [19]. To satisfy the demands of the broad customer base, true artisanal brands also started to offer mass produced items. As the family and artisanal luxury companies are competing against large conglomerates the true luxury is losing its charm. True luxury is the luxury that only few people can afford [12]. When luxury products are produced in volume, they are classified as an intermediate luxury. Mass luxury is where the luxury products are mass produced and communicated rigorously. To sum up, luxury is defined on a continuum with increasing of intensity from mass luxury to unaffordable luxury. Irrespective of the brands position, success in luxury is defined based on the brand equity, which is measured through brand's strength, description, and its ability to survive in the market in the future [19]. Among all groups of luxury products, fashion products expand to all categories of luxury with ease of creating brand equity.

There are two schools of thoughts regarding luxury and fashion: first group debates on distinction between luxury and fashion. They perceive fashion as short lived and fast. On the other hand, luxury represents long-lasting, maturity, and exceptional product quality. Second group argues that fashion industry is closely associated with the artistic world. They believe luxury fashion leads the fashion industry with fashion shows, creating a trend with new colors, new shapes, and designs. Through the fashion shows and constant renewals, luxury fashion stood at the forefront in media. In fashion industry, a brand can claim the status of luxury when only it achieves the objective of stability and a quality of being timeless [12]. A new fashion brand can only acclaim the status of luxury when it develops the classical best-seller models with a signature style. There is a growing demand for the luxury products, so when the brands expand their product range to luxury segment it creates sustainable business for the future.

3.2 Luxury Fashion: Global Scenario

The turnover of corporations manufacturing luxury products is valued at 300 billion euros in 2011 [12]. Luxury fashion is playing an important role in shaping economies and governments. It is the fourth largest revenue generator in France and a dominant sector in Italy, United States, and emerging economies like China and India. This sector provides highest employment rate in both Italy and France [25]. Historically luxury market is geographically centralized industry operating from France and Italy. Due to limited growth opportunities, the companies originated from these countries expanded their operations to other nations to reach a larger consumer database. The present-day luxury fashion originates from different designers and produced in several other countries and distributed all over the world. The global presence of the luxury industry increased the customer base from diversified groups. Today, brand image has become one of the most relevant aspects of the luxury market.

Traditionally fashion industry is clustered into two categories: firms selling low-cost products to large number of consumers and companies that provide exclusive and expensive products to selective customers. Consumer everywhere at every income level wants more luxury [13]. As a result, clusters of companies with low-cost products and exclusive products started offering ready-to-wear product range to target wide group of customers. Thus, couture, ready-to-wear, and accessories are the categories of luxury fashion goods [14].

In 2011, ready-to-wear and leather goods contribute a share of 45 billion euros of luxury business. The ready-to-wear category, Italy and France contribute to 60 and 20 % of the market share. In mid 1970s and 1980s, Italian brands started to create interesting and creative ladies ready-to-wear lines. The craftsmanship helped Italian brands to diversify their business. The advantage of Italian brand to gain the market share is that they are perceived as new, being creative with their global presence. Although Italian brands participated in fashion shows with haute couture range, they gave prominence to sell ready-to-wear products at stores. On the other hand, French were in luxury fashion since World War II. They emphasized more on creating haute couture range. American brands have been successful in creating luxury product range along with other ready-to-wear line. Britain, Germany, and Spain are the other nations with the international fashion luxury brands [12].

Fionda and Moore [14] studied the characteristics of successful luxury fashion brands. Based on the case study analysis of twelve international luxury fashion brands, they concluded that there are nine interrelated characteristics of successful luxury fashion brands such as clear brand identity, marketing communications, product integrity, design signature, premium price, exclusivity, heritage, environment and service, and culture. Interesting to note that even under serious pressure from not-for-profit organization, sustainability aspects that are not yet integrated with the luxury apparel industry. Chetty [11] stated that along with product characteristics organizational physical characteristics are crucial for success of a luxury apparel brand.

3.3 Apparel Luxury—Characteristics

Three major factors that differentiate luxury from non-luxury segment are company size, financial characteristics, and the time factor [12]. A brief discussion on each of these factors is provided below.

Company size Luxury brands are small to medium-sized enterprises with strong brand awareness and advertising presence all over the world [12]. It is common to see that luxury enterprises operate in small studio that designs and monitors the trend of the products and subcontracts or licenses all the other activities. Most of the luxury fashion brands outsource their production process to countries like China and India. Another possible reason for luxury businesses to be small is that they are developed through licenses that account for only 2–3 % of their sales. However, consolidation of smaller brands to form larger fashion conglomerates is an immersing trend in the luxury brand market segment [7].

Financial Characteristics Compared to a non-luxury brand, a luxury brand needs to invest a huge amount of resources to develop a positive strong image and credibility even before the production starts. The global presence of brand retail outlets, operating a flagship store in the home town of the brand, and conducting an expensive fashion shows to launch the products are some of the main activities that require huge investments. The major hurdle for any luxury brand is to reach the high break even. Once the brand sales meets the breakeven, margins are very high and are translated to profits. The luxury fashion is a pleasant ride for the successful businesses otherwise it is an ordeal for the survival. Luxury business is referred to as a jackpot business and recapitulated as win-all or lose-all. Researchers suggest that if a luxury brand is successful it leads brand extension and can become a life style brand [12]. Another important characteristic of a luxury brand is its survival capacity despite continues losses. There are evidences which suggest that a significant number of luxury brands survived despite of loses for five or even ten years. The reason for the acceptance of losses is due to the strong brand value and earlier profit that compensates loses.

