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Fundamentals of the Fibrous Materials

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1.1 Introduction

1.1.1 What Are Fibrous Materials?

A fiber is a material that is defined by Textile Institute [1] as units of matter characterized by flexibility and fineness and a high ratio of length to thickness. In different fields, fibers have very broad meaning such as those for food supplements and fibers in plants or in human body. A fiber is more often referred to the basic unit of making textile yarns and fabrics. Textile fibers should have some specific properties though. For example, cotton plant contains fibers that are strong and soft enough to be spun into yarns that can be woven or knitted into a fabric by textile processing, but human hair is not a textile fiber because it cannot fill up the above properties. So, we can say all textiles are made of fibers, but not all fibers can be used to make textiles. The important requirements for fibers to be twisted into a yarn include a length of at least 5 mm, cohesiveness, flexibility, and sufficient strength, and other important properties include elasticity, fineness, uniformity, luster, and durability. It is also important to remember that all textile fibers are not created equally [2]. Each fiber contains different qualities and will result in a different textile. Some retain heat better than others; some hold dye very well; some are more durable, while some are more comfortable [3].

The origin of fibrous materials may be of organic, inorganic, or metal. They are fine structures that are formed by joining component atoms into molecules. Fibrous materials can be grouped into two major categories: natural and chemical or man-made fibers. The growth of natural fibers is slow and controlled under genetics from fast production of manufactured fibers in terms of structures. Natural fibers include plant or vegetable fibers (such as cotton, flax, ramie, jute, and hemp), animal fibers (such as silk, wool, and hair fibers), and mineral fibers (such as asbestos). Synthetic fibers include regenerated fibers (such as viscose and acetate), synthetics (such as polyester, polyamides, polyolefins), and inorganic fibers such as glass and carbon fibers with completely amorphous or microcrystalline structures [4]. Another class is high-performance fibers that are manufactured ones with improved tensile and other mechanical properties.

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Finally, smart fibers are an emerging class of fibrous structures that are responsive to stimulus or an environment, tailored with advanced functionalities for many applications.

1.2 Historical Evolution of Fibers

Natural fibers are abundantly available in nature that are biodegradable and sustainable and have played a key role in the human race since nearly 7000 BC [5]. Human beings have been using the fibers from many ages for which there are no records, which itself is a distinct proof that fiber is present from several hundreds of years. The first choice for the human beings to use is natural fibers. Production of synthetic fibers was beginning only in 1910 by commercially producing the rayon fiber, and this was the result of technological development that has not stopped yet on the present era. Natural fibers have been used in many cultures traditionally across the globe in making utilitarian products. Fibrous materials can be obtained naturally from many resources such as plants, leaf, seeds, bark, stem, and grass. Flax is believed to be the oldest fiber and it was obtained in dates back to 6000 BC. Egyptians started to wear the cotton since 4000 BC, and later revolutionary changes occurred to discover ginning and production of different variety of cotton products. Wool fiber was also discovered around 3000 BC, and then around 40 breeds were explored to produce wide range of wool fibers. Dates back to 2500 BC, silk fiber is believed that it was first discovered by a Chinese princess that was obtained from the cocoons of silk worms. The silk processing was found to be kept secret for almost 3000 years and then started to spread all over the world in the later stage.

Even though natural fibers were comfortable and biodegradable, they had some drawbacks such as wrinkling of cotton and flax and delicate handling of silk and wool fibers receptive to shrinkage and moth attack. Growing needs of human race and these disadvantages of fibers paved the way to produce the first man-made fiber with revolutionary technological efforts into rayon, which is known as artificial silk to the present era. In the later stages, other man-made fibers such as acetate, nylon, acrylic, polyester, spandex, polypropylene, lyocell, and microfibers were produced with rapid transformation from science to market and end users around the world. The complete developments in the evolution of human civilization (Figure 1.1) and textile fiber (Figure 1.2) are presented below [6].

1.3 Classification of Fibrous Materials

A comprehensive classification of fibrous materials is depicted in Figure 1.3. Nature offers us abundant resources for getting fibrous materials that grow in various geographical locations and altitudes. Fibrous materials can be further classified into textile and non-textile fibers. The internal characteristics that are suitable for processing from fibers [7] to yarn, fabric, and other utilitarian products can be termed as textile fibers [8, 9]. However, the properties of fibers

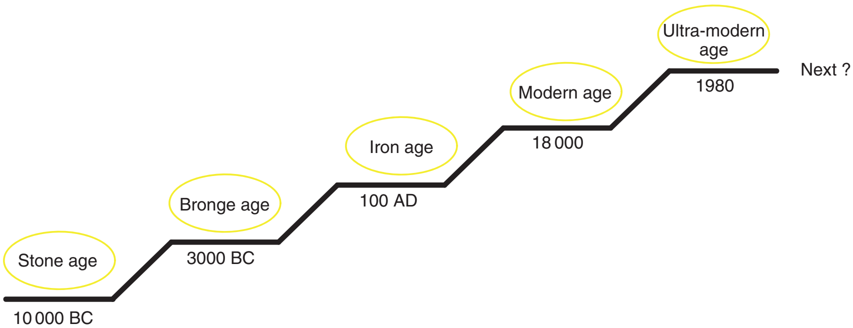

Figure 1.1 Evolution of human civilization.

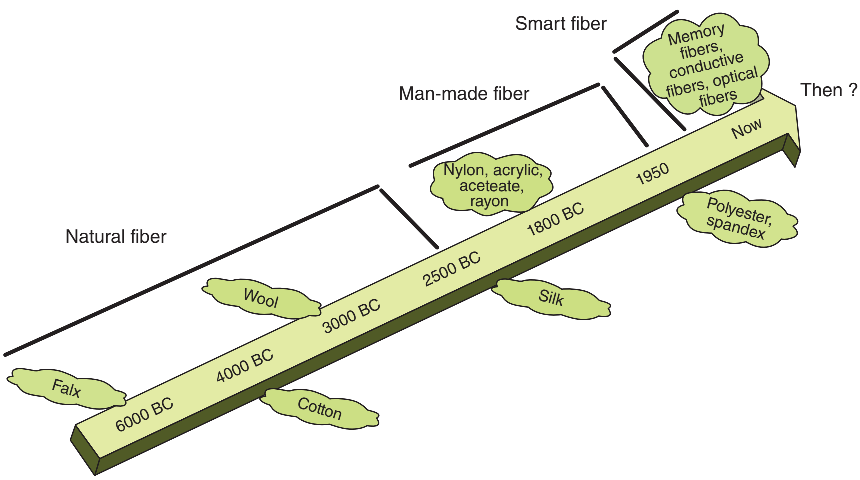

Figure 1.2 Evolution of textile fibers.

that are not suitable for clothing could be considered as non-textile fibers and have been found broad horizon of arenas to fulfill the human desired needs in many ways. Non-textile natural fibers are also used in building materials, animal and human food, ecofriendly cosmetics, agro-fine chemicals, and sources of energy.

Fibers can be classified into two major groups as natural and man-made or manufactured ones. Natural fibrous materials are basically from three origins; they are cellulosic/lignocellulosic (from plants), protein, and mineral, which is decided by the chemical composition and fiber morphology. Cellulosic fibers constitute long-chain molecule joined together with glucose rings by valence bonds and hydroxyl groups linked by hydrogen bonds in its chemical structure. Other cellulosic fibers such as flax, jute, hemp, ramie and sisal differ from cotton in various ways. Normally larger proportion of impurities contains in their structure. They are multicellular fibers composed of microscopic individual cells bonded together and running along the strands in the plant or leaf. Hair fibers are also termed as protein fibers that are morphologically formed by

