# Potential of Ligno-cellulosic and Protein Fibres in Sustainable Fashion

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

**Abstract** Fashion can be encapsulated as the prevailing styles manifested by human behaviour and the latest creations by the designers of textile and clothing, footwear, body piercing, decor, etc. Fashion can trace its history to the Middle East (i.e., Persia, Turkey, India and China). Natural fibres such as silk, wool, cotton, linen, jute and ramie (a flowering plant in the nettle family) and man-made fibres such as regenerated rayon, cellulose acetate, polyester, acrylic, bamboo, and soy protein are intensively used for the production of traditional to specialty apparel, home furnishings and interior decorative textiles. To prepare fibres for use they are enhanced during spinning, weaving, knitting and chemical processing. Linen/flax is considered the most important and useful natural fibre as far as fashion is concerned for tops, shirts and summer dresses. Recently (as of 2016), a few more protein fibres —such as angora, pashmina and yak—have also been exploited to produce luxurious fashionable textiles, owing to their exotic features. Natural fibre–based textiles are being increasingly dyed in a sustainable manner using eco-friendly natural dyes that are fixed by using bio-mordants (plants that accumulate alum in their leaves). Similarly, the potential naturally coloured cotton has for traditional to fashionable end applications is also highlighted in this chapter. As far as sustainable development is concerned, textiles are preferred to be made of natural fibres and to be value-added with eco-friendly chemicals and auxiliaries, preferably derived from natural resources such as plant/herbal extracts, bio-materials, bio-polymers and bio-molecules.

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# 1 Introduction

Clothing is essential for human beings and has a long history of use (over 7000 years). Fibres such as marijuana, hemp, paul and bamboo have been reported as having been used for such a purpose. Prehistoric peoples created their own culture, which has continued to evolve and develop right up to today (2016). As far as basic raw materials of the eco-fashion industry are concerned, natural fibres are key to growth of its sustainability. Natural fibres—such as silk, wool, cotton, linen and jute—and man-made fibres—such as regenerated rayon, cellulose acetate, polyester and acrylic—are used in the production of traditional to specialty apparel, home and interior decor textiles by giving them added value during fibre spinning, weaving, knitting, non-woven production and chemical finishing. Elegant textile products are currently being used in the fashion industry to make dresses for film stars, high-class executive casual and apparel wear, world-class luxurious interiors of airports, rail and ship carriers and for furnishing five-star hotels. Similar to vegetable fibres, protein fibres like wool and silk were also used in large quantities for the production of royal apparel and home furnishing textiles for royal families. At the time of the Byzantine Empire, fabrics made of silk were considered the most valuable luxurious products, as they were the very expression of power, wealth and aristocracy. Such luxurious and fashionable fabrics were mostly used in making secular clothes, religious vestments and interior furnishings and, even today, they are very popular in the Italian market. Recently, a few additional protein fibres—such as angora, pashmina and yak—have been utilized to produce luxurious fashionable textiles owing to their exotic features such as fineness, warmth, softness, desirable aesthetic attributes, elegance, whiteness and unique hand akin to sheep wool. Up to the 1950s these natural fibres were mostly used in the production of fashionable textiles; later on, synthetic fibres slowly penetrated the market due to advances in polymer science, material science and textile science resulting in the engineering of new polymers for fibre formation with improved characteristics and performance, high durability and low interaction with the environment. However, as a result of many positive aspects of natural fibres over petrochemical-based synthetic fibres—such as bio-degradability, renewablity, eco-friendliness, higher moisture regain, good moisture absorption and desorption, soft feel, adequate to fair strength, good appearance after chemical treatment, availability in large quantity and carbon neutrality—the demand for natural fibres is steadily increasing for textile application [1].

For the sustainable development of high-end textile products, specialty apparel and home textiles, natural fibres should preferably be used. They should then be processed and finished with eco-friendly chemicals and auxiliaries, preferably derived from natural sources. This will result in adding extra value to natural products, while preserving natural resources. In this regard, a number of bio-materials, bio-polymers, bio-molecules and bio-extracts—such as enzymes, natural dyes, aromatic and medicinal plant extracts, chitosan (a derivative of chitin), aloe vera, neem (a tree in the mahogany family), lignin, silk sericin (a protein), grape and mulberry fruit extract, banana pseudostem and peel sap, citrus oil and many more—have been extracted from agro-waste, plants and animals for the production of sustainable products for health care, skin care, wellbeing, comfort and UV-protective and flame-retardant functional textiles. The present chapter reports the same in detail [2–4]. Sustainability is the latest buzzword and covers the field of fibre, fabric, fashion, economics, food and agricultural production. The most common definition of sustainability is the "processes or products, which meet the needs of today's society, without compromising resources of the needs of future generations" [5]. Indeed, this means that for something to be sustainable it needs to be able to continue for a long time, without damaging the environment, society or becoming too expensive to continue such that one day it has to stop. Hence, for a fibre, fabric or fashion design to be sustainable, it requires to be produced without harming the environment, the people involved in the production value chain or without costing so much that one day it will not be economically viable to produce it. Sometimes it is assumed that "sustainable fibre" means an organic fibre or a natural one. It is also true that some man-made or synthetic fibres may be similar or more sustainable than natural ones as they do not use as many resources as natural fibres [5]. In the context of sustainable fashion, not only should basic raw material (i.e., the fibres) be sustainable, but the entire textile value chain, including chemical processing, dyeing, finishing and recycling/bio-degradation, is also expected to be sustainable in terms of water, energy and chemical conservation and effluent generation. Another dimension of sustainable fashion concerns the working conditions in textile and garment factories, which are often associated with long working hours, exposure to hazardous chemicals used in bleaching and dyeing processes and the scourge of child labour [1]. In the context of luxurious, fashionable textiles and specialty wear, clothing with smart attributes—comfort, soft feel, wrinkle free, light weight, pleasant, skin friendly, fragrant, contaminant free and easy on the eye—is preferred.

This chapter briefly discusses the physical, mechanical and end use characteristics of important natural fibres—such as jute, ramie, flax, hemp, banana, pineapple, wool, silk, yak, angora, and pashmina. The production of decorative/diversified fashionable yarns and fabrics from such fibres either in pure or various blended forms—such as jute/cotton, jute/banana, jute/ramie, jute/flax, jute/pineapple, jute/yak, cotton/ramie, angora/cotton, angora/silk and yak/wool fibres—has been reported in detail along with the characteristics of fashionable products—such as apparel, home textile, utility textile, lifestyle products, bags, shoes, blazers, jackets and so on—made from them. These fibres originate from natural resources and, moreover, are dyed with eco-friendly natural dyes with a bio-mordant. Similarly, the potential of naturally pigmented cotton for conventional to high end fashionable textile applications has also been reported.

## 2 Fibre, Fabric and Fashion

As already pointed out, "fashion" can be defined as the prevailing styles of human behaviour and the newest creations by designers of textiles, clothing, footwear, body piercing, decor, etc. Fashion originated in the Middle East (i.e., Persia, Turkey, India and China) and a few decades later spread to Europe. Initially, fashionable products were only affordable by the royals or the rich; however, as civilization progressed, at least since the end of the 18th century, slowly such products became affordable to the middle classes and finally to the people of the world. Fabrics have been an integral part of human lives and has a long historical existence (over 7000 years); the utilization of fibres such as marijuana, hemp, paul and bamboo has been reported for such purpose. For example, in Thailand, there is evidence of animal bones and crab shells being used in the extraction of fibres and spinning at that time. Indeed, this is an early example of how prehistoric people created their own culture—one that continued to develop right up to today [6]. As civilization has developed in the last few centuries, people have become increasingly concerned about their lifestyle, fashion, health, hygiene, medicine, food and drink, comfort, luxury, leisure and wellbeing. People in the rich to super-rich category surround themselves with luxury items such as iconic cars, mansions, posh flats, expensive home furniture, jewelry, paintings, sculptures, top-quality clothing and home textiles as part of their modern lifestyles. In this context, luxurious apparel and home furnishings also play important roles and are regarded on a par with other iconic items, providing the fashionable attributes with a functional touch. Natural fibres such as silk, wool, cotton and linen and man-made fibres such as regenerated rayon, cellulose acetate and polyester are used to a great extent in the production of such specialty apparel, home furnishings, and interior decor textiles by adding extra value during spinning, weaving, knitting, and during non-woven and high-end chemical finishing [7]. Of the various plant-based cellulosic fibres, abaca (*Musa textilis*), cotton, flax/linen, bamboo and soy protein fibres dominate in the fashion industry as a result of their light weight and strength. Of the cellulose fibres, fashion designers prefer linen/flax as the most important and useful wearable natural fibre for tops, shirts and summer dresses. It should be mentioned that linen has a number of important properties: original shine, moisture absorption, allows the skin to breathe, cooling sensation and comfortable fit next to the skin. Egyptian, Scottish and Irish linen fibre–made products are very popular with fashion designers for their unique white color and outstanding shine. Similarly, jute is used for fashionable and decorative applications—mainly ornamental products—owing to its elegant natural golden colour and other fibre properties. In the fashion industry, young designers now offer 100 % carbon-neutral collections that strive for sustainability at every stage of their garments' lifecycles: from production, processing and packaging to transportation, retailing and ultimate disposal [1]. Preferred raw materials include well-known natural fibres like flax and hemp that can be grown without agrochemicals; moreover, the garments produced are found to be durable, recyclable and bio-degradable [8]. High-value textile products are currently being used in fashion and reality shows, in making dress materials for actors and actresses, casual wear for top professionals, luxurious interiors of airports, rail and ship carriers and in furnishing five-star hotels. Recently, environmental and health concerns are behind the boom in organic cotton that not only has adopted biological practices of pest control without the use of any chemical fertilizers or genetically modified seed, but also is processed without using any chemical dyes or formaldehyde. In 2007, organic cotton was grown on almost 50,000 ha of farmland in 22 countries, with total production estimated to be around 60,000 t [1]. Mainstream fashion designers and clothing companies are now slowly introducing organic cotton in the form of jeans and sportswear. Global retail sales of organic cotton clothing and home textiles were reportedly worth more than $3 billion in 2008. Much like cotton and linen textiles, protein fibres like wool and silk in ancient times were also used in large quantities for the production of clothing and home furnishings for royal families due to their unique attributes: lustre, smoothness, shine, paper-like feel, silky appearance as well as being warm and soft. As mentioned earlier, at the time of the Byzantine Empire, fabrics made of silk were considered the most valuable luxurious products, as they were the very expression of power, wealth and aristocracy. Such luxurious and fashionable fabrics were mostly used in making secular clothes, religious vestments and interior furnishings and, even today, they are very popular in the Italian market. Similar to organic cotton fibre, fashion collections often feature organic wool (from sheep that have not been exposed to pesticide dips). Similarly, cruelty-free wild silk (harvested, unlike most silk, once the moths have left their cocoons) is increasingly used. The other important protein-based natural fibres for the fashion industry are cashmere, angora, yak and their blends with cellulosic, lignocellulosic and other protein fibres. Sustainable fashion intersects with the fair trade movement, which offers producers in developing countries a higher price for their natural fibres and promotes social and environmental standards in fibre processing. As far as synthetic fibres are concerned, rayon and lyocell (a form of rayon), cellulose acetate and polyester fibres dominate the fashion industry due to their lustrous, pliable, soft, absorbent, and wrinkle-free (e.g., polyester) properties. Acrylic fibres are cheaper and satisfy many of the properties of wool fibre. Spandex, an elastomeric fibre, is utilized by many textile industries for making sportswear and exercise wear as a result of its excellent elastic/stretchable property.