Time frame The fashion cycle of a luxury product is lengthy. First stage of the cycle starts when the fabric manufacturer presents their new collection to designers. Designers commit to purchase a minimum order of fabric and start to develop prototypes for the season year ahead. The next stage is conducting fashion shows with the prototypes that differentiate the luxury brands from others. Fashion luxury industry follows make-to-order strategy where in the manufacturing process takes place once the orders are received from the department stores and multi-brand retailers. In fashion, the major challenge is to make sure that the inventory is available everywhere in the world. The excess inventories after the season will be sold at a discounted price. The fashion cycle lasts for eighteen months and until the very end the cycle sales at bargain price then the results will be known. Due to lengthy fashion cycle, the brands need to plan and invest for long terms. If the deadline for the launch cannot be met, the launch will be delayed until the next season, which means that the brands will continue to lose money before it started to enjoy the gains. Unlike a fashion brand, luxury brands had lengthy turnaround times because of the strong image in the customers. This explains the lack of interests from private equity investments and also the brand ownership by families. The extensive lead-time for the product launch can be translated into the time frame required to enjoy the returns on investment [12].

Along with the above-mentioned characteristics, creative talent and worldwide presence are unique to the luxury apparel industry. Luxury is a most visible sector that is associated with high profile consumers and celebrates [23]. The success of a luxury brand depends on the strategies to create an identifiable brand along with the ability to expand the brand range. Responding to changing social and cultural trends creates legitimacy for a luxury brand [12]. ‘Sustainability development is on the agenda of the planet’ [23]. There is a need to integrate sustainability into the business model of a luxury brand to justify their existence in future.

4 Sustainable Luxury

Since the introduction by the Brundtland Commission in 1987, the concept of sustainable development gained attention in businesses. With increase in number of challenges faced by the organizations, sustainable development became a primary concern [21]. The most often used definition of sustainable development is referred to as meeting “the [human] needs of the present without compromising the ability of future generations to meet their own needs” [33, p. 16]. This definition creates ambiguity and vagueness in implementing sustainability practices in organizations. In the past, sustainability referred to as green initiatives but now a broader perspective of triple bottom line (social, environmental and economic) is adopted. For example, Seidman [31] stated “Sustainability is about much more than our relationship with the environment; it’s about our relationship with ourselves, our communities, and our institutions” (p. 58). Businesses adopted triple bottom line of sustainability and defined sustainable business as “the creation of resilient organizations through integrated economic, social and environmental systems” [22].

“We are living in an ethic era”; more and more corporations are implementing social responsible activities [1]. Since the evolution of the fashion, apparel production is associated with exploitation of both resources and people. It is only in last thirty years that there is an increase in concerns from consumers on their impact on people and environment [26]. Gradually, the fashion industry has realized that the time has come for them to be responsible to the society [4]. In comparison to food or cosmetics sector, fashion industry is less concerned about environmental and human impact on society. One of the major reasons for the negligence of ethical issues is that consumers never raised questions on the practices in garment industry. Unlike the food industry, it is very rear to see fashion brands using labels in their products to indicate the sources of raw materials used. Complexity and lack of transparency among fashion supply chains may perhaps explain the difficulty of ensuring that the components are ethically secured.

In the recent times, the luxury manufacturers are increasingly focusing on environmental and human aspects along with the product characteristics such as brand name, rarity, and quality of products [1]. Studies suggest that luxury consumers are becoming increasingly more aware about social and environmental issues. For example, a survey by the Luxury Institute in 2009 concluded that 57 % wealthy Americans are willing to pay a premium price for sustainable brands. Also, luxury brands are constantly being pressurized by 'not-for-profit' organizations and media to implement sustainability [10]. Thus, sustainable development offers brand differentiation and increases the brand image for luxury products. From the customer perspective, sustainable luxury is perceived based on the value systems such as socio-cultural value, ego-centered value, and eco-centered value. The customer value systems are explained as follows:

- Socio-cultural values: conspicuousness, sense of belonging, and national identity are the elements of socio-cultural value.
- Ego-centered values: These values are more intrinsic in nature and related to product characteristics.
- Eco-centered values: not doing harm and doing good are some of the eco-centered values [10].

Nevertheless, there are a number of divergence points between sustainability and luxury [1]. For long, sustainable luxury was considered as an oxymoron [10, p. 91]. Luxury refers to personal pleasure and superficiality, while sustainability is associated with moderation, ethics, and sobriety [1]. However, time has changed and consumers perceive that sustainability and luxury are complementary models. This has been appropriately captured in the words of Griskevicius et al. [18, p. 397]: "We used to spend money showing people how much money we have got; now we are spending our money on supporting our moral concerns': going green to be seen."

4.1 Luxury Apparel and Sustainability

In the period between 2006 and 2008, Eco fashion has transformed from philanthropic niche to commercial reality. During this period, fashion brands were under constant pressure to be transparent in their practices [4]. This resulted in two different scenarios. New businesses build their brand image as ethical firms in their all operations. Existing businesses on the other hand revisited their operations and incorporated principals of eco fashion. In sustainable fashion, the individuals who are responsible to implement sustainable aspects should ensure that the message is carried out in a transparent way. In the fashion industry, when a business supports sustainable practices all the associated firms in supply chain are also driven to maintain sustainable standards [10]. Sustainable fashion brands need to ensure that they go beyond esthetics, and sustainability should be integrated in all aspects of their firm. Business leaders can use corporate responsibility reporting to communicate the identified social and environmental risks associated with their suppliers and established systems to manage these risks [29].

Corporate responsibility or sustainability reporting is a process of gathering and analyzing data to understand the exposure to risks associated with social and environmental changes and to create a long-term value. It helps organizations to bring in sustainability as a core business strategy and to educate all the stakeholders including shareholders on sustainable practices. With the recent global initiatives such as Global Reporting Initiative's (GRI) G4 sustainability reporting guidelines and ISO 26000 standards, sustainable reporting has become a main stream business activity for companies. Sustainability reporting consists of both qualitative and quantitative information. Websites, Stand-alone reports, and other documents such as annual reports are the channels of sustainable reporting [24]. It is recorded that although over half of the firms report on corporate responsibility, however only 10 % of them have an integrated reporting system [29].