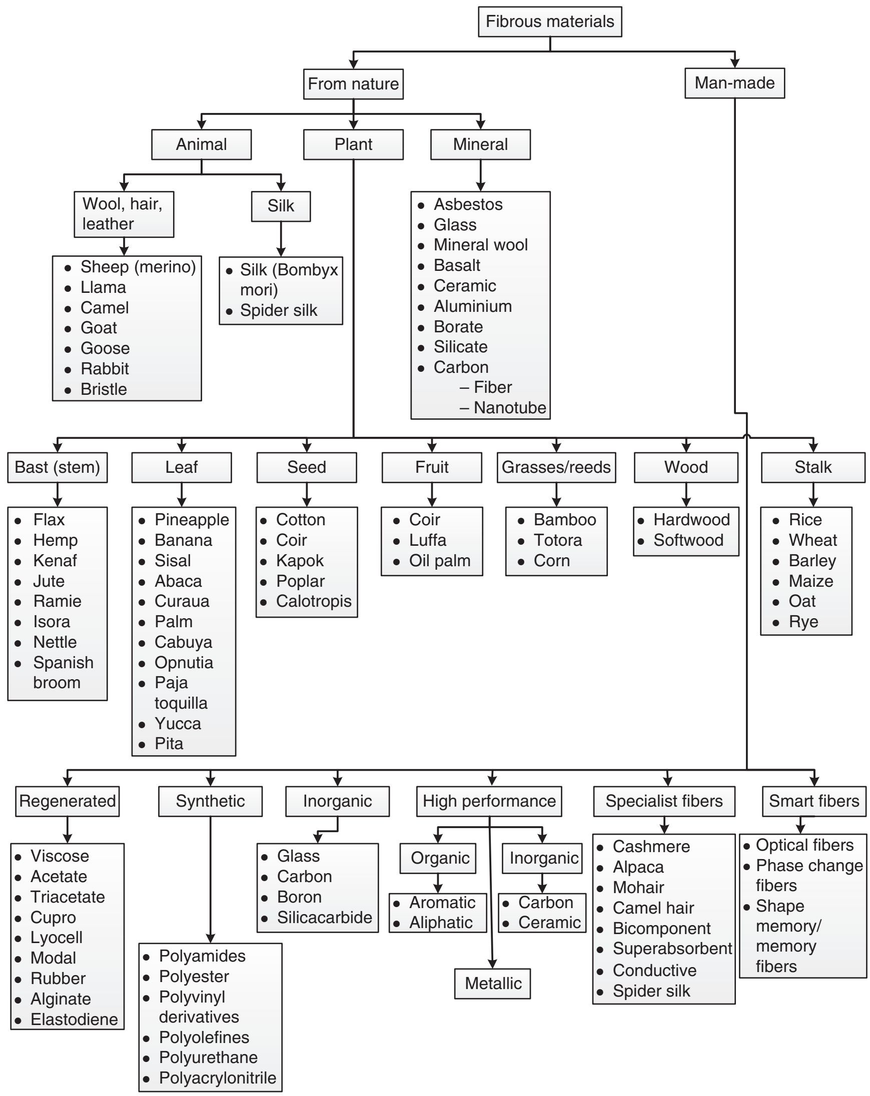

Figure 1.3 Classification of fibrous materials.

the polymerization of amino acids (NH_2–CHR–COOH) by peptide linkage (–CO–NH–) into long-chain molecules such as silk and wool. Mineral fibers are obtained from the naturally available inorganic substances such as rock, clay, and slag. Another group of fibers that have changed the world with revolutionary scientific discovery of mankind is man-made or manufactured fibers. Different classes of manufactured fibers are grouped in Figure 1.4, which includes fibers from natural polymers (regenerated or artificial or modified celluloses), synthetic polymers, and organic and inorganic substances. Regenerated fibers such as viscose rayon, acetate, and triacetate are produced from the celluloses that are

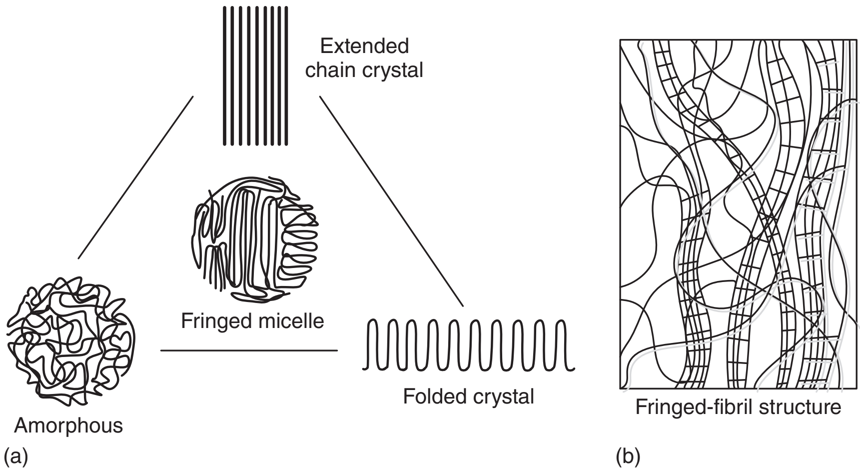

Figure 1.4 Phases of polymeric chains in fibrous materials. Source: Adapted from Morton and Hearle 2008 [2] and Kajiwara 2009 [26].

chemically regenerated from the natural resources such as wood pulp. The major difference in this class of fibers is thinning down or reducing the degree of polymerization by chemical modification of native cellulose. However, alginate fibers are produced from the alginic acid that can be obtained from seaweed. The acid is subjected to degradation and neutralization process to form the metallic salts that form the highly oriented and highly crystalline alginic acid fibers [3]. Synthetic fibers are spun from the polymers that are synthesized using monomers joined together by covalent bonds via process called polymerization. Polymerization could proceed with several variations, and thus they can be classified in various ways as listed in Figure 1.4 under synthetic group. High-performance fibers are of two types, namely, organic and inorganic. Glass is an inorganic with unoriented and amorphous network based fiber, which has a long history as decorative product. Carbon fibers are basis for making composites that are made of acrylic or cellulose precursors via carbonization. The high temperature ceramic fibers are produced by using organosilicon polymers or viscous liquid with aluminum salts. Discovery of liquid crystals led the way to produce fibers with almost perfect crystallinity, almost perfect orientation, and fully extended molecular chains. Aromatic and aliphatic polymers used to produce Kevlar and Nomex that are also called as aramid fibers. Liquid crystals can also be formed from polyethylene to produce ultrahigh molecular weight polyethylene to get highest strength. Specialty fibers are of normally hair fibers such as cashmere, camel hair, alpaca, and mohair. These fibers are generally straighter and smoother than wool [10–12]. Other specialist fibers that are produced by advanced and distinguished technology such as hollow fibers, bicomponent fibers [13, 14], superabsorbent fibers [15, 16], and conductive fibers [17]. Hollow and bicomponent fibers are generally spun using different types of spinnerets. Superabsorbent fibers are produced using acrylic-based products and characterized by improved liquid or fluid transportation that are used in medical, textiles, food packaging, and technical textiles. Other advanced fibers can also be considered as specialist fibers, but they are listed under smart fibers that are stimulus responsive such as optical fibers, phase change fibers, and shape memory fibers. Optical fibers are made of polymer or glass core materials with hollow core along the length for applications such as photonics and sensors, and they are called as bandgap fibers [18]. Phase change fibers are generally composed of thermoplastic polymer and luminescent materials as a composite structure [19]. Another smart fiber is considered as one of the most important class of stimuli responsive materials, i.e. shape memory polymeric (SMP) fibers. SMPs are made of segmented polyurethanes with custom tailorable switching or transition temperatures that can be spun via different spinning methods such as melt spinning, dry spinning, wet spinning, reaction spinning, and electrospinning process [20–23].

Increased demand and population explosion is alarming the world to look up for an alternative material that is sustainable and biodegradable. Researchers and industrial inventors may invent futuristic advanced material-based fibers for upcoming days. This is unstoppable and essential for groundbreaking revolutionary technological advancements for this present competent world to prepare for better future.

1.4 Fundamental Characteristics of Fibrous Materials

The era of synthetic fibers was beginning around ten decades ago, and until that time the usage of natural fibers was most popular owing to their natural properties useful for mankind. These natural properties were being considered as benchmark to consider a fiber to be useful in the production of textile materials [24]. These properties are imperative for textile processing and they can be divided as follows [6]. They are primary properties (such as staple, strength, elasticity, fineness, uniformity, and spinning quality) and secondary properties that are desirable. Fibers that are useful in textile processing should be elastic between 5% and 50% breaking elongation. Other non-textile materials like inorganic fibers such as glass, ceramic, and fully crystalline objects are neither flexible nor extensible. The materials that meet this requirement would be almost partially oriented, partially crystalline, and linear molecular arrangements. Functional applications need high-performance fibers that differ from textile fibers with high strength and low extension. Almost they are linear polymers and added with inorganic networks to integrate the flexibility. Elastomeric fibers are used for high stretch applications. There is also other sort of fibers that are interesting such as those in living organisms, wood fibers used for papers, and various tissues. In addition to general characteristics, there are other important features that characterize the fibers, and they are degree of order, degree of localization of order, length/width ratio of localized units, degree of orientation, size of localized units, and molecular extent in a fiber assembly [3]. Fibrous strand is composed of fibrils that are an assembly of polymer molecules and a primary unit called microfibril that is almost identical in all natural fibers. Man-made fibers also show a similar element in the structure [25]. Hess and Kiessing [27] suggested a schematic fringed micelle model to elucidate the structure of microfibrils of synthetic fibers as shown in Figure 1.4. The microfibril basically constitutes crystalline region (ordered polymer chains along the axis) and amorphous region (randomly oriented or less ordered), and an individual polymeric chain interconnects the two regions (Figure 1.4a). Hearle [27–29] proposed a fringed fibril structure (Figure 1.4b) for low crystalline fibers, which can be seen in stiffer molecular chains such as cellulose. This model combines fibrillar form and the concept in fringed micelle structure having distinct crystalline and non-crystalline portions with molecular chains running through each region continuously. High-performance fibers with highly crystallinity have more closely packed fibrillar structure. Natural fibers have specific fibrillar forms and wool with fibrils separated by various matrices.