## 3 Natural Fibre, Fashion and Sustainability

Natural fibres occupy centre stage of the current fashion movement in terms of being sustainable, green, ethical, eco-friendly and even eco-environmental [1]. Naturally coloured cotton, organic cotton, organic wool, wild silk and even flax and hemp are the important fibrous materials as far as sustainable fashion is concerned. Natural fibres put due emphasis on fashion for the environment, the wellbeing of fibre producers and consumers and the working conditions of the textile industry. The production of sustainable traditional to fashionable textiles also needs the associated raw materials, chemicals and the product value chain to be sustainable in terms of water, energy, cost, fibre and bio-degradability. Approximately 100 L of fresh water are used to process one kilogram of cotton or similar textile from preparatory processing to finishing, which is finally discharged as an effluent contaminated with residual dyes, pigments, salts, acids, alkalis, sizing ingredients, suspended solids and other auxiliaries. The discharge of such effluent into water streams has a serious consequence on flora and fauna, besides adversely affecting the fertility of agricultural land. Shortage of water in the near future will have a serious impact in the textile, agriculture, energy and allied industries. In the past, as a result of environmental norms and associated government legislation, various technologies have been developed, validated and/or implemented in the textile production/processing arena, so as to ensure reduction in water, energy, production costs and effluent load. These include (i) low material-to-liquid ratio processing; (ii) spray and foam finishing; (iii) use of enzymes; (iii) natural dyeing; (iv) digital printing; (v) infrared dyeing and drying; (vi) radio-frequency drying; (vii) ultrasound dyeing and dispersión; (viii) dyeing with supercritical carbon dioxide; (ix) plasma processing; and (x) UV and laser-assisted processing. The chemicals and auxiliaries used in large quantities in the textile chemical processing industry are caustic soda and other alkalis, acids, salts, dyes, pigments, oxidizing agents, reducing agents, hypochlorite, sizing material, and stain removers (carbon tetrachloride). Many of these textile chemicals and auxiliaries contain suspended solids and produce large quantities of effluent with high biological oxygen demand (BOD) and chemical oxygen demand (COD) values. Chlorinated compounds such as pentachlorobenzene, hexamethylene biguanide and quaternary ammonium are used in antimicrobial, rot resistance and moth-proof finishing. Similarly, phenyl salicylate, benzophenone and benzotriazole–based chemicals are used in UV-protective finishing. Some present day chemicals and auxiliaries used in textile processing have an adverse effect on the environment and users in terms of health and hygiene (e.g., synthetic dyes like azo are sensitive to the skin and have a carcinogenic effect). Due to increased global awareness of environmental pollution, climate change, carbon footprint, health and hygiene in the last two decades, the demand for organic material such as organic fruits, vegetable, crops and pulses, and organic cotton has been exponentially growing. In the context of sustainable fashion, natural fibres are gaining in importance owing to their advantages of bio-degradablity, renewablity and carbon neutrality as well as for possessing such properties as good moisture regain, soft feel, adequate to fair strength, and good appearance after chemical treatment [9]. Natural fibres will play a key role in the emerging “green” economy by reducing carbon emissions and recyclable materials that ultimately minimize waste generation [9]. During processing, natural fibres mainly generate organic wastes and leave residues that can be used for electricity generation or to make ecological housing material. For example, in a UN Food and Agriculture Organization (FAO) study, it was estimated that 10 % of the energy needed for the production of one tonne of synthetic fibres is required for the production of one tonne of jute fibre [1]. This is mainly because jute is cultivated by small-scale farmers who farm traditionally and the main energy input is only human labour—not fossil fuels. Jute, hemp and bamboo are often considered more sustainable fibres owing to the requirement for fewer or no chemical herbicides, pesticides and fertilizers. The processing of some natural fibres can lead to generation of high levels of water pollutants (as reported above), but they consist mostly of bio-degradable compounds. In contrast, chemicals including heavy metals are frequently released in the effluent during synthetic fibre processing. Most natural dyes require mordant for better colour exhaustion, fixation and desired fastness. Harda (*Terminalia chebula*), natural alum and vinegar have been explored as bio-mordants for the natural coloration of textiles. For the sustainable development of traditional to high end luxury and fashionable textiles, they should preferably be made of natural fibres and then processed and finished with eco-friendly chemicals and auxiliaries, preferably derived from natural sources. This will add extra value to natural products while preserving natural resources. In this regard a number of plant extracts, bio-materials and bio-polymers—such as enzymes, natural dyes, aromatic and medicinal plants, chitosan, aloe vera, neem, lignin, silk sericin, grape and mulberry fruit extract and citrus oil—have been explored for the production of sustainable, hygienic, wellbeing-related, skincare-related, comfortable, self-cleaning, and UV-protective textiles, which are reported below in detail. Another dimension of sustainable fashion is concern for the working conditions of employees in the textile and the garment industries as they are often associated with long working hours, exposure to hazardous chemicals used in bleaching and dyeing factories and child labour [1].

# 4 Important Sustainable Lignocellulosic Fibres and Blended Fabrics

## *4.1 Sustainable Lignocellulosic Fibres*

### 4.1.1 Jute Fibre

Jute is one of the most affordable natural lignocellulosic fibres. It is a quite strong, stiff, shiny and long vegetable bast fibre produced from plants in the genus *Corchorus* [10, 11]. The fibre is composed mainly of cellulose, hemicellulose and lignin and classified in the bast fiber category (i.e., derived from the bast or skin of the plant). Other similar fibres are kenaf (*Hibiscus cannabinus*), industrial hemp, flax (linen) and ramie. Two varieties of jute—*Corchorus olitorius* L. and *Corchorus capsularis* L.—are mainly cultivated in Asia and some parts of Africa and Latin America [12]. Around 90 % of total jute worldwide is produced in India, Bangladesh, China and Thailand. India is the major producer of this fibre—the second most important natural fibre after cotton fibre [12]. After retting, jute fibres look off-white to brown and sometimes golden due to the presence of minerals. It primarily consists of alpha-cellulose (61 %), hemicellulose (24 %) and lignin (11.5 %). The fibre has the advantages of having properties such as biodegradability, cost-effectiveness, elegant natural golden color, good strength and annual renewability. The fibre's properties are reported in Table 1. Despite having such important features the fibre is comparatively coarser than cotton, is mainly utilized for packaging of agricultural crops, food grains, and other commodities in the form

**Table 1** Physical and chemical properties of some stem fibres [15–19]

| Property | Jute (white) | Jute (tossa) | Kenaf | Roselle | Flax | Linseed | Ramie | Sunnhemp | True hemp | Banana |
|---|---|---|---|---|---|---|---|---|---|---|
| | *A. Fibre physical properties* | | | | | | | | | |
| 1. Ultimate cell | | | | | | | | | | |
| Length (mm) | 0.8–6.0 | 0.8–6.0 | 2–11 | 1.5–3.5 | 26–65 | 20–30 | 20–25 | 5–20 | 5–50 | 0.9–4.0 |
| Breadth ($\times 10^{-3}$ mm) | 5–25 | 5–25 | 13–34 | 10–32 | 10–35 | 0.3–0.5 | 15–80 | 12–36 | 10–40 | 12–33 |
| Length/Breadth value | 110 | 110 | 140 | 100 | 1700 | – | 3500 | 450 | 900 | 100 |
| 2. Filaments | | | | | | | | | | |
| Gravimetric fineness (tex) | 0.9–4 | 2–5 | 3.5–5.5 | 2.8–5.5 | 2.5–6.0 | 4–10 | 0.4–0.8 | 5.5–17 | 5–15 | 3–12 |
| Tenacity (g/tex) | 30–45 | 35–50 | 30–45 | 25–40 | 45–55 | 53.2 | 40–65 | 30–40 | 35–45 | 30–40 |
| Breaking extension (%) | 1.0–1.8 | 1.0–2.0 | 1.0–2.0 | 1.0–1.8 | 2.5–3.5 | 4.0 | 3.0–4.0 | 2.5–3.5 | 1.5–2.5 | 1.8–3.5 |
| Torsional modulus ($\times 10^{10}$ dyne/cm$^2$) | 0.25–1.3 | 0.25–1.3 | 0.65–1.4 | 0.6–1.2 | 0.8–1.1 | – | 0.7–1.3 | 1.0–2.0 | 0.6–1.5 | 0.33–1.2 |
| Flexural modulus (dyne/cm$^2$) | 3.0–5.5 | 3.5–6.0 | 3.5–6.5 | 3.5–6.5 | 1.8–2.5 | – | 0.8–1.2 | 125–175 | 25–80 | 20–25 |
| Transverse swelling in water (%) | 20–22 | 20–22 | 20–22 | 20–22 | 20–24 | 30–36 | 12–15 | 18–20 | 20–22 | 16–20 |
| 3. Bundle tenacity (g/tex) | 13–30 | 16–35 | 16–30 | 12–30 | 30–36 | 10–35 | 28–40 | 15–35 | 20–35 | 20–30 |
| 4. True density (g/cm$^3$) | 1.45–1.52 | 1.45–1.52 | 1.47 | 1.45 | 1.55 | – | 1.56 | 1.53 | 1.54 | 1.35 |
| 5. Apparent density (g/cm$^3$) | 1.23 | 1.23 | 1.21 | 1.22 | 1.44 | – | 1.44 | 1.34 | 1.35 | 0.62 |
| 6.Moisture regain (%) at 65 % r. h. | 12.7–13.7 | 12.7–13.7 | 13 | 12.5 | 7 | 8–9 | 6.5 | 10.5 | 11.0 | 15 |
| 7. Coefficient of friction; parallel & perpendicular | 0.54 & 0.47 | 0.45 & 0.39 | – | – | 0.44 & 0.39 | – | 0.61 & 0.50 | 0.50 & 0.40 | – | – |
| 8. Degree of crystallinity (%) | 50–50 | 55–65 | – | – | 55–70 | – | 66–74 | 45–50 | – | 45–50 |

(continued)

**Table 1** (continued)

| Property | Jute (white) | Jute (tossa) | Kenaf | Roselle | Flax | Linseed | Ramie | Sunnhemp | True hemp | Banana |
|---|---|---|---|---|---|---|---|---|---|---|
| | *B. Fibre chemical properties* | | | | | | | | | |
| (i) Alpha-cellulose (%) | 61.0 | 60.7 | 31–72 | – | 64.1 | – | 86.9 | 78.3 | – | 61.5 |
| (ii) Pentosan (%) | 15.9 | 15.6 | – | – | – | – | 3.6 | 3.6 | – | 14.9 |
| (iii) Uronic anhydride (%) | – | 5.9 | – | – | – | – | 5.6 | 1.7 | – | 5.3 |
| (iv) Acetyl content (%) | 2.9 | 3.5 | – | – | – | – | 0.6 | 1.5 | – | 2.8 |
| (v) Lignin content (%) | 13.2 | 12.5 | 8–19 | – | 2.0 | – | 0.5 | 4 | – | 9.7 |
| (vi) Minor constituents such as fat and wax; nitrogenous matter; ash (%) | 0.9; 1.56; 0.5 | 1.0; 1.87; 0.79 | – | – | 1.5; 3.9; 1.1 | – | 0.3; 2.1; 1.1 | 0.5; 1.4; 0.3 | – | 1.4; 1.6; 4.8 |
| (vii) Degree of polymerization of alpha-cellulose and hemicellulose | – | 1150 and 166 | – | – | 4700 and 120–150 | – | 5800 and 150 | 1002 and 49 | – | 1300 |
| (viii) Elemental percentage (C, carbon; O, oxygen; other elements) | C 62.72; O 37.11; Si 0.06; S 0.08 | | – | – | – | – | – | – | – | – |

of hessian and gunny (burlap) bags. In the last few decades with the advent of synthetic polymers—such as nylon, polyester, polypropylene and acrylic—and fibre technology, jute fibre is currently facing serious challenges for its traditional end use. However, more recently, it has found a promising application in technical textiles (e.g., in carpet backing, home textiles, geotextiles, agrotextiles, composites and auto-textiles [13]). In addition to its traditional use in packaging, jute fibre has a number of value-added end applications in making decorative and fashionable yarn and fabric, either in the pure form or in blends with other fibres—such as flax, ramie, wool, polyester and acrylic (as described in succeeding sections).

### 4.1.2 Ramie Fibre

Of the different fibre crops that are commercially important, ramie (*Boehmeria nivea*) occupies an important place [14]. It occupies first place among all commercial fibres because of its superior strength, as well as other desirable quality attributes such as fibre length, durability, absorbency and lustre, which make it a very useful fibre for manufacturing a wide variety of textiles and cordage products. Ramie has exceptionally long ultimate fibre cells (an average length of about 150 mm). The fibre is highly lustrous and has exceptionally high resistance to bacteria and fungi, including mildew [15]. Ramie fibre is very important in the context of moisture management, as it absorbs and releases moisture quickly, with almost no shrinkage and stretching. In undegummed ramie fibre 68.6 % cellulose, 13.1 % hemicellulose and 1.9 % pectin are present. On the other hand, in degummed ramie fibre about 96–98 % alpha-cellulose with very few trace amounts of lignin is present, when calculated on the dry weight basis. Despite several unique positive fibre attributes, it is still not considered a major textile fibre, mainly because of issues related to production and processing difficulties in large quantities. The word "ramie" comes from an ancient Malayan word. In Dutch it is *rameh*. In China it is known as *tchou-ma*, *chu-ma*, *ch'u*, *tsu*; in India it is *rhea*, *pooah*, *puya*. It is one of the oldest plant fibres cultivated in the Orient and is used in the Far East as a textile fibre of great quality. Ramie is known to have been grown in China for many centuries, even before cotton (*Gossypium* spp) was introduced by the Chinese in 1300 AD. The fibre is mentioned in ancient Indian literature like *Ramayana* and *Shakuntala*, a well-known drama written by Kalidas in about 400 AD. Yet, ramie remains a minor crop, with world production probably never exceeding 130,000 t. The major ramie-producing countries are China, Brazil and the Philippines, the others are Japan, Indonesia, Malaysia and India. All products that are manufactured from cotton, flax, hemp or silk could also be manufactured from ramie. Due to its unique textile properties, textile products made of ramie cannot be replaced by any other natural or synthetic fibre. Some of the important applications of ramie fibres are found in the making of premier-quality shirts and suits, knitwear, bed sheets, twines and threads, pulleys, belts, fire hoses, water-carrying bags, gas mantles, meat packaging, canvas, filter cloths and defence products—such as ammunition belts, camouflage nets and parachute cords. Figure 1

**Fig. 1** Picture of different important lignocellulosic fibres

shows some different lignocellulosic fibres while Table 2 gives the physical and chemical properties of some seed, leaf and fruit fibres.

### 4.1.3 Banana Fibre

Cotton, jute, flax, ramie, hemp, sisal, wool and silk are the important fibres widely used throughout the world for the manufacture of clothing as well as home and technical textiles. Apart from these widely utilized natural fibres a large number of other fibres are also grown in different parts of the world in much smaller quantities to meet the demand of local economies. One such fibre is banana, which is extracted from the leaf sheath (pseudostem) of the banana plant—a member of the monocotyledon family [15]. Banana plants (*Musa sapientum*) are grown in different parts of India. After harvesting the bananas the trunk or trunk sheath is commonly considered agro-waste [20]. It is estimated that post-harvest a large quantity (60–80 t/ha) of agro-biomass is generated causing pollution of the local environment during disposal [17]. The fibre is obtained from the sheath of the trunk after scotching, followed by washing in water or dilute chemicals. India is the largest producer of banana fibre globally. Total global production of banana fibre is between 80,000 and 90,000 t [15]. The price of banana fibre is US$0.43–0.81 per kilogram compared with hemp, kenaf and flax, which are US$0.15–0.60, 0.15–30 and 0.15–0.21 per kilogram, respectively [17]. The fibre has many properties resembling those of jute, hence the attempts have been made to produce yarn and fabric blended with jute using the jute-spinning system to develop different diversified products (as discussed below). However, prior to mechanical processing, it needs to be stapled for effective processing in jute-spinning machineries. Due to its high cellulose content, banana fibre has tremendous scope for making superior quality paper and as a reinforcing material in natural fibre bio-composites. The cultivation of bananas for clothing and other household end uses in Japan dates back to the 13th century.