In apparel industry, social reporting has become a common practice to address stakeholders' pressure. In response to the industry demands, GRI developed Apparel and Footwear Sector Supplement (AFSS) to address the specific needs of the apparel industry [16]. AFSS clustered performance indicators into four categories: Supply chain standards, social, environmental, and economic to communicate the organizations progress [16]. It is observed that increasingly more and more apparel brands are reporting sustainable practices using GRI guidelines. The 28 indicators of supply chain, social, and environmental specific to AFSS guidelines along with 9 GRI G4 economic indicators are listed in Table 1.

The standard provides guidance to understand to what extent the fashion companies are implementing sustainability in their business activities. Irrespective of the industry, economic, social, and environmental are considered as the conventional criteria of sustainable practices. However, apparel supply chains are globally dispersed with complex relationships raising issues related to transparency. So apparel brands have to undertake sustainable initiatives to cover entire supply chain, including the process of sourcing, production, distribution, retail, marketing, use, re-cycle, and final disposal. In line with the industry practices, AFSS integrated supply chain standards in their supplement along with conventional economic, social, and environmental GRI indicators. Turker and Altuntas [32] and Caniato et al. [9] examined on how apparel brands disclose sustainable aspects based on GRI indicators [24]. These studies concluded that GRI provides a basis to compare organizations against the sustainability initiatives. In recent times, there is a growing demand on luxury brands to implement sustainability aspects. However, no prior studies have examined that how luxury brands report sustainability initiatives using GRI. Bendell and Kleanthous [5] proposed that luxury brands in collaboration with stakeholders need to measure and report their

Table 1 Performance indicators of apparel industry

Category	Aspect	Indicator
Supply chain standards and practices	Code of conduct	AF7. Number and location of workplaces covered by code of conduct
	Audit process	AF8. Number of audits conducted and percentage of workplaces audited
	Non-compliance findings	AF9. Incidents of non-compliance with legal requirements or collective bargaining agreements on wages
		AF10. Incidents of non-compliance with overtime standards
		AF11. Incidents of non-compliance with standards on pregnancy and maternity rights
		AF12. Incidents of the use of child labor
		AF13. Incidents of non-compliance with standards on gender discrimination
		AF14. Incidents of non-compliance with code of conduct
		AF 15. Analysis of data from code compliance audits
	Remediation	AF16. Remediation practices to address non-compliance findings
	Business integration	AF17. Actions to identify and mitigate business practices that affect code compliance
Economic	Economic performance	EC1. Direct economic value generated and distributed, including revenues, operating costs, employee compensation, donations and other community investments, retained earnings, and payments to capital providers and governments
		EC2. Financial implications and other risks and opportunities for the organization's activities due to climate change
		EC3. Coverage of the organization's defined benefit plan obligations
		EC4. Significant financial assistance received from government
	Market presence	EC5. Range of ratios of standard entry-level wage compared to local minimum wage at significant locations of operation
		EC6. Policy, practices, and proportion of spending on locally based suppliers at significant locations of operation

(continued)

Table 1 (continued)

Category	Aspect	Indicator
	Indirect economic impacts	EC7. Development and impact of infrastructure investments and services provided primarily for public benefit through commercial, in kind, or pro bono engagement
		EC8. Understanding and describing significant indirect economic impacts, including the extent of impacts
	Procurement practices	EC9. Proportion of spending on local suppliers at significant locations of operation
Environmental	Materials	AF18. Programs to replace organic-based adhesives and primers with water-based adhesives and primers
		AF19. Practices to source safer alternative substances to those on the restricted substances list, including description of associated management systems
		AF20. List of environmentally preferable materials used in apparel and footwear products
		EN1. Materials used by weight or volume
	Energy	AF21. Amount of energy consumed and percentage of the energy that is from renewable sources
	Emissions, effluents, and waste	EN21. Total water discharge by quality and destination
		EN22. Total weight of waste by type and disposal method
	Products and services	EN26. Initiatives to mitigate environmental impacts of products and services, and extent of impact mitigation
Social	Employment	AF28. Percentage of foreign migrant workers as a portion of total workforce, broken down by region
	Labor/management	AF29. Percentage of workplaces where there is one or more independent trade union(s)
		AF30. Percentage of workplaces where, in the absence of a trade union, there are worker-management committees, broken down by country

(continued)

Table 1 (continued)

Category	Aspect	Indicator
	Occupational health and safety	LA7. Rates of injury, occupational diseases, lost days, and absenteeism, and number of work-related fatalities by region
		AF31. Initiatives and programs to respond to, reduce, and prevent the occurrence of musculoskeletal disorders
	Diversity and equal opportunity	AF32. Actions to address gender discrimination and to provide opportunities for the advancement of women workers
	Community investment	AF33. Priorities in community investment strategy
		AF34. Amount of investment in worker communities broken down by location
	Public policy	SO5. Public policy positions and participation in public policy development and lobbying

Source Adapted from GRI [8, 17]

sustainable performance using international guidelines such as GRI. The following case study illustrates on how luxury brands are implementing GRI standards.