1.5 Morphological and Structural Properties of Fibrous Materials

The structure of fibrous materials varies in several ways and depends on how actually they are formed whether naturally or artificially. Natural fibers grow slowly and are controlled under genetics to yield different structures, which vary from fastest passage of synthetic fiber production.

1.5.1 Plant or Natural Cellulosic Fibers

An essential feature of natural fibers is that they are aggregated into finer microfibrillar structures (Figure 1.5a,b). According to biological validation, during the growth glucose rings are joined together to form long-chain molecules of cellulose. The thickness of these natural microfibrils is about 4 nm. The molecular alignment takes place in parallel direction of crystal lattice with no chain folding. The crystallization occurs due to minimization of free energy, and forceful attractions are at the edge of molecules likely to form a ribbonlike structure (Figure 1.5a). Microfibrils are almost flexible and attract each other with strong hydrogen bonding at molecular edges or between the faces by weak van der Waals force. Cotton fibers show irregular, convoluted long ribbonlike structure, covered with cuticle, primary wall, and lumen at the center in a cross-sectional view (bean shape) (Figures 1.5a and 1.6a). Apart from cotton, other cellulosic fibers including jute, ramie, hemp, and flax are also multicellular fibrous structures. Smaller fibrillar cells run along the length from the stem or leaf as shown in Figure 1.5. The fibrils spiral around the fibers and are parallel to axis in all natural cellulosic fibers. However, in bast fibers, the spiral angle is reduced, and structures are highly oriented to fetch high strength with less extensibility.

1.5.2 Animal or Protein Fibers

Silk, wool, or hair fibers are considered as protein fibers originated from the living animals. Groups of amino acids combine into long-chain molecules

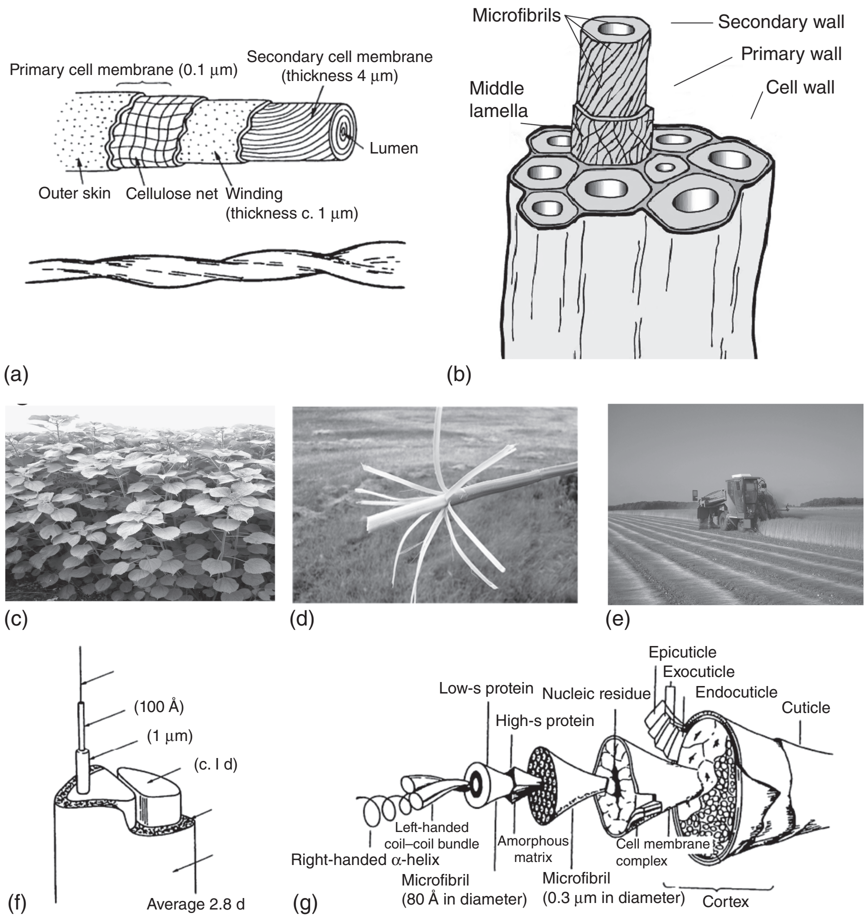

Figure 1.5 Structural and photographical images of natural and animal fibers. (a) Cotton. (b) Jute. (c) Ramie. (d) Hemp. (e) Flax. (f) Silk. (g) Wool. Source: Adapted from Kajiwara 2009 [26], Kozasowski et al. 2012 [30], and Roy and Lutfar 2012 [31, 32].

with polypeptide linkages to form protein fibers. The major protein of silk fiber is fibroin molecule that is 140 nm long with other 17 nm long segments composed of tyrosine and other concentrated side groups, with rest being fully glycine, alanine, and serine acids. Silk is spun by silkworm and constitutes two triangular fibroins covered with a sericin gum (Figures 1.5f and 1.6a). Hair or wool fibers show the most complex structures among any other fibrous materials (Figure 1.5g). The major protein in hair fibers is keratin that consists of several proteins. Wool fibers with α-keratin protein tend to reverse transformation when stretched to form β-keratin. α-Helix consists multiple twisted molecules, two chains makes a dimer, two dimers into a protofilament, two protofilaments a protofibrils, two protofibrils a half filament, and two half filaments gives an intermediate filament having 32 molecules in cross section [3].

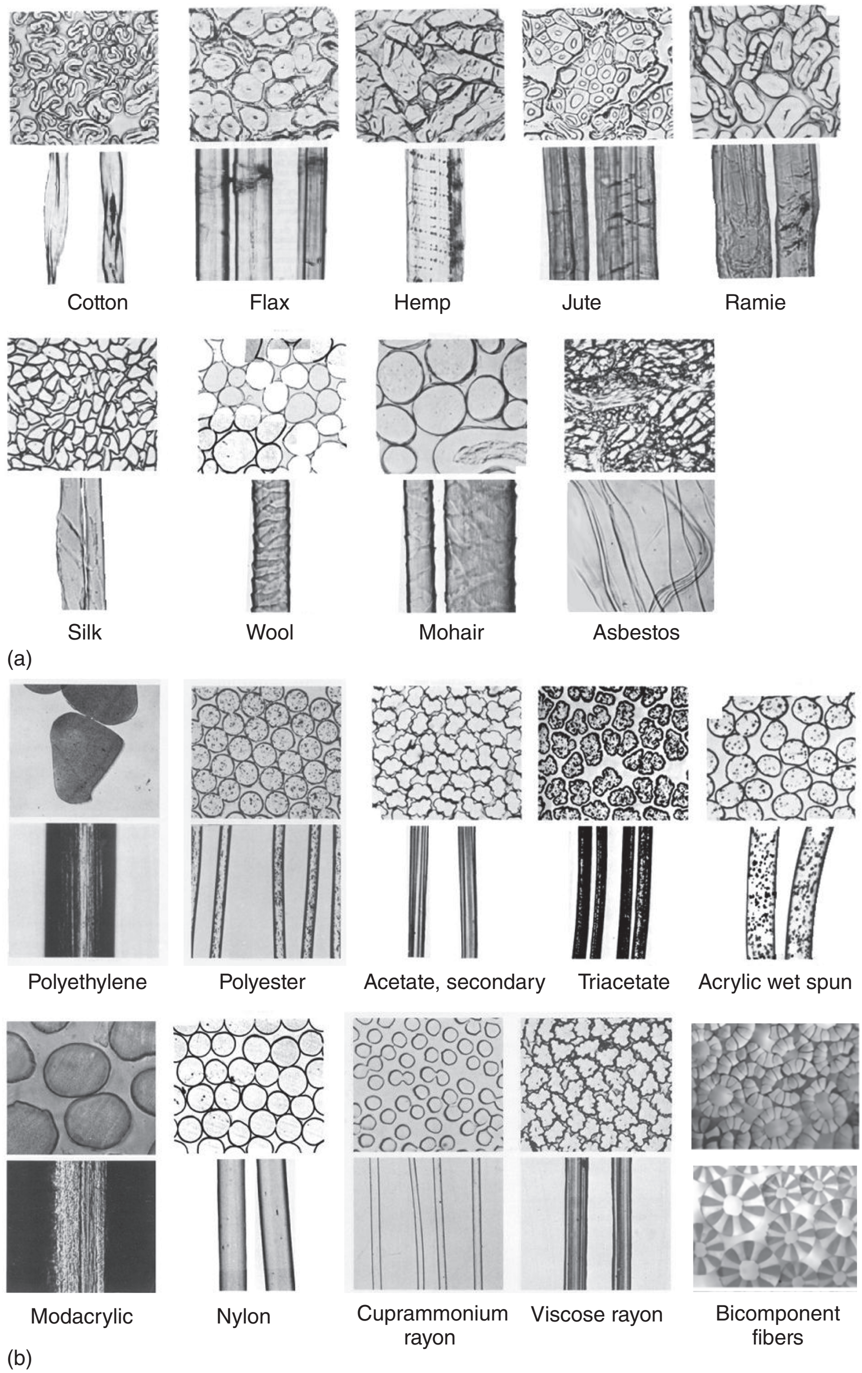

Figure 1.6 Microscopic structural images of fibrous materials. (a) Longitudinal and cross-sectional view of natural fiber. (b) Longitudinal and cross-sectional view of man-made fiber. Source: Adapted from Prahsarn et al. 2016 [14] and AATCC 2013 [34].