**Table 2** Physical and chemical properties of some seed, leaf and fruit fibres [15–19]

| Property | Sisal | Coconut | Pineapple | Aloe | Manila hemp | Cotton |
|---|---|---|---|---|---|---|
| 1. Ultimate cell | | | | | | |
| Length (mm) | 0.5–0.6 | 0.5–4 | 3–9 | 0.5–5.0 | 3–12 | 15–60 |
| Breadth ($\times 10^{-3}$ mm) | 5–40 | 7–30 | 4–8 | 5–35 | 10–32 | 15–20 |
| Length/Breadth value | 150 | 95 | 450 | 125 | 250 | 1300 |
| 2. Filaments | | | | | | |
| Gravimetric fineness (tex) | 16–35 | 25–50 | 2.5–6.0 | 10–25 | 20–35 | 0.1–0.3 |
| Tenacity (g/tex) | 40–50 | 15–35 | 25–45 | 25–40 | 35–45 | 20–45 |
| Breaking extension (%) | 2.5–4.5 | 8–20 | 2.5–4 | 3–10 | 2–3 | 6.5–7.5 |
| Torsional modulus ($\times 10^{10}$ dyne/cm$^2$) | 0.3–1.0 | 0.2–1.5 | 0.3–1.0 | 0.2–1.5 | 0.3–1.2 | 0.8–1.2 |
| Flexural modulus (dyne/cm$^2$) | 125–175 | 150–250 | 2.5–4 | 100–150 | 150–200 | 0.3–1.0 |
| Transverse swelling in water (%) | 18–20 | 5–15 | 18–20 | 16–20 | 18–22 | 20–22 |
| 3. Bundle tenacity (g/tex) | 22–36 | 10–15 | 20–30 | 15–30 | 20–35 | – |
| 4. True density (g/cm$^3$) | 1.45 | 1.40 | 1.5 | 1.47 | 1.45 | 1.55 |
| 5. Moisture regain (%) at 65 % r. h. | 11 | 10.5 | 13 | 12.0 | 9.5 | 7.0 |
| 6. Coefficient of friction (parallel) | – | – | 0.62 | – | – | – |
| 7. Coefficient of friction (perpendicular) | – | – | 0.57 | – | – | – |
| 8. Degree of crystallinity (%) | 40–45 | – | 55–60 | – | – | – |
| 9. Chemical composition | | | | | | |
| (i) Alpha-cellulose (%) | 63.9 | 32–44 | 69.5 | – | – | 83–90 |
| (ii) Pentosan (%) | 7.9 | – | 17.8 | – | – | – |
| (iii) Uronic anhydride (%) | 5.8 | – | 5.3 | – | – | – |

(continued)

**Table 2** (continued)

| Property | Sisal | Coconut | Pineapple | Aloe | Manila hemp | Cotton |
|---|---|---|---|---|---|---|
| (iv) Acetyl content (%) | 4.6 | – | 2.7 | – | – | – |
| (v) Lignin content (%) | 8.6 | 40–45 | 4.4 | – | – | <2 |
| (vi) Minor constituents such as fat & wax; nitrogenous matter; ash (%) | 0.7; 0.8; 0.7 | – | 3.3; 0.25; 0.9 | – | – | – |
| (vii) Degree of polymerization of alpha-cellulose and hemicellulose | 726 and 165 | – | 1178 and 116 | – | – | – |
| (viii) Elemental percentage (C, carbon; O, oxygen; and other elements) | – | – | – | – | – | C 53.2; O 46.8; S 0.08 |

### 4.1.4 Flax/Linseed Fibre

The common flax plant is a member of the small family Linaceae, which includes about a dozen genera and several species, widely distributed in the temperate and subtropical regions of the world [15]. *Linum usitatissimum* is the only member of the family used for fibre production. The seed of the flax plant is known as linseed from which linseed oil is extracted. The fibre extracted from the straw after harvesting is suitable for manufacturing coarser quality textiles. The plant is cultivated worldwide in countries as diverse as Belgium, Japan, Kenya, Uganda, Argentina, Canada and India with annual production of about 773,000 t [15]. Linen is laborious to manufacture, but the fibre is very absorbent and garments made of linen are valued for their exceptional coolness and freshness in hot weather [21]. The flax variety grown for fibre production has excellent textile properties such as good length, fineness, softness, good density, lustre and moisture absorbency. Fibre fineness (tex) varies in the range of 4–10 and fibre tenacity between 45 and 55 g/tex, whereas these values for jute are 1.2–4 tex and 30–45 g/tex, respectively. Detailed fibre properties are reported in Table 1. The fibre has slightly better elongation characteristics than jute fibre. Fine and regular, long flax fibres are spun into yarns for linen textiles. More than 70 % of linen goes to the clothing manufacture sector, where it is valued for its exceptional coolness in hot weather—the legendary linen suit is a symbol of breezy summer elegance [9]. Linen fabric maintains a strong traditional niche among the highest quality household textiles, such as bed linen, furnishing fabrics and interior decor accessories. In 2007 the European Union produced 122,000 t of flax fibre, making it the world's biggest producer followed by China with about 25,000 t. The bulk of linen production has shifted to Eastern Europe and China, but niche producers existing in Ireland, Italy and Belgium continue to supply high-quality fabrics to Europe, Japan and the USA. The fibre comprises 70 % cellulose, absorbs moisture from the air and allows the skin to breathe, with no irritating or allergenic effects. Aditya Birla Co. has been in the market place promoting flax-based clothing under the brand name Linen Club for quite some time. To provide the superior feel, look and bright colour the fabric is dyed and finished using the latest European technology. Such textile substrates are to some extent limited to the rich owing to their relatively higher price than other lignocellulosic textiles. Furthermore, flax fibre can be used for making table wear, clothing, surgical thread, sewing thread, elegant bed linen, kitchen towels, tapestries and artist canvases.

### 4.1.5 Pineapple Fibre

Pineapple (*Ananas cosmosus*) fibre is obtained from the leaves of the pineapple plant which belongs to the Bromeliaceae [15]. Its name is derived from the Spanish word *pina* meaning "cone shaped". The plant is widely cultivated in the Philippines, Malaya, Thailand, Ghana, Kenya, Mexico, Taiwan, China and India, with a total cultivated area of about 84,300,000 ha [15]. Brazil is the world leader in pineapple cultivation, followed by Thailand and the Philippines, supplying 52 % of global total output [22]. The leaves of the plant are about 3–5 ft long and 2–3 in. wide, tapering to a point akin to a sword. The fibre extracted from waste pineapple leaves is known as pineapple leaf fibre (PALF). The fibre is extracted from the leaves by hand as well as with a decorticator (a machine that strips skin, bark or rind of plants), though a combination of water retting and scraping is used in practice. The fibre has a fineness similar to jute fibre, but a tenacity that is significantly lower (Table 2).

### 4.1.6 Sunnhemp Fibre

Sunnhemp, a natural cellulosic bast fibre, is obtained from *Crotalaria juncea,* which is grown in India and neighbouring countries like China, Korea and Bangladesh as well as in Romania and Russia. It is a coarse, strong fibre that is brown-yellow in colour; the fibre is extracted after retting of the plant [15]. World production of this fibre is approximately 200,000 Mt. The fibre is fine and white in colour if it is harvested at the pre-flowering stage, but production remains 2 % lower in that case. The fibre gives a low lignin content (4 %) compared with jute, which has about 13 % lignin [15]. The fibre properties have been reported in Table 1. The fibre is coarser than jute and has comparable tenacity. Hemp has been used for centuries in making rope, canvas and paper. Long hemp fibres can be spun and woven to make crisp, linen-like fabric used in clothing, home-furnishing textiles and floor coverings [9, 21]. In China, hemp is degummed for processing on flax or cotton machinery. It is often blended with cotton, linen, silk and wool to give a soft, aesthetic feeling and to improve product durability. Pure hemp has a similar texture to linen. Hemp fashionable jewelry is the product of knotted hemp twine, done by macramé, and includes bracelets, necklaces, anklets, rings, watches and other adornments [21]. Different stitches are used to produce a wide range of fashionable hemp jewelry.

### *4.2 Jute-Based Fashionable/Decorative Fabrics*

Jute is mainly used for packaging of agricultural crops and commodities. In the early days, the jute packaging system had a monopoly in the world market. India used to contribute the major share of foreign revenue by exporting jute goods to Western countries. However, over the years, jute fibre has faced serious challenges from advances in synthetic polymers and fibres as well as in the field of material science [12]. Due to the introduction of lightweight synthetic polymers like polypropylene and polyethylene bags in developed countries in the early 1970s, Indian traditional jute-packaging products faced stiff competition in both national and international markets. India's Central and State Governments, the jute industry and research organizations put much emphasis on developing alternative products to packaging bags and discover other applications for jute and jute-blended (with natural and synthetic fibres) textiles. The use of synthetic polymeric fibres currently used in large quantities in place of natural fibres is now raising concern about environmental pollution, the preservation of natural resources and biodiversity. Hence, natural fibre–based textile products are once again in market demand. The main advantages of natural fibres—such as jute, cotton, flax, ramie, wool, silk and banana—are their biodegradability, renewability, cost-effectiveness, natural golden colour (as well as other colours), good strength, good moisture regain, very good thermal insulation, and non-toxicity. Over the last few decades, research and product development have been intensified to produce different jute-blended ornamental textiles and to establish a complete value chain from fibre to fabric or fibre to fashion. The jute industry is having a demand for diversified products in value-added end applications such as floor covering, upholstery, handicrafts and fashionable items [23, 24]. The production of decorative jute fabric with ornamental fashion attributes deserves special mention as far as handloom-made jute products are concerned. In this context, Roy and Basu reported the development of suitable and durable jute yarn, fabric and specialty textile-based products (bags/packs) for alternative or value-added end applications [25]. Such specially designed, engineered products were named "spun-wrapped yarn" or "covered yarn" when used in the hand-weaving machine. As expected, jute spun-wrapped yarns showed much lower hairiness, better tensile and flexural performance than those made from traditional jute yarn [25]. The same research group also described the development of

**Fig. 2** Full view of the handloom developed with a Jacquard-shedding arrangement for diverse product and ornamental fabric development [24]

**Fig. 3** Jute yarns and fabric products [12]

a handloom with a Jacquard-shedding arrangement with necessary modifications for the development of fashionable jute-blended fabrics (Fig. 2) [24]. They reported the development of various jute yarns and fabric products, such as a laptop carry bag with a price tag of INR 300 ($US4.44) and a school bag of INR 250 ($US3.67) from specialty jute yarn (Fig. 3) [12].

### 4.2.1 Blended Yarns

The blending of different fibres has primarily been adopted to improve the technological performance of major components and/or to improve the economic properties of yarn produced from such blends.

### 4.2.2 Fine Yarns

Fine yarns (84–207 tex) are needed to produce finer and stronger fabrics for furnishing, upholstery and industrial applications. Long, fine natural fibres—such as ramie, flax and PALF—are commonly blended with jute for such purposes.

An array of specialty yarns from jute and blends with other fibre/filaments/films has been developed at National Institute of Research on Jute and Allied Fibre Technology (NIRJAFT) in Kolkata (India). A simple gadget was designed, developed and fabricated for use in the existing spinning frame for manufacturing jute-covered yarn. Dyed viscose multifilaments were wrapped around the jute during spinning to mask the jute core fully. Moreover, such yarns were used to weave decorative fabrics with smooth and colourful surfaces. Polypropylene monofilament–covered yarns were also used to weave high-performance fabrics suitable for industrial use. High-density polyethylene (HDPE) slit film–covered jute yarns were spun to produce water-resistant fabric. Core spinning technology was also adopted to spin core yarns with HDPE/HDP core and jute sheath. These yarns had higher dry and wet strength and elasticity as well as improved evenness. All these properties were reflected in fabrics woven from jute/synthetic core yarns as well. Novelty/Fashionable yarns were produced from coloured synthetic tops and dyed jute slivers to produce fabrics for various end uses. Different filament-covered jute or jute-blended decorative/fancy yarns (276 tex) were also developed for a similar purpose. Computer bags, ski bags, school bags, office bags, upholstery, lifestyle products and garments were manufactured from various jute and/or blended yarns and fabrics as shown in Figs. 4 and 5.

Jute fibre is a major cash crop in India and is mainly used for the production of coarser packaging fabrics for the packing of rice, wheat, sugar, potatoes, onions, etc. However, ordinary jute yarn cannot be used for the development of decorative and upholstery fabrics. It is possible to develop high-value utility products—such as school bags, laptop bags, office bags, ladies' bags and folder files—from jute by

**Fig. 4** Fashionable jewelry products made of jute fibre and fabrics

**Fig. 5** Fashionable lifestyle products developed from jute-blended textiles

using specialty jute yarns. Fabrics developed with a different weave structure to manufacture such products, compared with ordinary jute fabric of similar constructional parameters, showed higher strength and elongation, but a drastic reduction in the bending modulus, resulting in a softer feel. Similar new products can also be developed from other natural fibres akin to jute—such as *Hibiscus cannabinus* (kenaf), *Hibiscus sabdariffa* (rossel), *Cannabis sativa* (hemp) and *Linum usitatissimum* (flax).