Sustainability reporting forms the basis for ranking the organizations and developing indices. World's most comprehensive index Dow Jones Sustainability Indices (DJSI) is based on the economic, social, and environmental indicators. In apparel sector, social dimension is considered as an important dimension and given a weight of 41 % in [29] assessment framework. Irrespective of reporting guidelines or assessment frameworks, luxury apparel brands are emphasizing on the implementation of sustainability dimensions. Although luxury brands realized the importance of the social and environmental efforts, they are failing to accept sustainability as a business strategy. Instead, to satisfy the current requirements of the social aspect, they had a fragmented approach to social responsibility. Organization response to social and environmental changes depends upon the performance and it forms the basis for classification. Based on several theories, frameworks are proposed for organizations to tackle the problems of our time [27]. "Greening Goliaths versus Emerging Davids" is a model that promotes the sustainable transformation of any industry [21].

4.2 Greening Goliaths Versus Emerging Davids

Organizations have an opportunity to gain economic benefits when they implement social and environmental aspects into their existing business processes. Sustainable entrepreneurship is regarded is an innovative process to discover and exploit economic opportunities through sustainable development. The term sustainable entrepreneurship is recent and still emerging [21]. Literature suggests that based on the level of participation in sustainable entrepreneurship, organizations are classified into Davids and Goliaths. Metaphorically these terms refer to the two different types of organizations with respect to size, age, and objective function. Wüstenhagen [35] was one of the earlier researchers referred to this framework. Majority of sustainable entrepreneurship literature covers either Goliaths or Davids.

Hockerts and Wüstenhagen [21] explained the interplay between Davids and Goliaths to drive industry towards sustainable development. Caniato et al. [9] contextualized framework to luxury industry and classified firms (supply chain orchestrators) into three clusters: fashion Goliaths, quality Davids, and Techstige. Gardetti [15] grouped few case companies into Goliaths and Davids. However, the exemplifiers in sustainable development and companies with no or limited initiation of sustainability are still missing in the framework. This research expands on

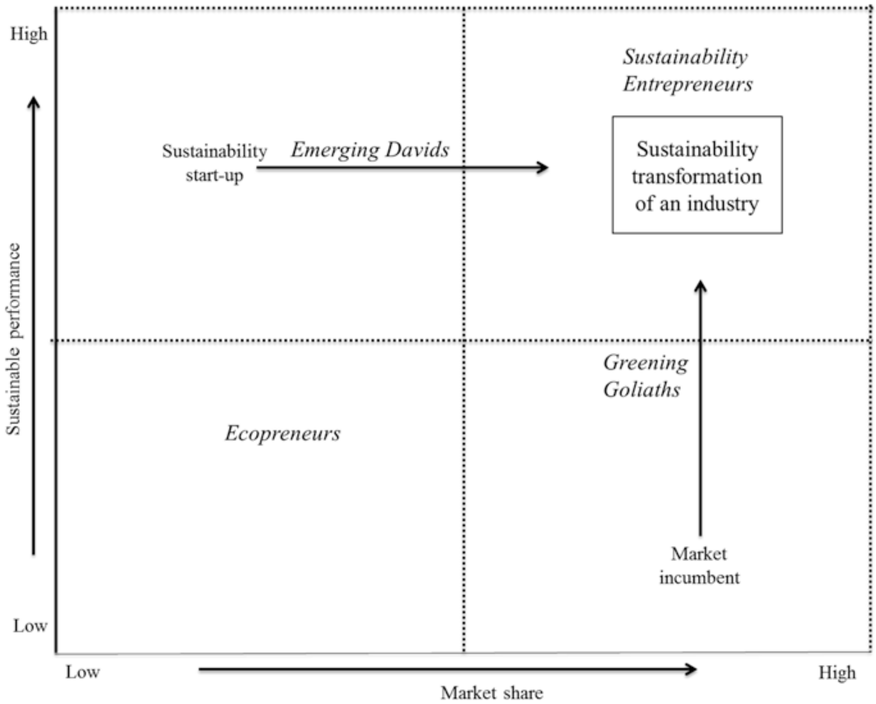

Fig. 1 SGED framework (*Source* Developed by authors based on Hockerts and Wustenhagen [21]

Table 2 Characteristics of 'Greening Goliaths versus Emerging Davids' in luxury apparel industry

Criteria	Ecopreneurs	Davids	Goliaths	Sustainable entrepreneurs
Age	Rather new	Rather new	Old, incumbent	Old, incumbent
Size	Small	Small	Large	Large
Objective function	Economic objectives dominating, social/environmental objectives complementary	Social and/or environmental objectives at least as important as economic	Economic objectives dominating, social/environmental objectives complementary	Social and/or environmental objectives at least as important as economic

Source Adapted from Caniato et al. [9]

conventional the quadrant Goliaths and Davids framework. Figure 1 illustrates the extended Goliaths versus Davids framework.

Sustainable entrepreneurs, Greening Goliaths, Emerging Davids, and Ecoprenuers are the four groups of organizations in framework. Sustainable entrepreneurs make the impossible to possible by developing new markets and drive towards sustainable development. "Greening Goliaths" and "Emerging Davids" have different visions towards sustainable entrepreneurship. Ecoprenuers, in this study, refer to the organizations with no or little emphasis on social and environmental activities. This classification framework conceptualizes the notion of mature, startups and incumbents, and their contribution towards sustainability.

During earlier phases of sustainable transformation in a particular industry, it is the small and emerging firms with less market share that contribute to sustainable development through radical innovation. These firms are referred to "Emerging Davids." Davids do not only aim for economic value creation but also address the aspects of social and environmental value creation [21]. At the same time, there is resistance from some small firms towards sustainability due to the lack of investment and innovative capabilities in non-economic activities. These relatively new firms with less market share are referred to as Ecoprenuers (Economic-entrepreneurs). Typically these firms emphasize on financial benefits of an economic activity.