1.5.3 Regenerated Cellulosic Fibers

The degree of polymerization is reduced and of the order of 500 compared to native cellulose. The crystalline region is less and of about one third of the total. However, the degree of orientation totally depends on the drawing during spinning. There are diverse forms of rayon with irregular shapes in the cross section (Figure 1.6b). Viscose rayon is formed by intermediate cellulosic xanthate, whereas acetate fibers are treated to replace the hydroxyl groups with acetyl groups. They have good dimensional stability and high softening point and are crease resistant with heat-set ability [3].

1.5.4 Synthetic or Manufactured (Textile and Non-textile) Fibers

Synthetic fibers lack in terms of their structural features. Spinning conditions and the spinneret being used decides the fiber cross section. Melt-spun fibers using circular spinneret shows circular shape and other shapes from shaped spinneret. However, fibers from solution spinning have different shapes such as acrylic fibers (dumbbell shape) due to mass transfer or loss of solvent (Figure 1.6). The longitudinal and cross-sectional views of other synthetic fibers are shown in Figure 1.6b [13].

Other additives such as pigments, delustrants, and antistatic agents can also be included to achieve desired properties. Most of the non-textile fibers that are required for engineering uses need high stiffness and strength and high-performance (high-modulus, high-tenacity [HM-HT]) fibers are the best choice for this. The presence of covalent strong chemical bonding gives high mechanical and chemical resistance to ceramic fibers. Ceramic fibers contain mixture of components such as silica, SiO_2, carbon, Al_2O_3, and B_2O_3. Carbon fibers are composed of graphite crystal lattice, and the carbon atoms are held together by covalent bonds. Aramid (para) fibers such as Kevlar and Twaron are composed of aromatic polyamide, poly(*p*-phenylene terapthalamide) (PPTA). These fibers are highly oriented with fully extended chains and high crystallinity [3].

1.6 Essential or Fundamental Properties of Fibrous Materials

The fundamental composition and morphological structure vary from fiber to fiber, and there are some important properties to be considered to intelligently utilize them into different applications for human needs. Fundamental properties of fibrous materials are most necessary to distinguish them from each other and find out other desirable properties via standard testing conditions.

1.6.1 Physical Properties

Primary processing of any fibrous material is to be decided by their physical properties such as fiber length, elongation, tenacity, moisture sorption and swelling behavior, color, luster, electrical behavior, specific gravity or density, and solubility. Fiber length of natural fibers varies, and they differ in their staple length except continuous filament such as silk. Physical properties of synthetic fibers can be tailor-made according to end user requirements. Physical properties of fibers materials are shown in Table 1.1.

1.6.1.1 Mechanical Behavior of Fibrous Assemblies

Textile fibrous materials differ from conventional engineering materials in different ways owing to their unique mechanical behaviors. Based on such behaviors, it is possible to predict general fashion and expected behavior to obtain the necessary characteristics. Fibrous materials are highly anisotropic, easy to deform, and inhomogeneous and have larger strains and displacement at lower stress and nonlinear and plastic nature at low stress and in room temperature. Hence they do provide essential characteristics suitable for the movement of human body, perception satisfaction, and other psychological and physiological requirements [1].

It is imperative to comprehend the behavior of fibers in a unit of assembly employed for multidirectional deformations. Figure 1.7 shows the complicated geometrical structure of a fibrous assembly, textile woven fabrics, which is an integration of warp and weft yarns through intersection points. The passage of fibrous strand in the cross-sectional shape is crimped and irregular with protruding the fibers from the strand surfaces. Porus structure of woven fabric is decided by the distance between two adjacent yarns differentiates from the continuum engineering material such as metallic sheets. Pierce has simplified and idealized the cross-sectional shape and physical properties of yarn assemblies through theoretical modeling approach [1].

Nonlinear Stress–Strain Behavior of Textile Fibrous Assembly The mechanical behavior of woven fabric structures is complicated upon deformation, and their typical stress–strain curves are depicted in the Figure 1.8, which shows tensile, bending, and shear deformations. The tensile stretching (Figure 1.8a) shows larger strain even at small force, and this is ascribed to straightening of crimped length of yarns in the woven structure. A typical fabric has a tensile modulus in the order of 10 MPa as compared to steel that is around 2×10^5 MPa. The woven fibrous assemblies are more prone to bending deformations under the transverse loading (Figure 1.8b). The bending stiffness of the fibrous strand to that of a solid rod of the same cross section can be easily determined assuming the slippage between the fibers is unconstrained. That is, $\alpha(\gamma/R)^2$, where α is denoted as porosity ratio and R and γ are the radii of the yarn and its constituent fibers, respectively. For a typical yarn that contains 100 fibers, this ratio is $\sim$1 : 10 000. Thus, it is possible to develop a thick yarn with more flexibility and is advantageous to have less bending stiffness in the woven fibrous structure. As mentioned earlier, the geometry of the woven fabrics is complicated, and when these materials are subjected into deformation, interesting phenomena could be seen, which is distinguished from conventional engineering materials. They are as follows:

(1) *Nonlinear stress–strain trend*: When the woven fibrous material is subjected to small strains, the corresponding stress will be nonlinear, which contrasts

Table 1.1 Properties of different types of textile fiber [6, 26, 30, 31].

Family/ group	Fibers	Tensile strength (cN/dtex)		Elongation (%)	Specific gravity (g/cm^3)	Young's modulus (cN/dtex)	Moisture regain (%)
		Dry	Wet	Dry			
Natural fibers	Cotton	2.3–4.3	2.9–5.6	3–7	1.54	60–82	8.5
	Jute	5.4–8.71	—	1–1.8	1.48	—	13.8
	Silk	2.6–3.5	1.9–2.5	15–25	1.33	44–88	11
	Wool	0.9–1.5	0.7–1.4	25–35	1.32	10–22	15
Regenerated fibers	Viscose rayon	1.5–2.0	0.7–1.1	18–24	1.50–1.52	57–75	11
	Triacetate	1.1–1.2	0.6–0.8	25–35	1.30	26–40	3.5
Synthetic fibers	PET	3.8–5.3	3.8–5.3	20–32	1.38	79–141	0.4
	Polyacrylonitrile	2.2–4.4	1.8–4.0	25–50	1.14–1.17	34–75	2
	Polyvinyl chloride	1.11–3.33	1.11–3.33	10–125	1.33–1.40		
	PTFE	1.11–2.22		10–30	2.1–2.3		0
	Nylon 6	4.2–5.7	3.7–5.2	28–45	1.14	18–40	4.5
	Nylon 6,6	4.4–5.7	4.0–5.3	25–38	1.14	26–46	4.5
	Vinylon (PVA)	3.5–5.7	2.8–4.6	12–26	1.26–1.30	53–79	5
	Polypropylene	4.0–6.6	4.0–6.6	30–60	0.91	35–106	0
	Polyethylene	4.4–7.9	4.4–7.9	8–35	0.94–0.96	—	0
	Polyurethane	0.5–1.1	0.5–1.1	450–800	1.0–1.3	—	1
Aramid fibers	Kevlar	8.8–24.44	7.7–23.33	3–20	1.45	133.3–144.4	3
	Nomex	6.66–13.33	5.55–12.22	20–30	1.38	125.5–133.3	3.5
High-performance fibers	Polycarbonate	4.44–5.55	—	20–45	1.23	—	0.4
	PBI	2.88–3.33	2.33–2.77	25–30	1.43	50–66	15
	Sulfur	3.33–3.88	—	25–35	1.37	33–44	0.6
Inorganic	Carbon	22.2–27.7	—	1–2	1.7–1.8	—	—
	Glass	6.6–11.1	5.5–8.8	—	2.5–2.6	—	0.5

PET, polyester; PTFE, poly(tetrafluoroethylene); PBI, polybenzimidazole.