## *4.3 Jute-Blended Yarns and Fabrics for Fashionable/Diverse Applications*

### 4.3.1 Jute–Ramie Fibre Blends

Degummed ramie contains approximately 4.3 % gum, whereas decorticated ramie contains 23 % gum. Blending of ramie with other natural or synthetic fibres can eliminate its inherent drawbacks, making it suitable for fabric formation for casual as well as formal wear, tablecloths, handkerchiefs, canvas, suit cloth and mat edging. It has been reported that 10–15 % blending of raw ramie (with 25–30 % gum content) or partially degummed ramie (with 9 % residual gum) with jute helps to spin good-quality yarns of finer count (100–105 tex) in jute or flax machinery [18]. Blending of ramie with jute helped to produce yarns of 103 tex, which is not achievable with wholly jute fibre. As the gum of ramie is gradually removed, spinnability and yarn characteristics were found to improve accordingly. To process ramie on jute-spinning machinery, it was found that a degumming treatment with residual gum content of 8 % might be sufficient. Indeed, as there is no specialized spinning system available in India, it was attempted to spin ramie fibre on the jute system [26]. The properties of jute/ramie–blended yarns of were found to be much better than those produced from completely jute fibres. Such blended yarns have potential application in such areas as furnishings, upholstery and clothing fabrics. Wholly ramie yarn spun in the jute-spinning system also holds a lot of promise for use in shoe canvas, soles, sewing twines, coarse fabrics, etc. Binary blending of degummed ramie has been optimized with fine fibres such as viscose, polyester, silk and tussar (a type of silk) waste. In another approach, degummed ramie fibres were cut into 40-mm staple lengths with a staple cutter. Flock blending of ramie and cotton fibres in different proportions has also been carried out. Ramie is highly appreciated for its lustre and strength, whereas cotton is well known for its fineness and elongation properties. Therefore, cotton–ramie blends have been spun using the short-staple spinning technique. A blend ratio of 65:35 of cotton:ramie has been found to give an adequate count strength product (CSP) for 40 s ring yarns intended to be used for making towels and knitted products. Ramie has been blended with polypropylene and acrylic fibres in various proportions at different stages of processing to obtain suitable blend proportions for specific end uses and for ascertaining the right stage of blending. Fabrics with different area densities have been woven from various combinations of cotton and ramie yarns blended with acrylic or jute for making safari suits, shirts and other clothing. T-shirts have also been designed and tailored from fabrics woven from ramie/acrylic–blended yarn and cotton yarns.

### 4.3.2 Jute–Flax Fibre Blends

Flax fibre from Belgium was blended with jute fibre to produce a good-quality yarn to be used as shoe twine and clothing-grade textiles. The blend was processed in a rove spinning system with a wet spinning attachment fixed on the spinning frame. Highly regular, strong and fine yarns (84–138 tex) could be manufactured with a jute:flax blend ratio of 50:50 [18]. Subsequently, flax tow (coarse, broken fibre) was blended with jute using a small-scale jute-spinning system developed by NIRJAFT, and yarns of 138–207 tex were spun with 50 % flax tow in the blend with jute. These yarns hold much promise to be used as furnishing fabrics. Flax/jute–blended yarn of 138 tex was also prepared successfully on a conventional jute-spinning system.

### 4.3.3 Jute–Cotton Fibre Blends

In the processing of jute–cotton fibre blends, jute fibre was first required to shorten and then blend with cotton [18]. Jute was initially cut and mixed with cotton fibre in the stack-blending technique. Then the blend was processed in the khadi-spinning system using such machines as a bale opener lap maker, comb-bladed carding, fixed flat metallic carding, drawing, apron drafting and the *Ambar Charkha* (sky wheel). (Khadi is a term for handspun and hand-woven cloth.) Then fabric was produced on a handloom. When jute was blended with cotton fibre in the cotton-spinning system the meshes of jute reed had to be broken first in the jute-carding machine to ensure a staple length of 25 mm. The jute fibre was subsequently blended, carded, drawn and spun in the cotton-spinning system. It was possible to mix 20 % of jute fibre successfully with cotton in the cotton-spinning system and, thus, the blended yarn could be used to weave scrim cloth. Research into the rotor spinning of jute/cotton–blended yarn was also carried out by Doraiswami and Chellamani (1993) [27]. Additionally, efforts have been made to standardize the spinning parameters for open-end spinning of a 50:50 blend of jute–cotton (with 31-mm staple length) to make a yarn of 312 tex at a rotor speed of 50,000 rpm and delivery speed of 80 m/min [18]. A comparative study was conducted to evaluate the physical properties of a jute/cotton–blended curtain compared with a 100 % cotton curtain [28]. Three different blend ratios—jute:cotton at 60:40, 50:50 and 40:60—were prepared; it was found that the strength of the blended curtain warpwise was close to the 100 % cotton curtain before washing, but the strength decreased after washing. Wrap-spun jute yarns with linear densities of 276, 190 and 120 tex with wrap density in the range of 250–450 wraps/m were produced with a 2-ply cotton yarn as the wrapping element using hollow spindle technology [29]. Instead of cotton as a wrapping component, wrap-spun jute yarn of 276 tex was also developed using a viscose rayon multifilament as the wrapping element.

### 4.3.4 Jute–PALF Fibre Blends

Special techniques have been adopted for processing PALF (which comes from the pineapple *Ananas comosus*) on the jute-spinning system. Similar to jute processing, PALF was first softened with a 15 % mineral-oil-in-water emulsion applied at 1 % of the weight of the fibre for improved spinning performance [18]. A jute finisher card and a full circular flax finisher card with progressively higher pin density were used for first and second carding, respectively. Blending of PALF with jute was found to improve the quality of the blended yarns noticeably. A minimum 10–15 % of PALF in the blend was enough to produce a finer yarn which cannot be produced by jute fibres alone. Blending of jute–PALF was also undertaken at NIRJAFT to investigate the extent to which the superiority of PALF may be utilized for upgrading the performance of jute yarn. It was found to produce stronger and finer yarn than yarn based just on jute fibre making it effective at producing diverse textiles. A suitable technique was developed at the institute to process the fibre in jute machinery. Finisher card slivers of jute and PALF were mixed in different proportions at the first drawing stage, keeping variables such as machine sequence and processing parameters identical. The performance of jute/PALF–blended yarn was improved in terms of strength by increasing the proportion of PALF fibre in the yarn. PALF has been used as raw material for manufacturing a number of products such as paper, rope, handkerchiefs, knitted shirts, interlining lace, mats, bags, blankets, insulators, soundproofing material, nanomaterial and composites [30].

### 4.3.5 Jute–Banana Fibre Blends

Banana fibre is obtained from the sheath of banana trunk after scotching and washing in water or in a diluted chemical. The fibre has many attributes similar to those of jute fibre, hence the attempts to produce yarns and fabrics adopting the jute-spinning system. However, the fibre needs to be stapled first for efficient processing in jute-spinning machine sequences. Due to its high cellulose content, banana fibre has tremendous potential for use in the production of good-quality paper and as a reinforcing material in the preparation of green-composite, fine-quality fancy yarn and decorative fabrics [20]. The possibility of blending Indian varieties of banana (*Musa sapientum*) sheath fibre with jute using the jute-processing system was explored by Sinha (1974) [31, 32]. White jute, tossa jute and kenaf were blended separately with 75 and 50 % banana sheath fibre at the jute finisher carding stage [18]. Yarns of 345 and 280 tex were spun, where quality was found to deteriorate marginally by increasing the proportion of banana fibre in the blends. The yarn can be used as hessian weft and sacking warp. Subsequently, an attempt was made to produce rope from banana fibre. This comprised 40 % banana fibre, 50 % aloe fibre and 10 % sisal waste tow [31, 32]. The performance of all these yarns was compared with a normal commercial agricultural rope containing about 40 % kenaf (mesta) fibre in place of banana fibre. Normal rope-making machinery, which consisted of a jute softener, teaser card, sisal tow breaker card, sisal tow finisher card, first-passage screw grill drawing, second-passage screw grill drawing, gill spinner apron draft (AD) for rope yarn, roll winder, rope-stranding machine and rope-laying machine were used. Before processing, the fibres were treated with an oil–water emulsion. Primary yarn of 24 s

**Table 3** Tensile properties of jute/banana fibre–blended yarn [20]

| Type of yarn | Yarn linear density—actual (nominal) (tex) | Twist (tpi) | Tenacity (cN/tex) | Breaking extension (%) | Work of rupture (mJ/tex-m) |
|---|---|---|---|---|---|
| 100 % jute | – | – | 10.9 | 2.0 | 0.96 |
| Jute/banana (75/25) | 268 (276) | 4.0 | 9.0 | 1.4 | 0.68 |
| Jute/banana (50/50) | 272(276) | 4.0 | 8.3 | 1.5 | 0.57 |
| Jute/banana (25/75) | 270 (276) | 4.0 | 7.4 | 1.3 | 0.52 |
| 100 % banana | 352 (345) | 3.5 | 7.4 | 2.4 | 0.88 |

**Fig. 6** Jute/banana fibre–blended fabric and clothing textiles (jackets) [20]

rope count (4600 tex) made of banana fibre instead of mesta was found to be stronger and more extensible than standard commercial rope made of aloe (50 %), kenaf (40 %) and sisal waste tow (10 %).

At NIRJAFT, extensive research has been conducted into different aspects of banana fibres such as fibre quality evaluation, processability and product development. Trials involving the spinning of yarn (6 lb, 5 tpi, in apron drafting) for blends of 100 % banana and jute/banana fibres (75/25, 50/50 and 25/75) have also been carried out. The spinning performance of 100 % banana and jute/banana (25/75) blends were not encouraging; however, spinning trials for production of coarser yarn (8 lb, 4 tpi and 10 lb, 3.4 tpi on a slip draft spinning frame) from jute/banana fibres in the same blend ratios and 100 % banana fibre yarn (10 lb, 3.4 tpi using a slip draft spinning frame) were successful. It was postulated that 100 % banana fibre can be processed smoothly in jute-processing machines and can be spun to 10-lb grist (345 tex) and above count [20]. The tensile properties of 100 % jute and banana, and jute/banana blended yarns are reported in Table 3. Different jute/banana fibre blended products are shown in Fig. 6.

### 4.3.6 Jute–Wool Fibre Blends

Exhaustive research work has been undertaken into spinning chemically softened jute, better known as "woollenized jute", in which jute fibre is treated with 18 % NaOH solution at 25 °C for about 30 min using various spinning systems [18]. It was observed that removal of crimps in woollenized jute fibre brought about a deterioration in the regularity of woollenized jute/wool–blended yarns at the carding and drawing stages when spun in the jute- or flax-spinning system. Hence, the spinning of woollenized jute/wool–blended yarn in jute- or flax-spinning machinery was not considered worhwhile. However, it is worth mentioning that good-quality yarn could be spun from a woollenized jute:wool 50:50 blend using woollen- or worsted-spinning systems. The yarn so produced is suitable for blankets, scarves, pullovers, wraps, and the face yarn of loop pile tufted carpets. Other researchers have also reported on blending wool fibre with jute using the jute-spinning system [33–35].

### 4.3.7 Jute–High Bulk Acrylic Fibre Blends

A simple and economical process of bulking jute/acrylic fibre–blended yarn has been developed in the laboratory. Such yarn has high potential for use as a substitute for woollen or 100 % acrylic-bulked yarn. The yarn has such properties as high bulk, high extension, low flexural rigidity and good strength compared with its parent blended yarn or pure jute yarn. After successful binary blending, the effect of blending, plying and bulking on tenacity, elongation, evenness, shrinkage, specific volume, and specific flexural rigidity of the developed yarn from ternary blends has also been studied. After several trials, a suitable blend ratio of 50:30:20 of jute: shrinkable acrylic:non-shrinkable acrylic was optimized. With this blend ratio, synthetic fibres—polyester, polypropylene and viscose—other than non-shrinkable acrylic fibre were also found suitable. Jute/shrinkable acrylic/viscose showed a shrinkage of 28 % with a specific volume of 11.8 $cm^3/g$. A substantial drop in tenacity and a large increase in extension on the bulking the ternary-blended yarns were also found, as expected. However, the tenacity and extension values were found to be comparable with similar-grade woollen yarns. The specific flexural rigidity of ternary-blended parent yarns was much less than pure jute yarns. Jute blended with hollow polyester fibre–bulked yarn (80:20) was prepared by chemical treatment. Warm fabrics like shawls and jackets were prepared from such bulk yarns. Nanofinishing was incorporated in the fabric to reduce bending rigidity. Nanopolysiloxane-based finishing was found to exhibit encouraging results. Jute fibre can also be blended with more than one fibre to impart the positive properties of other blended fibres to jute-blended yarn. Keeping this concept in mind, jute: shrinkable acrylic:hollow polyester (50:30:20) was successfully blended to get a bulk yarn of 275 tex for making upholstery, kurta (upper garments for male and female), shirts, ladies' waistcoats and gents' jackets.