Following the Emerging Davids, "Greening Goliaths" take initiatives towards sustainability. Goliaths are relatively old firms with large market share and are less innovative towards sustainability. These firms had a reactive approach towards sustainability. Overtime, Davids and Goliaths interact and impact each other and drive industry towards sustainability [21]. Sustainable entrepreneurs are relatively large and old firms with an objective of maintaining its position as a sustainable exemplifier in the industry. These companies are successful in new radical forms of implementation. From sustainable entrepreneurs, Davids and Goliaths can learn how to redesign the strategies to better serve the purpose of both people and nature [27].

Age of the firm, firm size, and aim of the firm are the characteristics that differentiate Davids and Goliaths [21]. These characteristics are also used to cluster Ecopreneurs and Sustainable entrepreneurs. In addition to these characteristics, Caniato et al. [9] proposed product fashionableness, product complexity, selling volumes, and brand reputation as the other differentiating dimensions. The characteristics of the clusters have been summarized in Table 2. The characteristics of this framework are further illustrated by case study.

Table 3 Information regarding case companies

Brand	Headquarter	Ownership	Year of establishment	Brand value 2014 $M	Dow Jones sustainability invitation
Louis Vuitton	Paris, France	LVMH	1854	25,873	Yes
Hermes	Paris, France	Listed (EPA)	1837	21,844	Yes
Gucci	Florence, Italy	Kering	1921	16,131	No
Prada	Milan, Italy	Listed (HKG)	1913	9985	Yes
Burberry	London, England	Listed (LON)	1856	5940	Yes
Fendi	Rome, Italy	LVMH	1925	3023	Yes
Ralph Lauren	New York, USA	Listed (NYSE)	1967	6323	Yes
Hugo Boss	Metzingen, Germany	Listed (XETRA)	1924	4526	Yes
Tommy Hilfiger	New York, USA	PVH	1985	2004	Yes

Source Adapted from BrandZ [7]

5 Case Study

5.1 Case Selection

Drawing from the 'Greening Goliaths versus Emerging Davids' framework, case study approach is a way to provide conceptual mapping of current sustainable supply chain management practices in luxury apparel industry. Case firms were chosen based on the top most valuable global luxury brands. BrandZ [7] study identified top 100 most valuable global brands from different categories. Since the introduction of global top 100 BrandZ report in 2006, the share of the portfolio companies has increased by 81 %. BrandZ report identifies top 10 brands from different categories. Among all the categories, apparel led the trend with a 29 % brand value increase. BrandZ report listed top 9 global luxury brands. Global apparel brands exhibiting a tremendous performance along with the top value luxury brands from the BrandZ report are considered for case study analysis.

The selection of cases is restricted to the luxury brands that had apparel products. Among 10 top luxury brands, there are only six companies with apparel and among them two belong to the same parent company (see Table 3). The inclusion of luxury brands from luxury category results in the exclusion of critical apparel group of companies with luxury product range. Therefore, four companies with luxury product range from apparel category that is included in the study. This

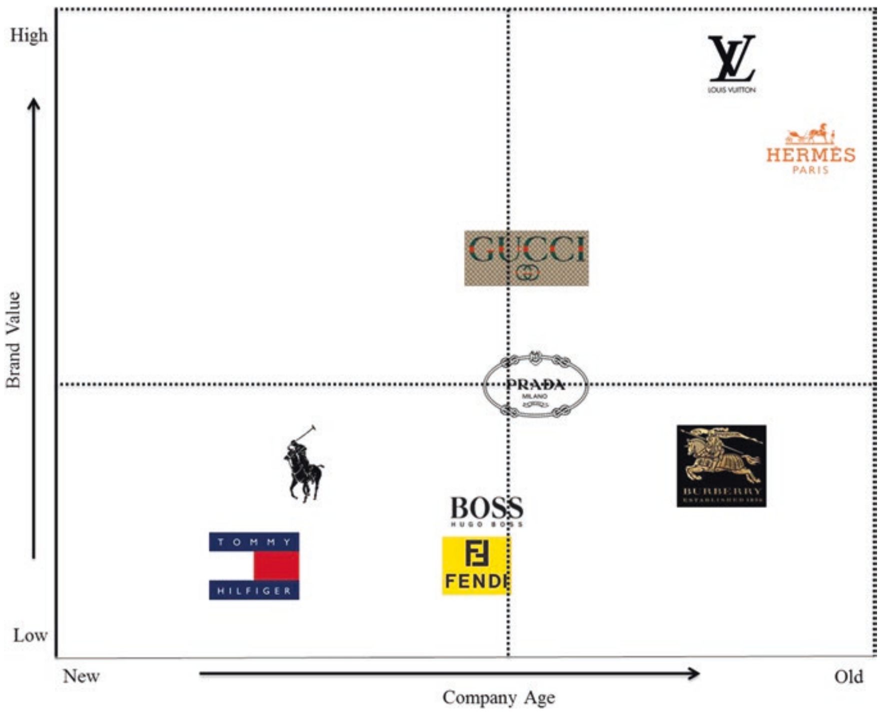

Fig. 2 Classification of case companies against age versus brand value (*Source* Developed by authors)

resulted in a total of nine brands and detailed information about these brands is shown in Table 3.

5.2 Analysis

5.2.1 Industry Characteristics

The characteristics of case study firms are analyzed and compared with the characteristics of luxury apparel brands explained in Sect. 3. The assumption of luxury brands as a relatively old is valid. True luxury brands like Hermes and Louis Vuitton have a history of more than 175 years and 160 years, respectively. On the other hand, ready-to-wear luxury brands like Tommy Hilfiger are relatively new (about 30 years old). This demonstrates that the artesian luxury brands that offer true luxury products are relatively older than the brands that are offering ready-to-wear luxury. Figure 2 illustrates the classification of case firms against company age and brand value. It can be seen in Table 3 that two French brands (Hermes and Louis Vuitton) have relatively high brand value (more than $47,700 million together), followed by three Italian brands. Three American brands are relatively new and have relatively less brand values. It clearly demonstrates that brands from France and Italy are perceived as a luxury brands. Among 9 cases, 3 large conglomerates own 4 brands. Despite being a part of the larger conglomerate, some brands still had family ownership. For example, Fendi family holds 10 % of stake in Fendi brand. The assumption of luxury brands as a family run businesses or a part of larger conglomerates is valid to a certain extent.