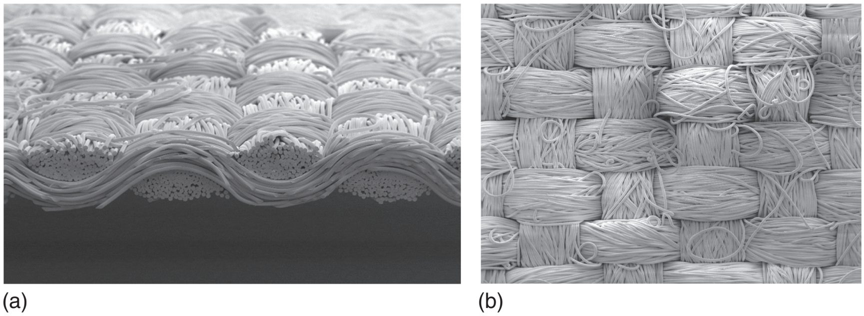

Figure 1.7 Structural photographic images of plain woven fibrous assembly. (a) Cross-sectional image. (b) Surface image. Source: Adapted from Denton and Daniels 2002 [1].

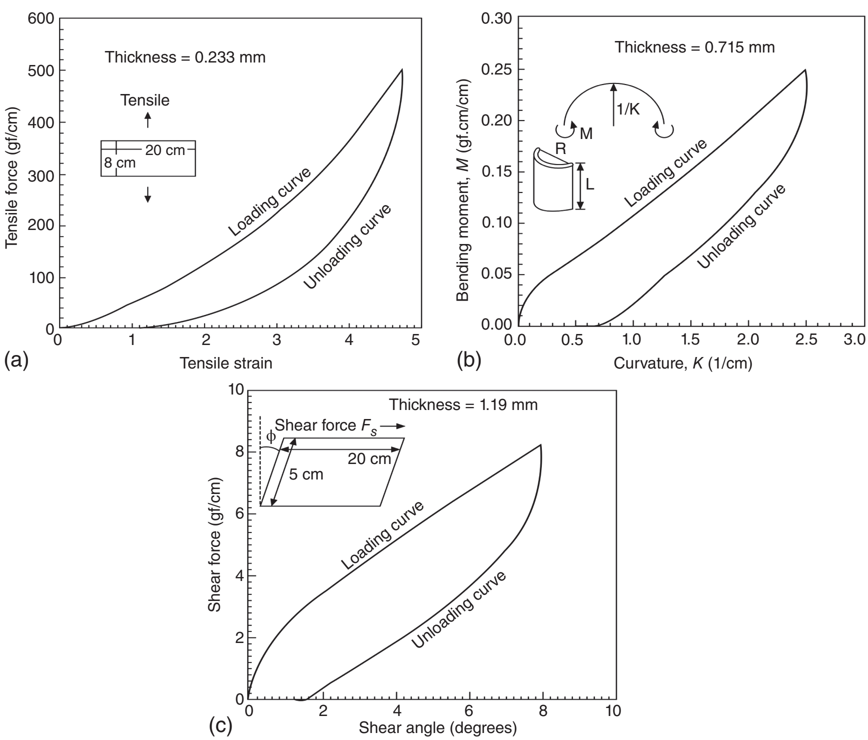

Figure 1.8 Typical stress–strain plots for woven fabrics. (a) Plot of stress vs. strain. (b) Plot of moment vs. curvature. (c) Plot of shear force vs shear angle. Source: Adapted from Hu 2004 [9].

with that of conventional engineering material with linear trend. The stress–strain curve in fabrics is nonlinear up to small strains, and it becomes linear beyond the critical stress region. This critical region is higher for tensile deformation and very low or nearly zero for bending and shear deformations. Due to porous and crimped nature of fibrous assembly in the woven fabrics, they tend to become straightened upon deformations, thus showing nonlinear trend during the consolidation process. Once the consolidation and reorientation is done, the stress–strain trend shows the linear that is like a solid conventional engineering material.

(2) *Irrecoverable deformation*: Woven textile fibrous assembly shows loops between the loading and unloading curves as shown in the Figure 1.8. It can be seen that, in three of the cases such as tensile, bending, and shear, the deformed length is not able to recover back to their original state. This is denoted as irreversible or irrecoverable deformation occurs at small stresses. This phenomenon differs from the conventional engineering material where the inelastic deformation occurs at high stress level where the failure may happen.

Textile fibrous assemblies do obviously differ from those conventional engineering materials in many ways such as inhomogeneous, anisotropic, and nonlinear behaviors. Complicated mechanical response occurs at low stress and room temperature for fabrics, whereas this happens at high temperature and high stress for engineering materials.

1.6.2 Chemical Properties

Natural and synthetic fibers have different chemical properties such as affinity and inertness to various chemicals. In general, most of the cellulosic fibers are resistant to alkalis and protein fibers to acids. There are some important chemical properties to be considered such as effect of acids, effect of alkalis, effect of oxidizing agents, effect of light or sunlight, and effect of insects.

1.6.3 Biological Properties

Biological properties of fibrous materials play an important role in some very specific applications. These properties include resistance to moths, mildews, and microorganisms, biodegradability, and biocompatibility of fibrous structures. Biodegradable natural or synthetic polymeric fibers such as silk, collagen fibers, and polyurethanes are used for implants and tissue engineering.

1.6.4 Thermal Properties

Fibrous materials are thermoset (natural fibers) or thermoplastic (manufactured) in nature. Thermal properties such as softening point, glass transition temperature, melting temperature, and degradation point or decomposition temperature range are important to be considered for processing or applications.

1.6.5 Other Desirable Properties

Manufactured fibers are modified into broad horizon of materials suitable for vivid smart applications needing desirable properties such as optical performance (photonics), electrical properties (energy storage), phase change behavior, and shape memory properties (memory behavior).

1.7 Textile Processing

Textile manufacturing or processing is a very complex process. The area of textile manufacturing process is too long (Figure 1.9). It starts from fiber to finished products. Fiber is the main material for textile product; properties of textile products mainly depend on fiber type. Textile fiber has few special features that vary between fibers and textile fiber. Textile fiber can be twisted into a yarn or made into a fabric by various methods like weaving, knitting, nonwoven, and braiding. Textile fiber needs to be stronger enough to hold their shape, flexible enough to be shaped into a yarn or fabric, elastic to stretch enough, and durable enough to last [33, 34].

1.7.1 Spinning

Spinning is the first step of textile product processing. The process of making yarns from the textile fiber is called spinning. Spinning is the twisting together of fibers to form yarn. There are different types of spinning process: ring spinning, rotor spinning, friction spinning, etc. Ring spinning is the most commonly and widely used spinning process.

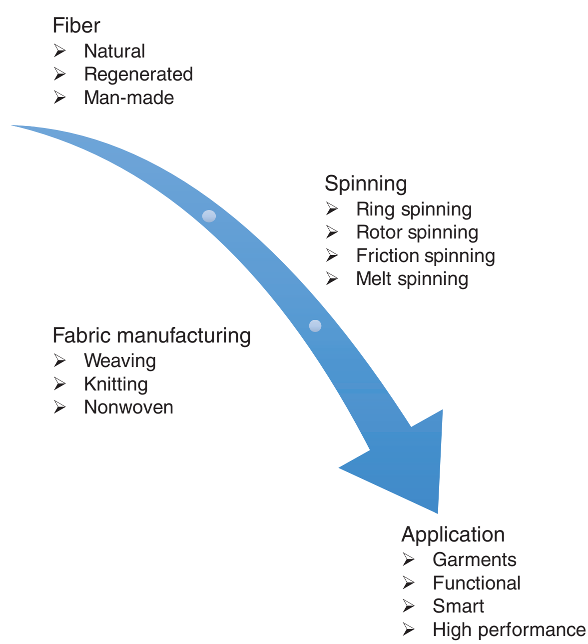

Figure 1.9 Flow process chart of textile manufacturing.

1.7.1.1 Ring Spinning

Ring spinning is a continuous system of spinning in which twist is inserted into a yarn by using a circulating traveler in ring spinning; the roving is first attenuated by using drawing rollers and then spun and wound around a rotating spindle, which in its turn is contained within an independently rotating ring flyer. Ring spinning is the mostly used spinning process. Ring spinning processes are as follows:

Blow room: The section where the supplied compressed bale is turn into a uniform lap of particular length by opening, cleaning, blending, or mixing is called blow room section. It is the first step of spinning process. It is even feed of material to the card.