### 4.3.8 Jute–Polypropylene Fibre Blends

Sengupta and Debnath described a new approach for making jute/polypropylene (PP)–blended yarn (70:30) by blending the fibres on a finisher draw frame [23]. The fabric was developed in a modified handloom at much lower cost. The fabric showed higher areal density, thickness and other mechanical properties. Soft, bulky, resilient and highly extensible jute/PP–blended yarns have been developed by texturizing yarns of different compositions and twist levels. Chemical texturization of different blended yarns has been standardized at NIRJAFT. The use of coloured PP fibre of 4–6 D (denier) in the blended yarn helped to produce a coloured texturized yarn, due to the emergence of coloured PP fibre on the surface of the yarn during texturization. Texturized jute/PP–blended yarn was found to have high extensibility, moderate strength, higher diameter and smoother surface feel compared with the parent blended yarn or the pure jute fibre yarn with similar construction parameters. A partially covered structured yarn has also been developed with jute and colored PP. It was aimed at covering jute yarn with synthetic staple fibres so as to reduce the harshness of jute yarn and improve its aesthetic appeal for use in clothing and furnishing fabrics. Two types of jute-based blended yarns were produced from jute:PP:hollow polyester (50:25:25) fibres and jute:shrinkable acrylic:hollow polyester (50:30:20) fibres in the conventional jute-spinning system [13]. The first blend could be used in making cushion cloth, mattress cloth, table cloths and bed sheets, whereas the second blend could be used for producing warm garments. Cross-laid, needle-punched non-woven fabrics were also prepared from 100 % jute and its blend with PP as a minor constituent for traditional to high-end applications [36].

### 4.3.9 Jute–Viscose Fibre Blends

As stated earlier, jute has limited end applications as a result of being a much coarser fibre. However, when it is blended with viscose—a very fine cellulosic apparel-grade fibre—the physical and mechanical properties of the blended yarn were found to improve, thus making it suitable for wider and diverse end applications [37]. Blended yarns of 50 % jute, 50 % viscose and 100 % polyester were used to make a yarn with three different ratios of jute–viscose and polyester (70/30, 50/50 and 30/70). A quaternary-blended plain woven fabric was produced on the handloom with cotton in the warp and jute–viscose–polyester yarn with three different ratios in the weft. The 30/70 jute viscose/polyester union fabric exhibited better performance than those produced with other ratios of the blend. It also reduced the cost of the product [37]. The technology of spinning covered yarn in the existing jute-spinning frame is quite novel, yet simple. A low-cost gadget has been developed that can be fitted to the spinning frame to produce a jute/viscose–covered yarn. A coloured viscose mul-tifilament of 150 D was wrapped on the surface such that the jute remains at the core of the yarn. Thus, a coloured jute/viscose–covered yarn was produced with a low proportion of viscose (10–30 %). This yarn was as fine as 84–130 tex with a smooth surface morphology and reduced hairiness compared with pure jute yarn of similar construction. Bamboo viscose—new kind of regenerated fibre—was also blended with jute. The fibre is known to have various small pores on the fibre surface that help improve moisture absorption and oxygen vapor permeation in garments. Moreover, the fibre exhibits excellent protection from ultraviolet radiation, infrared radiation and microbes [6].

# 5 Important Properties of Different Protein Fibres and Fabrics

## *5.1 Properties of Important Protein Fibres*

### 5.1.1 Wool Fibre

Wool fibre is obtained from the follicles of sheep, goats, camels, rabbits and camelids like vicuna, llama and alpaca as wool fleece and is an important animal hair fibre [38]. Wool is composed of 18 different amino acids; the important ones are cysteine (13.1 %), glutamate (11.1 %) and serine (10.8 %). Grease–wool fleece contains impurities such as wool grease and perspiration products (e.g., suint) as well as adhered materials such as dirt and vegetable matter. It has three distinct morphological parts: the outer is the cuticle layer, the middle is a group of spindle-shaped cortex cells and the inner is the medulla. Wool fibre is mainly used for men's and women's woven outerwear, knitwear, underwear, socks, hand-knitted yarn, blankets, upholstery, filled bedding, rugs and carpets [38]. India exports nearly INR60 billion ($US884,819,400) worth of woollen carpets and other handicraft items [39]. Wool fibre is inherently hydrophobic in nature due to the presence of covalently bonded lipid on the surface of the cuticle membrane [40]. This can be overcome in practice by a chemical treatment with strong alkali or chlorine or plasma treatment so as to remove parts of the bound fatty acids. The treatment will also help in formation of polar functional groups on the fibre surface.

### 5.1.2 Silk Fibre

Silk is derived from the silkworm *Bombyx mori* and is composed of two major proteins: sericin and fibroin. Fibroin is a fibrous protein, present as a delicate twin-thread linked by disulphide bonds, enveloped by successive sticky layers of sericin that help in the formation of a cocoon [41]. Silk sericin or glue material is a globular protein that comprises 25–30 % silk proteins [42, 43]. Silk protein consists of 18 amino acids, many of which have strong polar side chains like hydroxyl, carboxyl and amino groups. Its high hydrophilicity with a moisture regain value of 11 % is due to the high content of serine and aspartic acid (approximately 33.4 and 16.7 %, respectively). Silk fibre made of fibroin has many end uses—such as textile fibres and in medical, industrial and cosmetic applications—because of its unique properties such as durability, water absorbency, dye affinity, thermo-tolerance, lustre, softness, smoothness and insulation. India is the second largest producer of raw silk after China and the largest consumer of silk-based fancy products [44]. It is an important raw material for producing precious fabrics, parachutes, tyre-lining materials, artificial blood vessels and surgical sutures [45]. The manufacture of lustrous silk from the dried cocoons of silkworm involves separating fibroin from sericin by a degumming process; the sericin is mostly discarded in the wastewater.

Sericin, which until recently was considered a waste product of the silk-processing industry, is now an important industrial material for food, pharma, cosmetics and textile end applications because of such properties as excellent moisture absorption and release, UV resistance, cell protection and wound healing; it is also used in anticancer, anticoagulant and antioxidant activities and in the inhibitory action of tyrosinase [46, 47].

### 5.1.3 Pashmina/Cashmere Fibre

Animal fibres (hairs) have special attributes such as fineness, softness and lustre that are rarely associated with any other vegetable cellulosic or lignocellulosic fibres. In addition to providing softness and lustre to the product, exotic hair fibres in many cases carry an elegance value. Based on the fineness and physical attributes of the hairs obtained from the goat family, they have been classified as mohair/angora, cashmere/pashmina, cashgora (crossbred) and guard/goat hair [48]. Pashmina, popularly known as "cashmere", is well known for its fineness, warmth, softness, desirable aesthetic attributes, elegance, fashion, whiteness and unique hand compared with sheep wool [49, 50]. It is a more luxurious, softer and warmer fibre than superfine merino wool. The word "pashmina" comes from *pashm* meaning "soft-gold" in the local language and "wool" in Persian. It is composed of 18 amino acids with alpha-keratin arranged in a helical structure akin to wool [50]. The amino acid composition is very similar to wool except for the presence of cystine, tyrosine (12 % more than wool) and proline (9 % less than wool). The fibre has the ability to add warmth to the fabric without addition any weight. Of the various protein fibres, pashmina is the finest animal fibre; it is produced in fairly large quantities. Pashmina consists of down fibres from the undercoat hair of the domesticated goat *Capra hircus*, which is indigenous to Asia. It is always mixed with coarser outercoat fibre better known as "guard hair". Worldwide production of pashmina fibre is about 10,000–15,000 t/yr. The major producing countries are China (70 % share), Mongolia (20 % share), Iran, Afghanistan, Pakistan, Nepal and India. India produces about 40–50 t/yr, which is less than 1 % of total cashmere production. Indian cashmere fibre is 12–13 μm in diameter, 55–60 mm in length and available in white, gray and brown colours [49]. The proportion of undercoat to guard hair is 40–50 %.

The quality of cashmere fibre produced in different countries differs significantly. The fibre is properly known by its origin—for example, Mongolian, Chyangara (Nepal) and Australian cashmere [10, 50]. The fabric is usually hand woven and made from hand-spun yarn. A specially designed ladies' woven shawl with unique embroidery work can cost as much as INR10,000–50,000 (US$147–737). Moreover, there is demand in international markets. The fibre is used to produce different fashionable textiles with functional attributes such as knitwear, scarves, shawls, blankets, gloves, hats, woven fabrics and overcoats (Fig. 7). The hair obtained from Indian Changthangi and Chegu breeds of goat is distinctly called "Pashmina fibre" or "Indian Cashmere", due to its fineness (10–14 μm), softness

**Fig. 7** Value-added pashmina shawl [48]

and warmth [48]. It is one of the costliest fibres and mostly used for the production of high-end fashion garments.

### 5.1.4 Angora Fibre

Angora rabbit fibre is considered one of the world's finest luxury fibres owing to such properties as extreme warmth, excellent whiteness, very good lustre, soft silky touch and lightness. Most products made of angora fibre are very expensive, reflecting the laborious harvesting process and the small number of producers [51, 52]. It occupies third place in animal fibre produced in the world after wool and mohair [52]. It is no secret that the world's softest garment fibre comes from the Angora rabbit [53]. Quiet and calm by nature, these animals have been used for fibre harvesting for hundreds of years and are thought to have originated in Turkey. The fibre is 10–20 µm in diameter and 40–70 mm in length and has air-occluded cavities that ensure high thermal insulation. Longitudinal and cross-sectional scanning electron micrographs of Angora rabbit hair show that it is somewhat scaly but has a smoother surface structure with a prominent medulla [54]. Similarly, the lower density of 1.15–1.18 g/cm$^3$ makes it a better choice than wool (1.33 g/cm$^3$) and cotton (1.54 g/cm$^3$) fibres for making lightweight clothing and fashionable luxury garments [53]. Angora garments are very lightweight, extremely warm and soft, hence their use in trimming sweaters and the knitting of hats and scarves.

### 5.1.5 Yak Fibre

Yak is one of the world's most exotic specialty rare animal fibres. The total yak population is about 14.5 million [55]. Yak herds are found in mountainous regions of Afghanistan, Bhutan, Mongolia, Russia, China, India, Kyrgyzstan, Tajikistan and Nepal on the Central Asian plateau. Mongolia has the second largest yak population in the world followed by China [54, 56]. Yak skeleton hair and down fibre are seasonal in nature; abdominal and tail hair fibres are gradually shed and replaced by new ones, ensuring the thermal balance of the body during cold seasons. Fine yak hair is very similar in appearance and fineness to cashmere and has good crimp and tensile strength (9.18 cN/tex) [55]. There are four different colours of yaks, hence yak fibre can be black (68.5 %), brown (16.9 %), blue (8.9 %) or white (5.7 %) [56, 57]. Yak hair, a rare resource of specialty animal fibre, is mainly produced in China. Fibre yield (hair) is about 410,000 t/yr; 10,000 t of which is fine hair. Yak fleece also contains a large amount of coarse hair/fibres that are quite thick and stiff [58]. Each yak produces about 100 g of down fibre annually and the fibre comes in a few natural colours, of which white is the most valued [56]. The quantity of yak fibre produced depends on factors such as the sex, age and breed of the yak [59]. The coat of the yak is composed of three types of fibre varying significantly in appearance and characteristics [59]. The proportion of different layers varies throughout the seasons. Coarse-grade fibre (79–90 μm) forms an outercoat of long hair, mostly used by nomads in tent making—which characterizes the appearance of the yak. Down fibre—the finest fibre (16–20 μm) generally shed by the animal during late spring/early summer—is suitable for textile application. Middle-grade fibre (20–50 μm) is naturally strong (but not as strong as the outer layer) and mostly utilized in making ropes and tents. Consequently, decreasing the diameter of the fibre would be a good way to improve the economic value of yak hair. Stretching slenderization is a means of modifying animal fibres which involves chemical treatment and physical drawing of fibres. Yak hair fibre has been utilized by nomads in the Transhimalaya for over a thousand years to make clothing, tents, ropes and blankets. Recently, the fibre has also been used in the garment industry to produce premium-priced clothing and accessories for well-known companies/brands like Louis Vuitton and British heritage brands like Dunhill, Eileen Fisher and Vince. Since the mid-20th century, material science experiments into yak fibre have been carried out whetting the appetite of the garment industry for yak wool, by proving its exotic nature and favourable performance attributes, making it an attractive alternative to cashmere fibre.

## *5.2 Protein Fibre–Blended Fashionable Yarns and Fabrics*

### 5.2.1 Cashmere–Polyvinyl Alcohol Fibre Blends

The limited availability of specialty cashmere fibre has resulted in most of it being utilized locally. Yarns are made with the help of specially designed manual spinning wheels, locally known as *charkha* or *yander* [50]. The fibre available in India is 12–13 μm in diameter and 55–60 mm in length and comes in white, grey and brown colours [49]. Harvested fibres are traditionally spun by manual spinning wheels producing yarn of R 25/2 tex, suitable for making lightweight shawls. The proportion of undercoat to guard hair is 40–50 %. It is very difficult to spin cashmere fibre mechanically (rather than manually) owing to problems associated with softness, shortness of fibre length and slipperiness which creates lapping during the carding and spinning processes, in addition to generation of high static charges [60]. Several attempts have been made to spin cashmere wool mechanically after incorporation of another fibre, known as a “carrier fibre”. One such method is blending either with nylon or water-soluble polyvinyl alcohol (PVA) fibres for spinning on a worsted-spinning system, followed by weaving. The carrier fibre is then removed to manufacture high-end fashionable textile products. The carrier nylon or PVA fibre is removed from the fabric by treating with hydrochloric acid or hot water, respectively. The PVA-based process was considered to be more eco-friendly than the nylon-based process; however, the whiteness and hand properties of such fabrics were inferior to the latter process [49]. To improve the problem of whiteness and hand an alternative method was developed, in which dilute sulphuric acid was used in place of hot water to remove PVA component fibre. Thus, it was possible to enhance the whiteness index by 28 % and the hand index by 20 % compared with the hot water-based process. Traditionally, pashmina was also manually wound on a small flange bobbin known as a *parota.* Sizing of the yarn was carried out in hank form using *saresh* (a collagen and fat-based glue) as an adhesive to improve weavability; the weaving of pashmina yarn shawls was carried out in a special type of handloom [50].