Table 4 Case companies sustainable report characteristics

Brand	Title of the report	Period	Total pages	GRI reporting
LVMH-Moet Vuitton	Environmental report	2013	59	Yes
Kering Group	Pano-rama: a year of sustainability	2013	28	Yes (A+)
Prada SpA	Social responsibility	2013	49	Others
Burberry Group	Corporate responsibility	2014	35	No
Ralph Lauren Corp	Citizenship report	2013	31	No
Hugo Boss AG	Sustainability report	2013	60	Yes (B+)
PVH Corp	Corporate social responsibility	2013	55	Yes (C)

Source Compiled by authors

Table 5 Summary of AFSS and GRI disclosed indicators in the study

Supply chain indicator	Number of brands reporting	Economic indicator	Number of brands reporting	Environmental indicator	Number of brands reporting	Social indicator	Number of brands reporting
AF7	6	EC1	4	AF18	0	AF28	5
AF8	5	EC2	3	AF19	4	AF29	4
AF9	4	EC3	2	AF20	1	AF30	4
AF10	3	EC4	2	EN1	4	LA7	2
AF11	3	EC5	3	AF21	5	AF31	4
AF12	3	EC6	3	EN21	3	AF32	5
AF13	3	EC7	3	EN22	5	AF33	5
AF14	4	EC8	1	EN26	4	AF34	3
AF15	6	EC9	1			SO5	2
AF16	5						
AF17	3						
Average	4.09		2.44		3.25		3.77

Source Authors

5.2.2 Sustainable Reporting

Corporate reports provide intentions of organizations towards sustainability, so these were analyzed and interpreted. Today, there is an increased trend for organizations to disclose sustainability practices in annual or integrated reports. Several brands use different nomenclatures for the integrated reports. Titles of reports and total number of pages dedicated to these reports in 9 case firms are seen in Table 4. Louis Vuitton and Fendi belong to the LVMH, so there is only one group report for both organizations. On the other hand, Hermes does not have an integrated sustainability report. A total of 7 sustainability reports are considered for the analysis with a number of pages varying between 28 and 60. Among 7 sustainability reports, 4 of them were reported based on GRI reporting guidelines. External independent organizations are appointed to provide ranking and assurance of the performance data reported. Ranking of the GRI reporting is disclosed in Table 4.

Sustainable reports of case firms are examined to analyze the acceptance of GRI performance indicators. Table 5 summarizes the acceptance of GRI indicators. Among all the performance indicators, it is evident that 'code of conduct' implementation in supply chain (AF7) and the remediation practices to address non-compliance (AF15) appeared in 6 brand reports. Social indicators such as community investments (AF33), employee breakdown structure (AF28), and diversity of workforce (AF32) are also often reported by the 5 brands. On the other hand, economic indicators such as organizations defined benefits plans (EC3), financial assistance received from governments (EC4), and indirect impacts (EC8) are presented in two brands. No brand has disclosed information on how

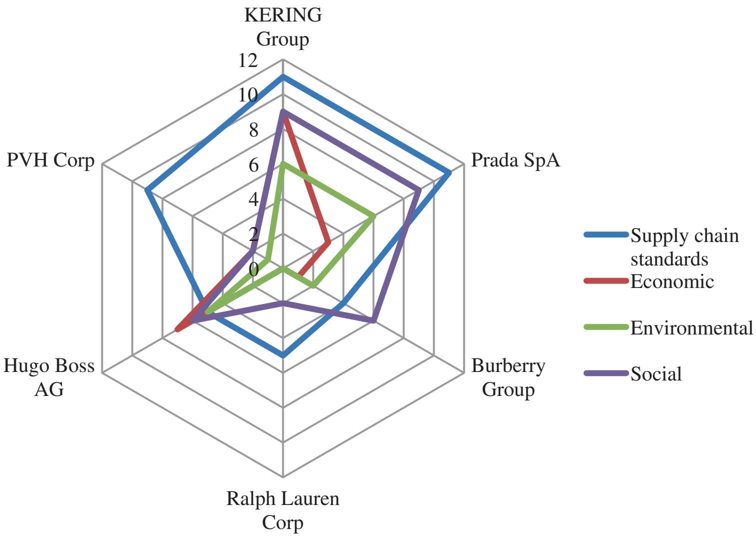

Fig. 3 Number of reported indicators per brand (excluding LVMH) (*Source* Authors)

they are replacing organic adhesives with water-based adhesives (AF18). Overall, on an average, there are at least four brands disclosing supply chain performance indicators (can be seen in Table 5). It is evident that supply chain indicators dominate the reports while economic indicators are sparingly appeared in reports.

There was a great range of variability in terms of the number and types of indicators represented by the case study companies. For instance, Kering group reported the greatest number of indicators [35] compared to LVMH with only environmental indicators [7]. Figure 3 details on the performance indicators of each brand against each category. As LVMH has only environmental indicators, it is excluded from the Fig. 2. Kering, Prada, Ralph Lauren, and PVH each reported the greatest number of supply chain standards followed by social. On the other hand, Burberry and Hugo Boss reports are dominated by social indicators. Next to LVMH, Ralph Lauren report presents only supply chain and social indicators. The degree of variance in the number of indicators can form the basis on how sustainability is progressed in the industry. Further to understand the content of the report a content analysis is performed.