Carding: It is the heart of spinning process. This is where the flock from bales will be open into individual fiber. Thus, it will ease to remove the excess impurities on the fiber surface. At this point, short fiber that is not suitable for production in terms of length requirements will be removed. Carding is one of the most important operations in the yarn processing as it directly determines the final features of the yarn. The main objectives of the carding can be summarized as opening the tufts into individual fibers, eliminating all the impurities contained in the fiber that were not removed in the previous cleaning operations, selecting the fibers based on length and eliminating the shortest ones, removing the neps, and parallelizing and stretching the fiber.

Drawing: At this stage, the sliver will be pulled in lengthwise direction over each other. Thus, it will cause it to be stronger and thinner in production, which is very important in evenness of the yarn. Card slivers fed to the drawing machine have some degree of unevenness. The drawing machines are very much important in the yarn manufacturing process. One of the main and most important tasks of the draw frame is improving evenness.

Combing: The cotton sliver produced by the card contains several contaminants that obstruct with the spinning of fine high and good quality yarns. This is a process where the yarn will be straightened again so that they are arranged in parallel manner. While at the same time, the remaining of short fiber will be removed completely from the fiber. The main functions of the comber are to remove a substantial amount of the short fiber as "noil" and eliminate the smallest trash particles and neps.

Roving manufacturing: In this stage, sliver will be further drafted and twist will be inserted to produce roving sliver. Enough twist is given to keep the fibers together but still has no tensile strength. The roving in bobbins is placed in spinning frame where it passes several sets of roller that run at high speed to convert into yarn forms.

Ring spinning: The ring spinning is the most broadly used form of spinning machine due to significant advantages in comparison with the new spinning processes. The ring spinning machine is used in the textile industry to continuously twist staple fibers into yarn and then wind it onto bobbins. The following are the core objectives of ring spinning:

- To draft the roving fed to the ring spinning frame, i.e. to convert roving into very fine strand called yarn.

- To improve strength to the yarn by inserting the necessary amount of twist.
- To collect twisted strand called yarn onto handy and transportable package by winding the twisted thread on a cylindrical bobbin or tube.

Cone winding: In the spinning process, winding is the last step. After winding yarn packages are used for making woven or knitted fabric. Winding process can be defined as the transfer of spinning yarn from one package to another large package (cone). A process of assemble yarn on a package to facilitate the next process is called as winding.

1.7.1.2 Rotor Spinning

In rotor spinning, sliver is fed into the opening end of rotor; then fed sliver is opened into single fibers, and then the singled fibers are reassembled, twisted, and wound on a package. Moreover, sliver from the carding machine goes into the rotor, is twisted into yarn and comes out, wrapped up on a cone shaped bobbin; so there is no roving stage in rotor machine and no need to use the auto-coner to winding the yarn in a cone because output of rotor machine is sliver to yarn into a cone shaped package. Advantages of rotor machine are less labor, less time, and high productivity compared with ring spinning. But the disadvantages are low strength, difficult to produce fine yarn, and difficult to keep spinning condition constant.

1.7.1.3 Friction Spinning

Friction spinning system is an open-end system or a "core-type" spinning system, where the yarn formation takes place by the frictional forces. In friction spinning, fibers are supplied onto the drum surface, which transport it and stack fiber to the fiber bundle circulating between two surfaces passing in opposite directions; then opening or individualization of fibers will happen, followed by reassembling of single fiber and then twisting of assembled fiber by frictional force, winding the final yarn. Advantages of friction spinning are excellent yarn regularity, lower preparation and spinning cost, and very high twist insertion rate, and few disadvantages are low yarn strength, high air consumption leading to high power consumption, and friction spun yarns having higher snarling tendency.

1.7.1.4 Yarn Numbering System (Count)

Count is a numerical value, which expresses the coarseness or fineness (diameter) of the yarn and indicates the relationship between length and weight (the mass per unit length or the length per unit mass) of that yarn. The fineness of the yarn is usually expressed in terms of its linear density or count.

According to Textile Institute, "Count is a number indicating the mass per unit length or the length per unit mass of yarn."

There are a number of systems and units for expressing yarn fineness. But they are classified as follows:

Direct count system: The weight of a fixed length of yarn is determined. The common features of all direct count systems are that the length of yarn is fixed and the weight of yarn varies according to its fineness. In the direct system, the higher the yarn count number, the heavier or thicker the yarn. It is based on the fixed length system. This system is generally used for jute or silk yarn.

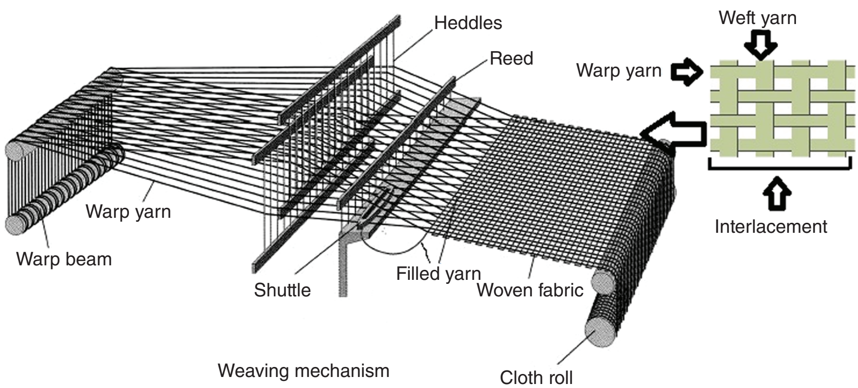

Figure 1.10 Weaving mechanism. Source: Reproduced with permission from https://textilechapter.blogspot.com/2017/03/weaving-loom-principle-mechanism.html.

Indirect count system: In an indirect yarn counting system, the yarn number or count is the number of "units of length" per "unit of weight" of yarn. This means the higher the yarn count number, the finer or thinner the yarn. It is based on the fixed weight system. This system is generally used for cotton, woolen, worsted, and linen yarn [35–37].

1.7.2 Fabric Manufacturing

1.7.2.1 Weaving Process

Weaving is one of the major processes of making fabric. In it, two individual sets of yarns called the warp and weft are interlaced with each other to form a fabric (Figure 1.10). Yarn is a long continuous length of interlocked fibers. The lengthwise yarns that run from the back to the front of the loom are called the warp. The crosswise yarns are the filling or weft. A loom is a device for holding the warp threads in place while the filling threads are woven through them. Yarns made from natural fibers like cotton, silk, and wool and synthetic fibers such as nylon and Orlon are commonly used for weaving textile. Before start weaving we have some work like weaving preparation. In weaving preparation work, we must do the following:

- *Warping*: A process of transferring the warp yarn from the single yarn packages to an even sheet of yarn representing hundreds of ends and then winding onto a warp beam.
- *Sizing/slashing*: Sizing of yarn is carried to improve its strength and produce a smooth surface.

To interlace the warp and weft yarn, there are three operations often called primary motions that are necessary:

Shedding: The process of separating the warp yarn into two layers by raising the harness to form an open area between two sets of warps.

Picking: The process of inserting the filling yarn through the shed by means of the shuttle less while the shed is opening.

Beating: The process of pushing the filling yarn into the already woven fabric at a point known as the fell and done by the reed.

Taking up and letting off: With each shedding, picking, and beating operation, the new fabric must be rolled on the cloth beam that is called "taking up." At the same time, the warp yarns must be open from the warp beam that is called "letting off" [38–40].

1.7.2.2 Knitting

Knitting is a method by which yarn is turned to create a textile or fabric. Knitting is the process through which the yarn is turned into knitted fabric by joining consecutive row of loops (course and wales) using different types of knitting machines. In knitted loop terminology, a course of knit is a mainly horizontal row of needle loops produced by adjacent needles during the same knitting cycle. Wales of knit are a mainly vertical column of interlaced needle loops generally produced by the same needle at successive knitting cycles.

Mainly two different types of knitted fabric are produced. They are as follows.

Warp Knitting The general direction of path of yarn is along the length of the fabric. Warp knit fabrics are constructed with yarn loops formed in a vertical or warp direction. Warp knitting are four types. They are tricot knit, Raschel knit, crochet knit, and milanese knit. Warp knitted fabrics are normally using inner wears (brassieres, panties, sleepwear), sportswear lining, and household (mattress, mosquito nets).

Weft Knitting The general direction of path of yarn is across the length of fabric. Weft knitted fabrics is categorized by a series of horizontal loops formed by horizontally running threads and binds with previously formed series of loops of the same thread. End uses of weft knitting are underwear, T-shirts, sportswear, baby clothes, jumpers, scarves, hats, gloves, etc. https://textilechapter.blogspot.com/2017/03/weaving-loom-principle-mechanism.html [41].