### 5.2.2 Angora Fibre Blends

Despite the many positive attributes of angora fibre, its full potential has yet to be reached. The reason for this is the outer surface of the fibre is very slippery, making it challenging for yarn spinning. Hence, it is most often blended with other cellulosic or protein fibres such as wool, mohair, cotton or silk for spinning, followed by production of fashionable garments, winter clothes and underwear. Besides the production of cotton/polyester blends, Indian fine short Angora rabbit hair (11.1 μm, 32.3 mm) has been blended with cotton (30:70) for production of yarn with low-shrink properties [61]. Softness and an elastomeric feel is brought about by microderm softening [62]. Such fabrics are primarily used for making such items as sweaters, mittens, baby clothes, shawls and millinery (Fig. 8) [51]. In this regard,

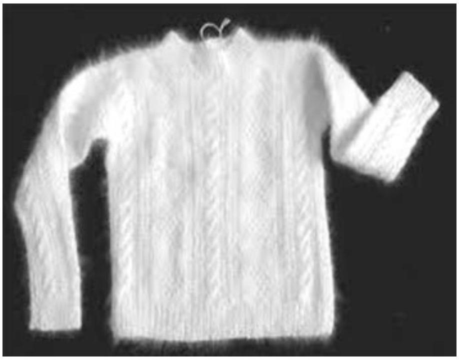

**Fig. 8** Sweater made from Angora rabbit fibre [53]

Chattopadhyay et al. reported the blending of Angora rabbit fibre with cotton fibers. The softer feel and low-shrink properties of cotton/angora fibre–blended knitted fabrics were found to be suitable for women's underwear and children's wear [52, 61]. Some commercial blends of angora knitting yarns are:

- 70 % angora, 30 % nylon
- 50 % angora, 25 % merino wool, 25 % polyester
- 40 % angora, 50 % wool, 10 % nylon
- 70 % angora, 30 % silk
- 50 % viscose, 25 % nylon, 15 % angora, 10 % wool

To produce 100 % Angora rabbit yarn the fibre surface needs to be modified so as to introduce crimps or roughness on the surface. With this in mind, the National Institute of Design (NID), Ahmedabad (India) in collaboration with Institute for Plasma Research (IPR), Gujarat (India) developed a prototype atmospheric pressure plasma treatment for angora fibres. The treatment between 1 and 10 min could enhance surface friction. Plasma—an ionized gas composed of ions, electrons, protons and UV light—were used to increase the coefficient of friction from 0.10 in the untreated sample to 0.30 in the 1-min air plasma–treated sample [63–65]. This modification enables the production of 100 % angora fibre yarn that can be used to produce stoles, shawls, scarves, caps, sweaters and multilayer products for soldiers. Attempts have also been made by other research groups to spin rabbit hair in blends with sheep wool, viscose and polyester fibres using woollen-spinning or cotton khadi–spinning systems [52]. However, very little work has been carried out into spinning this hair fibre in blends with cotton using the short-staple cotton-spinning system. Chattopadhyay et al. explored the possibilities of producing cotton/rabbit hair–blended yarns by adapting commercial cotton-spinning systems to run at economical production speeds. Hair was blended with cotton having a 2.5 % span length of 33 mm and a micronaire value of 2.9 μg/in. [52]. Samples with angora:cotton blend ratios of 10:90, 20:80, 30:70, 40:60 and 50:50 were prepared. Increasing the angora–hair fibre content in the blended yarn led to a decrease in lea CSP, breaking tenacity and elongation of both single and double yarns [52].

### 5.2.3 Wool Fibre Blends

Pre-treatment of wool fibre can modify its physiochemical and mechanical properties to meet process requirements [38]. Oxidizing or reducing agents are frequently applied to wool to make it reactive, so as to ensure effective and uniform post-treatment results. The effect of protease/lipase enzyme pre-treatment, followed by polysiloxane-based combination finishing to enhance the hand properties of wool–cotton union fabric has been studied by Ammayappan and Moses [40]. It was observed that both enzymes could improve the hand of the union fabric, which could be further improved by different polysiloxane formulations.

### 5.2.4 Yak Fibre Blends

Coarse-grade yak (guard) fibre does not contribute much to the production of value-added products and little has been reported in the literature. This may be due to the stiffness of guard fibres and/or the slippery surface of yak hair, posing challenges to the production of yarn, either from 100 % yak fibres or as a major component in blended yarn. Moreover, yak fibre—either as fine/down or coarse/guard hair—has not been blended with jute fibre with the objective of developing jute-blended yarn and fashionable fabrics using the jute-spinning system. With this in mind, NIRJAFT, after several initial attempts, developed an 8-lb 50:50 jute (unbleached):yak guard fibre–blended yarn that can be converted into a plain woven fabric (Fig. 9). Yak is one of the few exotic fibers that tempts shoppers who have grown weary of ubiquitous cashmere [66]. Recently, the British luxury brand Alfred Dunhill introduced a small collection made of yak wool blended in equal parts with merino. Other well-known brands that have developed yak wool collections include Eileen Fisher and Vince [59]. As a result of natural high strength and coarseness the guard hairs are typically carded and then worsted spun [67]. Multiple plies of guard hairs can then be braided into ropes, halters and belts or weaved into very durable rugs and bags. In contrast, down fibre with a diameter of 14–16 µm is very soft and comparable with cashmere or camel fibre; it is processed into sliver and roving and then spun into yarns for the exotic fibre market.

Tibetan cloud worsted is a precious, natural yarn spun from Tibetan yak down fibre. It is a plied, uniform, very soft yarn that is manufactured in heather colours [68]. It is suitable for all kinds of knitwear and accessories, including men's and babies' clothing. Different premier clothing textiles made of yak down fibre blended with other natural fibres are also available: typical blends are 70 % mulberry silk/30 % yak down hair, 50 % mulberry silk/50 % yak down hair, 70 % Tibetan yak/30 % baby camel and 75 % Tibetan yak/25 % bamboo viscose.

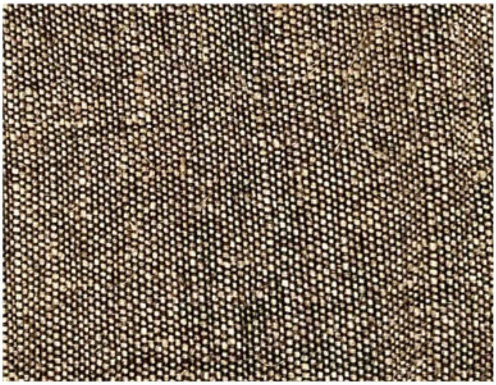

**Fig. 9** Jute/Yak fibre–blended woven textile

# 6 Sustainable Colouration of Textiles

## *6.1 Sustainable Dyeing and Printing Using Natural Dyes*

### 6.1.1 Lignocellulosic Textiles

Natural dyes have been used for colouring food products, leather goods, protein fibres like wool and silk and cellulosic and lignocellulosic fibres since prehistoric times [69]. With the advent of widely available and cost-effective synthetic dyes with moderate to excellent colour fastness properties since 1856, natural dyes were slowly replaced with synthetic colours. Synthetic dyes presently are mainly used for colouration of jute and other textile substrates in the production of value-added textiles and other diverse products due to such advantages as wide colour range, different categories of dyes, mordant-free processes and availability in large quantities [70]. Dyeing such textiles with synthetic dyestuff is sometimes characterized as having a highly negative impact on the environment and its users. The use of natural dyes for the colouration of textiles worldwide has mainly been confined to craftsmen, small-scale/cottage-level dyers and printers, small-scale export houses, and producers dealing with high-valued eco-friendly textiles and sales [69]. In the recent context of health and safety, eco-concern, sustainability, carbon footprints and global warming, natural dyes and dyed textiles are once again in market demand by eco-concerned users. Therefore, the use of natural dyed textiles is steadily increasing owing to being environment friendly, having effects that are relatively less toxic and less prone to allergens, availability of a large plant base, and additional functionalities like UV protection and antimicrobial activity [60, 70]. In the case of jute fabric, some attempts have been made to elucidate the fundamental aspect of natural dyes as well as to enhance its washing and light fastness properties using several metallic mordants [69, 71]. However, little work has been reported into the application of combinations of bio-mordants and chemical mordants, and their efficacy on different fastness properties, evenness of dyeing and colour yield. Chattopadhyay et al. reported the application of natural dyes extracted from four common natural dye sources: manjistha (*Rubia cordifolia*), annatto (colouring from the seeds of *Bixa orellana*), ratanjot (*Onosma echioides*) and babool (*Acacia nilotica*). Samples were mordanted by single/double-mordanting processes using bio-mordants and chemical mordants. Bio-mordanting followed by chemical mordanting resulted in substantially improved uniformity and evenness of naturally coloured dyed jute fabric, higher K/S (colour strength) value, good to excellent wash fastness and moderate to good light fastness [70]. Pan et al. reported the application of natural colour in bleached and ferrous sulphate–mordanted jute fabric using deodara leaves (*Cedrus deodara*), jackfruit leaves (*Artocarpus integrifolia*) and eucalyptus (*Eucalyptus globulus* L.) [72]. Even deeper shaded samples exhibited good washing fastness. Grey jute fabric was bleached by grey bleach, scour bleach and grey ambient bleach to produce a white fabric prior to dyeing with direct and reactive dyes. White and dyed jute fabrics were padded with a finishing formulation comprising resin, softener and non-ionic surfactant, followed by drying and curing [73]. They found no alteration in the colour of bleached and dyed jute fabrics, before and after such value-added finishing.

Similar to the dyeing of jute fabric with natural dyes the printing of bleached jute fabric with natural dyes has also been explored after extracting the dyes using an aqueous extraction method. Scoured and bleached jute fabrics were padded with potash alum/ferrous sulphate and dried [74]. The fabric was then printed with a print paste consisting of thickener, urea and natural dye, followed by drying and steaming at 110 °C for 3 min. The printing of single- or double-mordanted jute fabric using manjistha and annatto dyes was found to be encouraging. Natural dyes when used in powder or paste form produced a better result. Wet- and dry-rubbing fastness values were found to be excellent in the case of printed jute fabric with manjistha and good in the case of annatto.

### 6.1.2 Cellulosic Textiles

Dyeing textiles using natural dyes is an ancient craft in India; however, it received a setback from growing research in Europe into textile coloration using synthetic dyes. Presently, a large number of synthetic dyes are used for colouration of cotton textiles, a few of which are carcinogenic in nature, as they are derived from petrochemical products [75]. Various synthetic dyes—such as reactive, direct, disperse, acid, basic, vat, sulphur, napthol and metal complex—have been developed and the efficacy of such dyes on natural and man-made textiles in terms of shade depth, number of shades, colour consistency, economy and wash durability has been thoroughly studied. Moreover, various natural dyes imparting such colours as yellow, red, blue and black are available in the market and used to produce fashionable textiles. Yellow-coloured natural dyes are extracted from turmeric, carotenoid and annatto—used to impart yellow shades to cotton textiles. The orange flowers of tesu (*Butea monosperma*), onion (*Allium cepa*) skins and marigold (*Tagetus patula*) have also been explored to see how effective they are at imparting yellow colours to cellulosic textiles. In all these cases, it was noted that mordanting was essential [76]. During the dyeing of pre-mordanted cotton with fabric marigold flower and pomegranate (*Punica granatum*) peel the dyed fabric showed adequate antimicrobial properties, in addition to imparting on attractive yellow colour [77]. The natural red colour imparted to cellulosic textiles could be produced without any mordanting of the fabric. In this regard, carthamin from safflower (*Carthamus tinctorius*) petals and bark extracts produced a strong red colour with good fastness properties. Root extract of ratanjot, Indian madder (*Rubia cordifolia*) and European madder (*Rubia tinctorium*) also imparted a similar attractive red color due to the presence of carthamin [78]. Plant extracts that contain a high amount of tannin generally produce brown to black shades. Similarly, catechu (*Acacia catechu*) imparts a dark brown colour to cotton fabric. It has been reported that—apart from tannic acid—tannin also contains catechin and quercetin that act as an astringent and antioxidant. Similarly, Wannajum and Srihanam reported on natural dyeing of bamboo fibres with indigo [6]. Fibres dyed with indigo revealed a good level of light and sweat fastness.

### 6.1.3 Protein Textiles

Besides its utilization for traditional textile products, wool is also used for the production of various fashionable garments. Wool and silk—being protein fibres—contain amine and carboxylic acid groups. Unlike silk, aqueous solutions of wool contain no net charge due to the presence of equal numbers of positively and negatively charged molecules. Presently, a large number of synthetic dyes are used for colouration of woollen textiles; however, in recent years the application of natural dyes to protein fibres has increasingly met the demand for green fashion. Therefore, the selection of mordants, dyeing time, temperature and pH during the colouration process using natural dyes play critical roles. Tannin-rich materials—such as harda and gallnuts—and metal salts—such as alum, aluminium sulphate and ferrous sulphate—are suitable for mordanting protein fibres. After mordanting at 80–90 °C with 5 % mordant for 30 min the fabric can be dyed under acidic conditions at 60 °C for 30 min, with a material:liquor ratio of 1:25 [79]. Mogkholratasitt et al. (2011) reported on the dyeing of protein wool fibre using leaf extract of eucalyptus, which contains tannin and quercetin as chromophoric colour materials [80]. Various kinds of natural mordant combinations—such as lemon juice and stannous chloride, lemon juice and ferrous sulphate, lemon juice and copper sulphate—have also been attempted for the natural dyeing of woollen textiles. Dyed wool fabric mordanted with those compounds exhibited better light and wash fastness. Pashmina yarns/fabrics have also been dyed using natural dyes obtained from varying sources to produce different colours: for example, annota seed for red, indigo for blue and henna and myrobolan (*Terminalia chebula*) for yellow and brown [50]. Color from babool bark has been extracted and its efficacy for woollen textiles studied [75]. Colourant extraction was found to be higher in slightly alkaline media than aqueous, acidic and alcoholic media. Similarly, alkaline extracted samples showed higher K/S values with very good fastness to light and washing than those of other media. Dried extract in different media imparted different shades of brown and grey to woollen yarn, both in mordanted and non-mordanted samples.