Table 6 Percentage of most frequently appeared sustainable words

Word	Weighted percentage (%)							
	Overall	LVMH-Moet Vuitton	Kering Group	Prada SpA	Burberry Group	Ralph Lauren Corp	Hugo Boss AG	PVH Corp
Sustainab[a]	0.52	0.39	2.23	0.07	0.3	0.2	1.1	0.29
CSR	0.17							0.85
Responsibility	0.21	0.08	0.25	0.65	0.6	0.12	0.08	0.12
Ethic[a]	0.18		0.82	0.83	0.99	0.08		
Economic	0.06		0.08	0.13			0.15	
Quality	0.18	0.16	0.12	0.46		0.24	0.14	0.08
Performance	0.18	0.14	0.2	0.2	0.17	0.1	0.27	0.18
Supply	0.22	0.11	0.16		0.68	0.13	0.22	0.46
Chain	0.19	0.08	0.12	0.09	0.55		0.27	0.39
Suppliers	0.3	0.27	0.2	0.48	0.26	0.23	0.34	0.27
Production	0.21	0.29	0.35	0.34	0.13		0.24	0.08
Sourcing	0.12	0.04	0.08		0.64	0.25		0.14
Code	0.18	0.05	0.39	0.75	0.21	0.07	0.19	
Compliance	0.23	0.11		0.41	0.09	0.39	0.4	0.07
Standards	0.18	0.17	0.08	0.15	0.3	0.21	0.26	0.1
Audits	0.09	0.14			0.3		0.16	
Training	0.21	0.22	0.2	0.26	0.43	0.14	0.18	0.18
Environmental	0.55	0.95	0.59	0.32	0.72	0.29	0.46	0.32
Resources	0.15	0.16	0.16	0.26		0.09		0.19

(continued)

Table 6 (continued)

Word	Weighted percentage (%)							
	Overall	LVMH-Moet Vuitton	Kering Group	Prada SpA	Burberry Group	Ralph Lauren Corp	Hugo Boss AG	PVH Corp
Energy	0.3	0.58	0.12	0.12	0.26	0.23	0.27	0.11
Water	0.25	0.49	0.16				0.11	0.37
Materials	0.21	0.21	0.27	0.3	0.21	0.12	0.2	0.19
Chemicals	0.06				0.09			0.22
Emissions	0.25	0.36	0.27	0.07		0.34	0.23	0.18
Waste	0.22	0.51	0.08	0.18	0.09		0.1	0.14
Co_2	0.12	0.27	0.16	0.08	0.17			
Carbon	0.08	0.07	0.2		0.13	0.13		0.17
Footprint	0.07	0.07	0.08			0.09		0.1
Recycl[a]	0.13		0.2	0.16		0.27	0.11	
Packaging	0.11	0.24		0.08		0.09		
Social	0.25	0.13	0.35	0.7	0.13	0.18	0.31	0.15
Rights	0.14		0.16	0.07	0.34	0.11	0.22	0.3
Foundation	0.17		0.47	0.11	0.43	0.54		0.14
Society	0.08		0.2			0.19	0.15	
Human	0.2		0.23	0.28	0.3	0.11	0.24	0.41
Employees	0.49	0.1	0.59	0.71	1.11	0.79	1.01	
Labor	0.08						0.11	
Communit[a]	0.23		0.08	0.29	0.13	0.3		0.23
Customers	0.09			0.16	0.21			0.09
Children	0.12			0.18		0.15		0.34
Health	0.12			0.18	0.09	0.11	0.22	0.16
Diversity	0.1		0.2			0.31	0.11	0.1
Content percentage	8.02	6.39	9.85	9.07	10.32	6.51	7.85	7.12

Source Compiled by authors
[a]Expands the word for example, ethic[a]-ethics and ethically

5.2.3 Content Analysis

Through the content analysis of the reports, categories and sub coding relevant to sustainability aspects are identified. The most frequently appearing sustainable words among all the reports were used to evaluate the performance on sustainable reporting practices. A software tool NVivo is used to find words and their relative content percentage in reports. There are few thousands of words in each report, so the words related to the sustainability themes with a content percentage of greater than 0.07 are included. More specifically, the themes related to sustainability reporting practices in apparel industry as discussed in Sect. 4.1: (1) environmental, (2) social, (3) economic, and (4) supply chain aspects are analyzed.

To facilitate comparison between reports a content percentage of each word is recorded. Content percentage is the relative percentage of the words to the overall word count of the report. Table 6 lists the frequently used sustainable words with a content percentage of greater than 0.07. The content percentage of sustainability issues varies between 6.39 and 10.32 % (see Table 6). CSR, sustainability, responsibility, and ethics terms cannot be a part of pre identified themes, rather all these words are related to all the themes. Among all the brands, LVMH and Ralph Lauren have the lowest content percentage of 6.39 and 6.51, respectively, and Kering group, Prada, and Burberry with the highest percentage of 9.85, 9.07, and 10.32, respectively.

Overall among all the reports, the word environmental is frequently used (0.55 %), followed by the terms sustainability and sustainable together (0.54 %), whereas CSR is relatively less frequently used (0.17 %) as only PVH report referred to this term. Against the prominence given to social aspects in non-luxury apparels, in luxury segment, social aspects are given equal consideration with other categories (2.16 %). It is observed that LVMH gave prominence to all environmental aspects in comparison to other organizations. Similarly, supply chain aspects such as code of conduct, compliance, and audit terms are relatively more important for Prada than other dimensions. On the contrary, Kering group reports all the sustainability aspects in an equal proportion. In summary, content of the report matches with the title of the report. Finally, it is evident that the results from the content analysis are consistent with the total number of performance indicators disclosed by the brands in Sect. 5.2.2.