1.7.2.3 Nonwoven

Nonwoven fabric is a fabric-like material made from long fibers, bonded together by chemical, mechanical, heat, or solvent treatment or using proper moisture or heat rather than by spinning, weaving, and braiding. Nonwoven fabric is a molded product with planar structure made by interweaving natural, chemical, and metal fibers according to their mutual characteristics to form a web in the shape of a sheet and bonding them together by mechanical or physical means. Nonwovens may be a limited life, single-use fabric or a very durable fabric. Nonwoven fabrics provide specific functions such as absorbency, liquid repellency, resilience, stretch, softness, strength, flame retardancy, wash ability, cushioning, filtering, bacterial barriers, and sterility [42].

1.7.3 Wet Processing Technology

1.7.3.1 Pretreatment Process

Natural fibers and synthetic fibers both contain primary impurities that are contained naturally and secondary impurities that are added during different process like spinning, knitting, and weaving processes. Textile pretreatment is the series of cleaning operations. All impurities that cause unfavorable effect during dyeing and printing are removed in pretreatment process. Pretreatment processes include desizing, scouring, and bleaching that make dyeing processes easy. Desizing is for the removal of the size coating after weaving. Desizing with enzymes ensures complete removal of starch-based sizes, which means excellent batch-to-batch dyeing reproducibility and evenness. Scouring is a cleaning process used to remove impurities (wax, oil) on fibers, yarns, or cloth. Bleaching is decolorizing the impurities that mask the natural whiteness of fibers to obtain white cloth and increase the ability of the fabric to absorb dyestuffs uniformly.

1.7.3.2 Dyeing

The process of applying color to fiber, yarn, or fabric is called dyeing. Dyeing is the process of giving colors to a textile material through a dye (color). Dyeing can be done at any stage of the manufacturing of textile: fiber, yarn, fabric, or a finished textile product including garments and apparels. The property of color fastness depends upon two factors: selection of proper dye according to the textile material to be dyed and selection of the method for dyeing the fiber, yarn, or fabric.

1.7.3.3 Dyeing Methods

Color is applied to fabric by different methods of dyeing for different types of fiber and at different stages of the textile production process. Mostly used methods are fabric dyeing and yarn dyeing. When a dye is applied directly to the fabric without the aid of an affixing agent, it is called direct dyeing. When dyeing is done after the fiber has been spun into yarn, it is called yarn dyeing. Yarn dyeing is slightly different from woven or knit dyeing. Yarns are dyed in package form by yarn dyeing process.

1.7.3.4 Dyes

Dyes are used for coloring the fabrics. Dyes are molecules that absorb and reflect light at specific wavelengths to give human eyes the sense of color. There are two major types of dyes: natural and synthetic dyes. The natural dyes are extracted from natural substances. Synthetic dyes are made in a laboratory. Chemicals are synthesized for making synthetic dyes. Mostly used dyes are reactive dyes (used for dyeing cellulose fibers and protein fiber), direct dyes (used for dyeing wool, silk, nylon, cotton, rayon, etc.), vat dyes (used for dyeing wool, nylon, polyesters, acrylics, and modacrylics), disperse dyes (used to dyeing nylon, cellulose triacetate, and acrylic fibers), sulfur dyes (used for dyeing cotton and linen, viscose, and jute), basic dyes (used for dyeing cotton, linen, acetate, nylon, polyesters, acrylics, and modacrylics) [43–46].

1.7.3.5 Finishing

In textile manufacturing, finishing refers to the processes that convert the woven or knitted cloth into a usable material and more specifically to any process performed after dyeing the yarn or fabric to improve the look, performance, or hand feel of the finish textile. To impart the required functional properties to the fiber or fabric, it is customary to subject the material to different type of physical and chemical treatments. For example, wash and wear finish for a cotton fabric is necessary to make it crease-free or wrinkle-free. In a similar way, mercerizing, singing, flame retardant, water repellent, waterproof, antistatic finish, peach finish, etc. are some of the important finishes applied to textile fabric [47].

1.7.3.6 Printing

Textile printing is the process of applying color to fabric in definite patterns or designs. In a proper printed fabric, the color is affixed to the fiber, so that it may not be affected by washing and friction. The dyes used for printing mostly include vat, reactive, naphthol, and disperse colors, which have good fastness properties. The pigments, which are not truly dyes, are also used extensively for printing. These colors are fixed to the fiber through resins that are very resistant to laundering or dry-cleaning. Mostly used printing methods are direct printing, discharge printing, resist printing, roller printing, block printing, screen printing, transfer printing, and electrostatic printing [48, 49].

1.8 Textile Applications

Textile structures are now being used for various applications due to their unique advantages. In fact, we can divide their applications into apparel, technical textile, and functional and smart textiles. Apparel manufacturing industries include establishment that process fiber into fabric and fabric into clothing, and other textile products includes shirt, pant, socks, shoes, bra, etc. Technical textiles are indicated to be the quickest improving sector of the textile industry. Functional or technical textiles are the textiles that have been developed to fulfill the high-performance requirement in industries other than conventional clothing [50, 51]. Applications of advanced textiles will be discussed below. The applications of textile materials are presented in Figure 1.11.

1.8.1 Advanced Applications of Textile Material

In this exiting era of advanced materials, we are seeing their widespread contribution in diversified areas, starting from clothing sector to biomedical field, civil engineering, filtration, fiber optics, aerospace, automobile industries, and energy storage and harvesting applications. The convergence of different science and engineering fields is a reason for these astonishing results. Advanced materials are driven by special technical functions that require specific performance properties unique to these materials. Based on their functionality they can be classified into materials for functional, high performance, sensors/actuators,

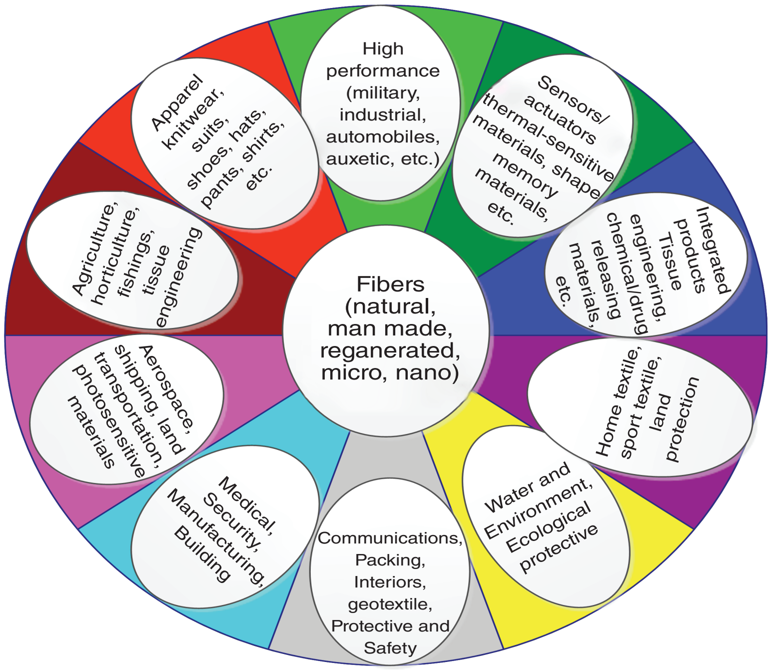

Figure 1.11 Applications of textile materials.

integrated assemblies, and sensitive/smart. Functional materials include water repellent/waterproof, crease resistance, flame retardant, water vapor permeability, etc. High-performance materials usually exhibit high modulus and strength and are used in areas like military, industrial, automobiles, building, auxetics, and land protection applications. The sensors and actuators include fiber optics, nanomaterials, microcapsules, and intelligent membranes/coatings. For integrated products, photonics, tissue engineering, chemical/drug releasing materials are used. Sensitive and smart materials include conductive materials, memory materials, photonic materials, etc. The advanced application of textile materials is shown in Figure 1.12.

1.8.2 Functional Textile

Functional textiles are a class of textiles with integrated property of adjusting textiles according to requirements and functions such as temperature and humidity responsive, water repellent, water vapor permeable, flame retardant, etc. The widely used fibers for functional textiles are viscose, polyester, and polyurethane fibers. The properties of functional textiles are shown in Figure 1.13.