## *6.2 Camouflaged Fashionable Textiles*

Active camouflage entails blending into the visual surroundings present in nature as done by several groups of animals including cephalopod mollusks, fish and reptiles. Two principal factors are responsible for the active camouflage effect in the animal body. The first is counter illumination and the second colour change [81]. Efforts have been made in the past to impart such camouflage effects to textile substrates to produce fashionable textiles. Camouflage is frequently used for defence applications—such as military dress, vehicles and helicopter painting—for safety and security purposes. It is worth mentioning that CSIRO (Commonwealth Scientific and Industrial Research Organisation) scientists have developed camouflage military fabrics by mixing different dyes that reflect visible, UV and infrared light in such a way as to mimic the reflectance spectrum of backgrounds such as plants, soils and buildings. It works best when reflected light from a fabric matches background reflection [81]. Zhang et al. (2007) studied four different vat dyes to measure the camouflage effect they had on the fabric. Application of 1–2 % C.I. Vat Blue 13 dye plays an important role in green camouflage as fabric reflectance matches the reflection of green leaves [82]. (C.I. stands for Colour Index™.) The visual effect of camouflage could be changed by altering cotton fabric construction. Recently, Goudarzi et al. (2014) reported camouflage effects on cotton fabric in the visible and near infrared (NIR) region using three different vat dyes—C.I. Vat Blue 6, C.I. Vat Yellow 2 and C.I. Vat Red 13—to get a reflectance curve similar to the green of forest leaves and NATO green shades [83]. Tulip Ltd provides a tie dye T-shirt in camouflage colours to provide a stylish fashionable look. The flat work surface of the fabric is covered and then a suitable mixture of kit colours are applied until it is saturated, followed by color fixation on the fabric for 6–8 h while it is still moist [84]. It is also possible to make a person invisible by finishing the garment with highly reflective material. The first research into this area was initiated in the 1960s by Harvard University and the University of Utah in the USA [85].

## *6.3 Natural Pigmented Cotton*

Naturally pigmented or coloured cotton and the fine fabrics made from them for nearly five millennia in Peru probably constitute the oldest record of yarn spinning and weaving in human history [86–92]. Naturally coloured cotton is believed to have originated in America around 5000 years ago when plants were selected for different natural colours (red, green, brown and tan) other than the normal yellowish off-white. The vast array of naturally coloured cotton has been well documented since the time of the New World explorers. There were originally shades of cotton ranging from brown, dark green, black, red and blue. The natural color of cotton fibre comes from natural pigments such as caffeic acid and cinnamic acid that are deposited in alternating layers with cellulose on the outside. These varieties of cotton were widely used by Native American people. However, coloured cotton later became obscure and unavailable to markets, as farmers and manufacturers found them difficult to spin mechanically owing to their shorter staple length. The colour attributes of cotton fibre solely depend on the plant genotype and on manipulating plant genes. In India, it has been possible to produce red, green and brown shades in recent years [86–92]. The green attribute, less common than brown, occurs in two shades: light green and green. Green is not only more prone to fading than brown—it fades faster too. Prolonged exposure to sunlight during boll opening leads to rapid fading of green and finally leads to a white, off-white or brownish colour. On the other hand, the portion of lint not directly exposed to sunlight retains its original lint colour. Green is mostly observed in *Gossypium hirsutum*. To date, naturally pigmented cotton is not considered an industrial crop in India and little research in this area has been undertaken possibly due to lower farm yields. Growers are usually paid a higher price because of the lower yield of such fibre. In 1993 the coloured cotton price was in the range US$3.60–4.50 per pound compared with conventional white cotton in the range US$0.60–0.90 per pound.

Nevertheless, coloured cotton plants have higher resistance to pests and do not need any toxic pesticides. Thus, coloured cotton is also known as "eco-friendly cotton", hence it can be used for the sustainable fashion industry. Moreover, by virtue of possessing intrinsic colour the fibre does not require post colouration such as dyeing or printing. Therefore, the colouration process could also be considered sustainable by meeting the requirements of green fashion and environmental pollution norms. Despite its several advantages, coloured cotton is still not well accepted in the traditional market as a result of challenges in spinning finer count yarn from low fibre quality as well as the low availability of desired shades. Unlike conventional cotton, natural coloured cotton does not fade during laundering. On the contrary, its colour is reported to improve and become stronger. Naturally pigmented cotton, especially green cotton, has excellent sun protection properties with higher ultraviolet protection factor (UPF) values than conventional bleached or unbleached cotton. Compared with white cotton, it has been observed that brown cotton exhibits excellent antibacterial properties, with a bacterial reduction rate of 89.1 and 96.7 % against well-known gram-positive and gram-negative bacteria (Staphylococcus aureus and Klebsiella pneumoniae), respectively.

As already mentioned, naturally coloured cottons, such as brown- and green-coloured cottons, have been grown and used by humankind for some 5000 years. Coloured lint samples recovered from coastal areas of South America have been dated to 2500 BC. In India, brown, khaki and red cottons were commercially grown in specific locations like Rayalseema in Andhra Pradesh and exported up to the 1950s. Even the world-famous Dacca muslin was woven using white and coloured cotton lints. These coloured cottons suffered the drawbacks of low yield and poor fibre quality. Hence, their cultivation was abandoned, and they were eventually replaced by white cottons of higher yield and superior fibre quality. When Europe and the USA started demanding cotton textiles free from harmful dyes and pesticide residues, there was a revival of interest in organic cottons and naturally coloured cottons. Subsequently, commercial cultivation of coloured cottons was started in the USA. Indeed, owing to this renewed interest, agricultural scientists in India began trials for new coloured cotton in 1995 as part of the All India Coordinated Cotton Improvement Project (AICCIP) [87]. Assessments of such cottons for spinning potential as well as yarn and fabric characteristics are necessary to improve fibre quality. The trials highlighted the spinnability of a number of coloured cottons developed indigenously [87]. Moreover, trials looking into full-scale spinning, weaving and knitting as well as into yarn and fabric characteristics have also been undertaken. Coloured cotton was found easy to open, clean and draw due to having a higher wax content on the fibre surface, but produced inferior-quality yarns than white cotton of equivalent length, quality, fibre maturity and higher wax content. Thus, the spinnability of such cotton was limited to 24 s Ne (24 tex) maximum as a result of having a shorter fibre length (24–25.8 mm), smaller uniformity ratio (44–48) and lower micronaire value (2.7–6.1). It was found that naturally coloured cottons are best utilized in preparing fabrics, along with white cotton, to produce attractive stripe and check effects.

Despite having many environmental advantages, there are limitations to coloured cotton. It is simply not viable owing to low yield, poor fibre quality, limited colour range and limited market demand [89]. The Central Institute for Cotton Research (CICR) in Nagpur (India) and several other state agriculture universities began in 1990 looking into finding ways of improving fibre length, strength, maturity and yield in 1990. Similarly, the Northern India Textile Research Association (NITRA) began cultivating camel brown and olive green naturally coloured cottons of *Gossypium hirsutum* in its fields along with white cotton (J-34 variety). This led to various fibre and textile properties being evaluated and compared [90]. It was found that fibre length and strength of coloured cotton were inferior to J-34 (white cotton). Fibres were subsequently converted to 1/3 twill fabric of white ring-spun yarn (8 s) as warp and 8 s blended weft yarn (white and colour blended). Post-scouring, it was found that untreated samples of coloured cotton fabrics showed greater colour depth than treated samples. This may be attributed to leaching of the natural colour pigment on washing. There was a drastic change in colour on treatment with hydrogen peroxide in both the green and brown cotton samples. Post-treatment, all the brown-shaded fabrics turned white with a whiteness index of 80–84, comparable with the index (86) of white cotton. The same value for green cotton was 74–84. No difference in colour fastness to light was found both pre- and post-treatment in the case of white cotton. On the other hand, coloured cottons had a moderate light fastness rating (2–3) which could be improved to 4–5 after applying various chemical formulations. However, wash fastness in terms of staining on white fabric of the same was fairly good (3–4). As above, after treatment with suitable chemicals it was possible to improve colour fastness to washing in terms of change in shade, whereas staining on white cloth did not show significant change. Significant research has been carried out in this area at Central Institute for Research on Cotton Technology (CIRCOT) in Mumbai (India) where various fibre parameters, yarn properties and textile performance were evaluated in terms of washing and light fastness. It was found that coloured cotton contained more wax than white cotton. Other fibre properties like moisture regain, scouring loss and degree of polymerization remained similar to those of normal cotton. It was observed that scouring generally reduced colour intensity by 20–40 %, while soap washing led to an improvement in colour intensity of 25–50 %. The micronaire value of green- and brown-coloured cotton was in the range 3.4–4.1 and tenacity 32.1–36.0 g/tex for those qualities of the fibres. The advantages of natural coloured cotton are:

- Being naturally coloured, no additional dyeing is required and the process is considered eco-friendly and sustainable.
- Some varieties are inherently resistant to insects and disease and thus require fewer pesticides during cultivation.
- It has drought and salt tolerance properties.
- Fabric made of naturally coloured cotton exhibits excellent UV-protective and Sun-protective properties.
- Fibres made of coloured cotton exhibit good antimicrobial properties.
- Growers are normally paid higher prices for cultivation.

The disadvantages of natural coloured cotton are:

- Fibre spinning is challenging owing to shorter fibre lengths, hence it is normally blended with white cotton. Such hybrid yarns are used by brands like Levi Strauss, L.L. Bean, Eileen Fisher and Fieldcrest for making clothes (e.g., khakis).
- It needs to be grown at isolated farms so as to avoid any contamination with white cotton.
- It has poor light and washing fastness.

## 7 Textiles with Fragrance-Imparting Finishes

Globalization has resulted in people being increasingly busy in their personal and professional lives. Subjected to a raft of time-bounded responsibilities, they frequently get stressed physically and mentally. To keep stress manageable and live a healthy and relaxing life, they normally resort to exercise, yoga, leisure and trips to the spa; sleep of course is important too. Luxurious clothing and home textiles can play important roles by imparting a fresh, healthy and hygienic feel to the wearer and user of such textiles. As a result of repeated everyday use, home textiles, clothing, T-shirts, socks, bed linen, pillow covers and bed sheets do not remain fresh. Moreover, textiles constantly exposed to sweaty, hot and humid conditions offer favourable conditions for microbial growth leading to bad odours. A solution would be to get plant extracts/plant molecules/bio-molecules or synthetic chemicals that impart fragrance by incorporating them in textile products. This could provide users with pleasant and fresh surroundings by masking bad smells. Aroma is mostly composed of oils extracted from plant products and synthetic materials consisting of large aromatic molecules. Market demand for high-value, aroma-imparting, fashionable textile products is being met by Bombay Dyeing & Manufacturing Co. Ltd, which has launched a new collection of aroma-based textiles imparting a pleasant and refreshing fragrance to bed linen and decor in living rooms and bedrooms, providing much-needed relief to otherwise busy lives. They also have a collection of luxurious bed linen made of high thread count, soft cotton satin smelling of natural lavender, jasmine and rosewater which revitalizes the senses and rejuvenates the soul. Furthermore, perfumed bed linen helps to relieve mental stress, while ensuring comfortable sleep. Such finishes are applied to textiles by microencapsulation which facilitates the slow release of fragrance for lengthy periods of time. The actual use of such textiles results in the breaking of microcapsules owing to pressure or friction and the diffusion of fragrance molecules into the air, making the surroundings fresh and pleasant [93]. Similarly, Scottish researchers have developed a microencapsulated aroma-therapeutic luxury textile that is highly beneficial for cancer patients; it involves airtight hard-shell capsules containing a particular type of aroma which have been shown to alleviate the side effects of chemotherapy and radiotherapy [94]. Functional textiles can be obtained using newly engineered fibres or by incorporating functional agents in conventional fabrics. Microencapsulation is effective at protecting these functional agents from reactions with moisture, light and oxygen. If a fabric is treated with microencapsulated functional agents, such as an aromatic essential oil, the durability of such finishing is expected to be higher [95]. Specos et al. reported the development and post analysis of two types of microcapsules containing essential oils for application to cotton fabrics [95]. A lemon-perfumed essential oil encapsulated in GAM increased fragrance durability in cotton fabrics compared with non-encapsulated essential oil that could only withstand one washing cycle. Electronic nose analysis is an objective and adequate method for monitoring the fragrance released from microcapsules.

Jasmine, lavender and sandalwood are the preferred aromas for textiles and home furnishings; they contain active ingredients like santalols, fusanol, santene, teresantol, benzyl acetate, linalool, linalyl acetate, benzyl benzoate and geraniol [96, 97]. Besides their mind-blowing fragrance, these materials help in revitalizing the immune and central nervous system, skin nourishing, smoothening of facial lines and wrinkles, cell regeneration and are used as an antidepressant and antiseptic agent. The absorption of such molecules from different herbs into the bloodstream improves blood circulation and inhalation by clearing the throat and lungs. Clevertex has developed bath towels finished with seaweed extract and ZnO, which have been directly incorporated into the inner structure of fibres. Towels finished in this way provide comfort and relief from stress and their functional attributes are unaffected by repeated washing and wearing. Additionally, such finishes possess good antimicrobial and liquid absorbency properties resulting in a product that is comfortable and odour-free [98]. An Andrew Morgan's collection of USA recently introduced a novel aromatherapy-infused eco-friendly textile, in which tiny polymeric microcapsule shells impart a long-lasting unique fragrance when diffused in the air [99]. In similar vein, Prince Kataria Textiles has launched a high thread count, luxurious, soft-cotton, satin bed sheet that is lightly fragranced with the pleasant aroma of natural products. This kind of aroma-embedded fabric ensures relaxation and comfortable sleep [100].