5.3 Greening Goliaths Versus Emerging Davids

Hockerts and Wüstenhagen's [21] notion of "Greening Goliaths versus Emerging Davids" can expand the investigation of case studies. Case studies are organized into cluster depending on their position relative to brand value and content percentage. Classification of companies outlines the role of companies in transforming industry towards sustainability. In luxury fashion, brand value exhibits the value perceived by the consumers which generates the revenue. It is a critical measure for the existence and future survival of the brand. Quantitative content analysis through word count and number of performance indicators disclosed could provide guideline on the sustainable performance through reporting. In addition to "Goliaths and Davids," case companies also belong to the other two coordinates. The attributes discussed in the Sect. 4.2 are considered to cluster the case study companies. Figure 4 exhibits the classification of case companies.

It is observed that LVMH is a Greening Goliath with high brand value, but less content percentage related to the sustainability aspects. LVMH is following GRI guidelines to report environmental performance leaving social, economic, and supply chain aspects unaddressed. This could be one of the reasons for less content percentage and its position as Goliath. Hugo Boss and PVH are under Emerging

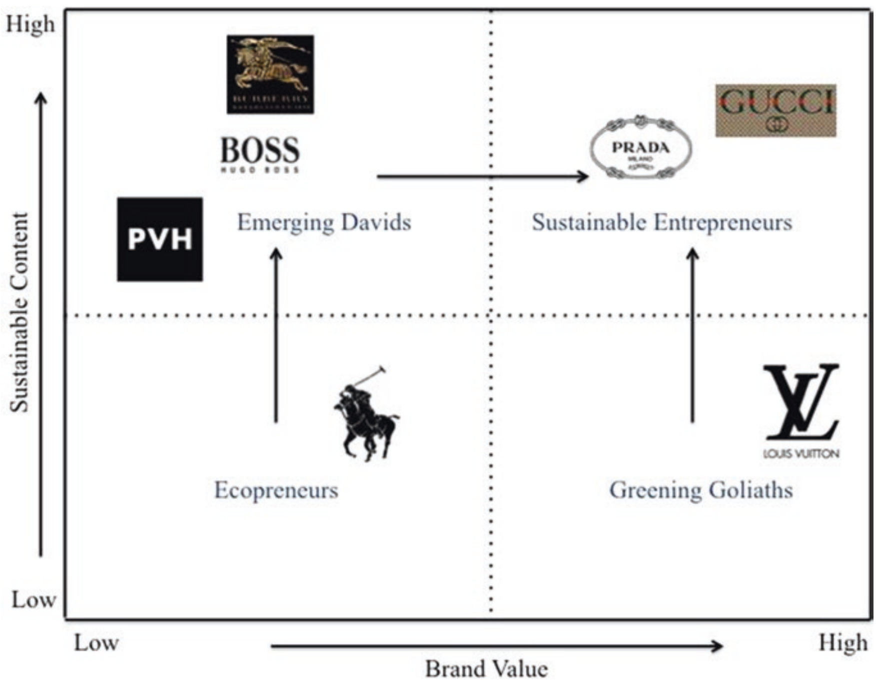

Fig. 4 Framework on Sustainable entrepreneurs, Greening Goliaths, Emerging Davids, and Ecoprenuers (*Source* Authors)

Davids cluster with less brand value and high content percentage reports following GRI guidelines. On the other hand, Burberry is not following GRI guidelines but the group's report is prepared under the assertion of full independent party. Thus, Burberry with high content percentage is also an emerging David. Furthermore, Ralph Lauren citizenship report emphasized all the aspects of sustainability without the routine of GRI guidelines or third party assertion. Thus, Ralph Lauren is considered as an Ecopreneur with emphasis on economic value. Ralph Lauren should emphasize on reporting sustainable practices according to guidelines to move to the Emerging David cluster. Prada's "social responsibility report" is a comprehensive report with an emphasis on all aspects of GRI guidelines, a summary of future projects along with code of ethics. In the same way, Kering group earned A+ for GRI reporting and was also listed in Dow Jones sustainability indices. So Kering group along with Prada is considered as Sustainable Entrepreneurs. It demonstrates that 7 companies are distributed across the entire quadrants matrix. Overall, case firms that belong to the Davids, Goliaths, and Ecopreneurs should aim to move to Sustainable Entrepreneurs. All in all, the case study analysis demonstrates that the initial concern that 'the luxury apparel industry is lagging behind when it comes to the sustainable question' is no longer valid.

6 Conclusion

Globalization along with emerging new rich has accelerated the growth in the number of luxury fashion consumers. At the same time, the increased awareness of social and environmental values amongst luxury consumers has exerted immense pressure on firms to implement social responsibility in their business practices. This chapter provides an overview of luxury apparel industry and its sustainability practices. The discussion from literature restates that pleasure and superficiality of luxury and moderation and sobriety of sustainability as the diverging points of the two concepts. It raises the concerns that the luxury apparel industry is lagging behind when it comes to the sustainable question. Based on the sustainable reporting and brand value, this chapter develops a framework for assessing sustainable performance of luxury brands. Sustainable Entrepreneurs, Greening Goliaths, Emerging Davids, and Ecoprenuers are the elements of the framework used to classify the case firms. The proposed characteristics of luxury apparel brands and adoptability of framework was applied to top most valuable luxury apparel brands. Based on the BrandZ report, nine case firms with luxury apparel products were chosen for the analysis. The results indicate that the brands with comprehensive reports prepared under the guidelines of international standards and third party auditions are emerged as Sustainable Entrepreneurs whereas firm reports with no international guidelines are classified under Ecopreneurs. This proposed framework can be employed to assess the current state of firms and formulate strategies to emerge as Sustainable Entrepreneurs.

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