# 8 Sustainable Healthcare and Skincare Textiles

## *8.1 Healthcare Textiles*

Antimicrobial health and hygiene attributes have been incorporated in textile substrates to control bacteria, fungi, mold, mildew and algae, as well as their associated side effects such as product deterioration, staining, odours and related health issues [101]. Hospital textiles—such as theatre drapes, gowns, masks, sheets and pillow covers—are known to be major sources of cross-infection, hence the textiles used in their manufacture need to be dressed with antimicrobial treatments prior to their use in hospital, so as to prevent or minimize the transmission of infection diseases. The term "antimicrobial treatment" refers to a broad range of technologies or applications that can provide varying degrees of protection against microorganisms. Such microorganisms have a negative economic effect on producers, retailers and users of textiles [101]. Providing customized textiles economically to address issues related to human health is the natural thing to do; however, it is a key challenge facing the textile industry that needs to be addressed appropriately. As described above, various cellulosic, lignocellulosic, protein and man-made fibres are used in large quantities in the production of sustainable fashionable textiles. Natural fibres/fabrics—such as cotton, ramie, flax, jute, silk and wool—under hot and humid conditions provide a very favourable microclimate for rapid microbial growth which results in skin diseases, foul smells and reduces the service life of valuable products. Such damage can be addressed by incorporating antimicrobial, antibacterial, antifungal, rot-resistant and moth-resistant chemicals into textile substrates. Since some of these agents cause environmental pollution because of their synthetic origin, in the last two to three decades academic and industrial research has been intensified to find alternative sustainable formulations that can provide the necessary antimicrobial efficacy at a lower cost.

Many natural materials and/or bio-materials—such as neem, nanolignin, silk sericin, aloe vera, chitosan and tulasi (*Ocimum sanctum*)—have been applied for antimicrobial, UV-protective, antioxidant, 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 humankind and the environment. Plants containing phenols and oxygen-based derivatives are considered secondary metabolites that can act as antimicrobial and insecticidal agents [96, 97]. Similarly, tannins (naturally occurring polyphenols) are also responsible for the antibacterial activity of natural dyes. The antimicrobial efficacy of chitosan, aloe vera, neem, tea oil, eucalyptus oil and tulasi leaves on various natural and synthetic textiles has also been investigated. Chitosan is derived from chitin and is an effective natural antimicrobial agent due to the presence of an amine group that can easily react with the negatively charged bacterial cell wall and finally destroy it. Similarly, chitosan citrate has been explored for durable-press and antimicrobial finishing of cotton textiles. Thilagavathi et al. (2010) identified the active antimicrobial molecules in neem, pomegranate and prickly chaff flower that can control the growth of microbes

[102]. Neem leaves contain limonoid-based azadirachtin, salannin and nimbin that are actually responsible for antimicrobial and insecticidal properties in textile substrates. The combined effect of neem and chitosan in the form of neem–chitosan nanocomposites has also been utilized and applied in cotton textiles for eco-friendly antimicrobial finishing [103]. A recent patent on microencapsulation of neem oil and its application to cellulosic and blended textiles showed good antimicrobial efficacy. Joshi et al. (2007) reported the antimicrobial properties of neem seed extract on polyester/cotton–blended textiles using glyoxal, aluminium sulphate and tartaric acid in the two-dip, two-nip method on a padding machine; the treated fabric exhibited excellent antimicrobial activity against both gram-positive and gram-negative bacteria for five washing cycles [104]. Recently, Ahamed et al. (2012) developed a new method of preparing antimicrobial textiles (i.e., by herbal coating in neem extract nanoparticles) [105]. Nano herbal extract–treated textiles were found to show excellent antimicrobial activity against both gram-positive and gram-negative bacteria and the finish was durable up to 20 washing cycles, in contrast to 10 washing cycles for the neem extract–treated sample. Tulasi has been well known for its medicinal effects since ancient times and for its capacity to cure or resist many infections and diseases. Tulasi leaf extract contains caryophyllene, phytol and germacrene antimicrobial compounds; its efficacy on cotton textiles after methanol extraction has been studied. Tulasi-dyed bed sheet fabric shows good antimicrobial properties; it has been used as a bedding material for patients suffering from chest colds, coughs, itchiness and mucus problems. Sathianarayanan et al. (2010) applied tulasi leaf and pomegranate extract to cotton textiles using a number of methods: direct application, cross-linking and microencapsulation [106]. Methanol extract and pomegranate molecules showed 99.9 % reduction in bacterial growth on cotton fabric when applied directly by the pad dry method. As expected, microencapsulation and cross-linking of such formulations led to better results in terms of wash durability (15 washing cycles) of the finish. Recently, aloe vera gel—another important industrial bio-material—has been utilized on cotton textile to improve antibacterial efficacy against *Staphylococcus aureus* [107, 108]. Specimens treated with 5-gpl aloe vera gel showed excellent antimicrobial activity in terms of greatly reduced number of colonies and clear zone of bacteria inhibition. The antimicrobial finish imparted was durable to 50 washing cycles (slightly decreased to 98 %). Henna and juglone (obtained from black walnut) contain napthaquinone that acts as an antibacterial and antifungal agent. Curcumin has been used as a natural dye and an antibacterial agent for woollen textiles. Similarly, cotton textiles treated with turmeric, cumin, clove oil, karanja (*Millettia pinnata*), cashew shell oil and onion skin have shown good antibacterial properties. Such fabrics can also be used for medical purposes and casual clothing. Gupta et al. (2006) investigated the antimicrobial activity of cotton fabric treated with tannin-rich extract of *Quercus infectoria* (QI) in combination with different mordants—such as alum, copper and ferrous sulphate [109]. QI extract (12 %) on its own showed antimicrobial activity of 40–60 % against both the gram-positive and gram-negative bacteria. After application of the same plant extract to cotton textiles with 5 % alum and 1 % copper sulphate, antimicrobial activity was found to be significantly enhanced (70–

90 %). Samples treated with QI on its own lose antimicrobial activity after five washing cycles, whereas many more washing cycles could be sustained when treated with a mordant.

Ammayappan and Moses reported the antimicrobial efficacy of aloe vera, chitosan and curcumin either alone and in combination with each other in cotton, wool and rabbit hair fibres using the exhaustion method [51, 110]. Aloe vera showed better antimicrobial efficacy than chitosan and curcumin when applied on its own. It was possible to enhance its efficacy by adding both chitosan and curcumin. Application of the three antimicrobial agents together to peroxide-treated cotton and formic acid–treated wool/rabbit hair substrate was found to be durable up to 25 washing cycles. In similar vein, Raja and Thilagavathi evaluated the effect of enzymes and mordants on antimicrobial finishing of woollen textiles [111]. Akin to the mordanting process of wool fabric to improve colour fastness and dye uptake, it was found that enzyme treatment could also improve dye uptake. The antimicrobial activity of natural dyed textiles could be significantly influenced by the presence of mordant and enzyme treatments. Jute is susceptible to microbial attack under normal atmospheric conditions owing to the presence of hemicelluloses, hence it is quickly degraded by microbes; a detailed degradation study on this was performed by Basu and Ghosh [112]. Humidity, warmth, and a medium pH of 6.5–8.5 are favourable conditions for microorganisms to degrade jute, much like the case with cotton. Finishing chemicals preventing the growth of various microorganisms on textile substrates are the bactericides which destroy bacteria and fungi and bacterial state/fungal state inhibitors that inhibit their growth. The most important antimicrobial agents are phenolic compounds, quaternary ammonium salts and organometallic compounds [10].

## 8.2 *Skincare Textiles*

In recent years, wipes rather than conventional woven fabrics have increasingly been used in skincare, cosmetics, surface-cleaning and other skin applications due to their being less expensive, more hygienic, softer, disposable and more convenient to use [113]. Other benefits are smaller size, lighter weight, high flexibility and ease to use as well as being easy to carry and allowing quick action and drying [97]. Wipes are used to clean the body; treat wounds, rashes or burns; and to provide a fresh energetic feel to the skin. Wipes can be made of paper, tissue paper or non-woven fabric; subjected to mild rubbing or friction they remove dirt, oil and liquid and/or release soothing fragrances, medicinal ingredients and moisturizing agents. Wipes made of tissue paper or non-woven fabric are subsequently soaked with different skincare/nourishing products as discussed below. Superwipes made of Recron® bi-component yarn have been introduced by Reliance Industries Ltd; they are specially designed to hold a lot of water and provide improved cleaning capacity [114]. Johnson & Johnson has also marketed baby wipes specially designed to take care of the tender skins of newly born babies. It is much softer than other wipes and contains baby lotion to provide adequate moisture to the skin [115]. Aditya Birla Group has also marketed wipes under the brand name "Kara", suitable for face care, hand care, skin care and baby care [116]. These products are engineered with various natural ingredients—such as jojoba, avocado, honey, almonds, aloe vera, cucumber, mint and chamomile—for their outstanding effectiveness at preventing skin infections as well as soothing and moisturizing as a result of the presence of essential nutrients. They soften the skin; reduce wrinkles and fine lines (signs of ageing); strengthen skin tissue; keep the skin hydrated, nourished and refreshed by effectively removing dirt and excess oil; and provide antiseptic and anti-inflammatory properties. As these products are made of cellulose and finished with natural ingredients, they are completely natural, biodegradable and sustainable. Aloe vera (*Aloe barbadensis* Miller) belongs to the Liliaceae family and has been utilized for cosmetic and medical applications. It has excellent skincare properties that include anti-inflammatory and anti-ageing attributes. Kimberley-Clark Inc. Ltd. has patented an aloe vera application as an anti-ageing and moisturizing agent. In similar vein, DyStar Auxiliaries GmbH has 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 [46, 117]. Silk protein (sericin) holds a lot of potential for biomedical applications because it imparts oxygen permeability to textiles, protects cells from UV radiation and microbes and has antioxidant, moisture regulation and wound-healing properties [97, 118]. Lenzing 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 a long history of use in cosmetics and pharmaceuticals for relieving (from itching), regulating and protecting skin and for antibacterial finishing. Stockings made with Tencel C have been reported as protecting the skin, allowing it to retain more moisture, improving the skin and stimulating skin cell regeneration. Lenzing is promoting the fibre for use in clothing worn next to the skin and in home furnishings like bed sheets [119].

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 good antioxidant and moisture-binding properties. Human skin generates free radicals during exposure to the Sun and UV light, which may damage the skin. Tocopherol antioxidants act as radical scavengers, hence their use for skin ailments and for protecting skin cells from oxidative stress [120, 121]. The antioxidant properties of silk sericin have also been evaluated; radical scavenging activity was enhanced by 56 % in a treated sample compared with a control sample [46]. Natural products—such as sericin, chitosan and aloe vera—can be effectively used in the development of sustainable traditional as well as fashionable textiles, while imparting added value to such products.

## 9 Summary

Fashion can be encapsulated as the prevailing styles manifested by human behaviour and the latest creations by the designers of textile and clothing, footwear, body piercing, decor, etc. Fashion can trace its history to the Middle East (i.e., Persia, Turkey, India and China); it then gradually spread into Europe. Initially, fashionable products were only affordable by the royals or the rich; however, as civilization progressed, at least since the end of the 18th century, slowly such products became affordable to the middle classes and finally to the people of the world. With the evolution of society in the last few centuries, people have become more and more concerned about their lifestyle, fashion, health, hygiene, food and beverage, comfort, luxury, leisure and wellbeing. Until the 1950s, natural fibres—such as cotton, flax, ramie, hemp, wool, silk, pashmina and paul—were utilized in the production of fashionable textiles. Later on, many synthetic fibres—such as polyester, acrylic, spandex, viscose rayon, cellulose acetate and nylon—began to penetrate the fashion market due to advances in polymer science, material science and textile science, bringing substantial changes in fibre and fabric design and development, engineering new polymers for fibre formation, understanding and controlling fibre morphology, fibre characteristics and performance, their durability and interaction with the environment in greater depth. Fashionable textiles based on wholly natural or synthetic fibres as well as blends of both have been developed to impart the requisite fashion attributes during spinning, weaving, knitting, non-woven production and high-end chemical finishing. As some traditional textile-processing chemicals and auxiliaries have significant adverse effects on the environment, much research has taken place into sustainable fibre formation/application, dyeing and chemical finishing in attempts to mitigate issues such as global warming, environmental pollution and climate change. Since natural fibres are sustainable, they are gaining in importance for making green, ethical and sustainable eco-fashion owing to such properties as bio-degradability, renewablity, carbon neutrality, high-moisture regain, soft feel, adequate to fair strength and look good quality after chemical treatment. Naturally coloured cotton, organic cotton, organic wool, wild silk, flax and hemp are the important fibres and raw material for the sustainable fashion industry. Efforts have also been made in recent times for sustainable dyeing and value-added finishing of textiles using various plant/herbal extracts, bio-materials, bio-polymers and bio-molecules—such as enzymes, natural dyes, bio-mordants, aromatic and medicinal plants, chitosan, aloe vera, neem, lignin, silk sericin, grape and mulberry fruit extract, citrus oil, lemon oil and tulasi extract.

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