1.8.2.1 Water Repellent

Water repellent is the special type of finishes that repel water, oil, and dry dirt. Water repellent properties are very important for garments, home, and technical textiles. The aim of water-repellent finishes is that the drop of water on the fabric

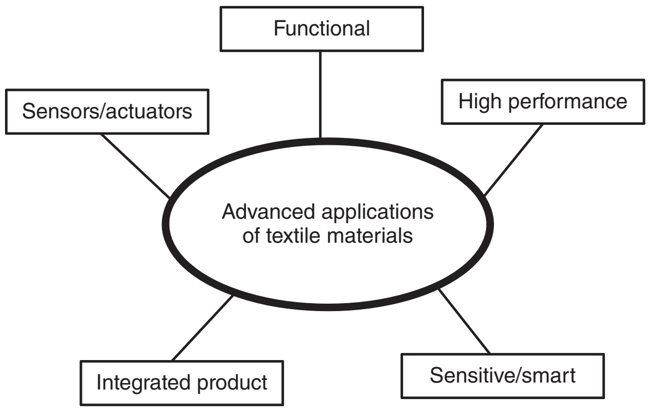

Figure 1.12 Advanced applications of textile materials.

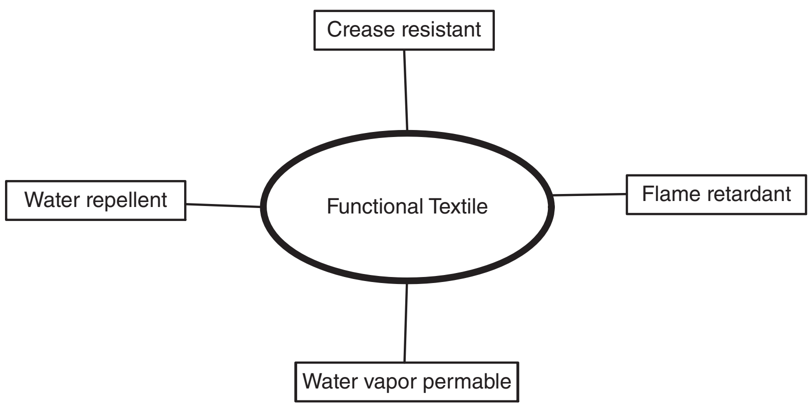

Figure 1.13 Properties of functional textile.

surface should not spread and should not wet the textile; wetting will happen only when the droplet is absorbed by textile. Water repellency is attained by using different products, but oil repellency is achieved only by using fluorocarbon polymers. In water-repellent fabric it is expected that the drop of water will stay on the surface and easily can drips off or it can be brushed off. The air permeability of the finished fabric should not be significantly affected because of water repellency, so water-repellent fabric maintains air permeability. In waterproof breathable fabric, droplet of water should not penetrate into textile, but perspiration should penetrate into textile. In the waterproof breathable fabric coating with micropores, size is small for water droplets to penetrate, and at the same time pores are big enough for perspiration vapor.

1.8.2.2 Water Vapor Permeability

Water vapor permeability is the property of a textile material that allows the passage of water vapor through fabric. It is very important for the textiles used for garment applications to transport the vapour especially when the temperature

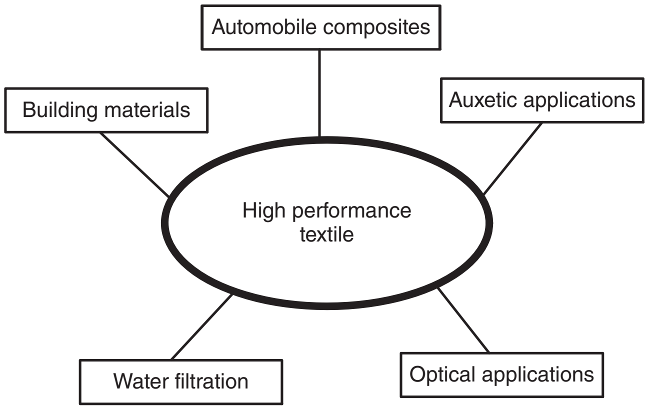

Figure 1.14 Application of high-performance textile.

is high. For getting water vapor (perspiration) permeability properties, we need to coat the fabric by special type of polymer. Water vapor permeability property will help us to avoid physiological problems. Nowadays there are a wide range of woven, laminated, or coated fabrics which are water vapor permeable and waterproof [52–54].

1.8.3 Applications of High-Performance Fibrous Materials

Fiber-reinforced composite materials have been playing an important role for many decades. There are many potential applications of high-performance fibrous materials such as automobile industry, building materials, auxetic application, water filtration, and optical applications. The different applications of high-performance fibrous materials are shown in Figure 1.14.

1.8.3.1 Fibers for Automobile Composite

The polymeric composite materials are widely being used in automotive industry. Fiber mat thermoplastics and compression-molded thermoset polymers are used to manufacture large parts of automotive industries. Composites used for nonstructural functional components are composed of glass fiber-reinforced plastics in the range of 10–50% reinforcement. Such nonstructural composites are used in pedal systems, mirror housing, and so on. To improve the fuel efficiency, hybrid valve lifter used in automotive internal combustion engine was made from carbon fiber/phenolic composite and steel. Semi-structural composites like sheet-molded compounds (SMC) are increasingly used in automotive industry for manufacturing low mass body panels with high strength to weight ratio. The materials that replaced steel with high strength to mass ratio are aluminum, glass SMC, and carbon SMC. Structural polymer composites that are studied have been gradually replacing metal components due to their reduced weight and durability and their resistance to crash. Carbon, glass, aramid, and graphite fiber-reinforced polymers and nanocomposites were studied for impact energy absorption, durability, and crushing behavior.

1.8.3.2 Fibers as Building Materials

Natural and synthetic fibers are used as building materials. They are used in constructing bridges, roads, nonstructural gratings and claddings, structural systems for industrial buildings, roof structures, tanks and thermal insulators, etc. High-performance synthetic fibers are more suitable fibers for building materials. Fibers like nylon, polyester, polypropylene, and aramid fibers are widely used as reinforcements for building materials. Natural fibers like jute, hemp, ramie, and flax are used as reinforcement in building materials. Lower cost of textiles and less energy required to make them most suitable for building materials. Among other natural fibers, jute is widely used as reinforcing fiber in composites for civil engineering applications due to its low specific gravity and high specific modulus when compared with glass.

1.8.3.3 Fibers for Auxetic Applications

The auxetic effect improves the material's mechanical properties, such as enhancement in fracture toughness, shear moduli, and indentation resistance, and allows porosity and permeability variation (under pressure) and dome shape. Due to this wide range of characteristics, auxetic materials can be used in various areas, including medicine, architecture, civil engineering, sport clothing, high-performance equipment, protection against explosives, insulation, and filters. Therefore, the use of high-performance fibers in advanced fibrous architectures like auxetic structures may offer lightweight, excellent mechanical performance and several interesting characteristics that can fulfill the explicit demands imposed by several advanced technical sectors. Auxetic structures for high-performance applications are currently studied using polyester, aramid, carbon, nylon fibers, and shape memory materials [55, 56].

1.8.3.4 Fibers for Environmental Protection: Water Purification/Filtration

There are many examples of using fibers in water treatment process. The advanced fiber technologies led separation membranes made of ultrafine fibers, ion exchange fibers, hollow fiber membranes, and aromatic polyamides in reverse osmosis membrane materials. These membrane technologies are used in many application fields from small-scale home water purification to large-scale filtration of fresh water from seawater sources. Microfine filtration membranes, ultrafine membranes, and reverse osmosis membranes made using the fiber technologies are used to remove small impurities like red rust, bacteria, particles, chemical products and salts from water. Many kinds of natural, inorganic, metallic, and synthetic fibers have been used in filtration. Synthetic fibers have played a significant role in the growth of several segments in the filtration industry. Nonwoven fabrics have been successfully used in the industry as membrane support for microfine, ultrafine, and reverse osmosis filtration. Filters with large surface area and many fine pores are required to filter fine particles. Large surface area can be achieved by using micro- and nanofibers. Hydrophilic or hygroscopic fibers are used to improve or reduce the particle adhesion to the filters. To prevent generation of static charge in filters, conductive fibers like carbon and metallic fibers are used. In hot gas filtration and high temperature filtration and other processes mineral, ceramic or metal fibers are used as filter materials.

1.8.3.5 Fibers for Optical Applications

Optical fibers are those very fine long glass fibers that allow light signals to travel through. The demand for fiber optics has grown enormously. They are used as network carriers; in data transmission, transmitting broadband signals, intelligent transportation systems, and biomedical industry as telemedicine devices for transmitting digital diagnostic images; and in detecting target biomolecules like enzymes, antibodies, and oligonucleotides. It is also used in military and space and automotive sectors. Optical fibers are usually made up of molten solution of silica or silicon dioxide with other materials such as arsenic, quartz, etc. Polymeric optical fibers can be doped with photosensitive material to change the refractive index when exposed to bright light usually in UV range of spectrum. A structured fiber with combination of cores, holes, and electrodes is used for variety of specialty applications. Optical fiber for imaging is made of multiple noninteracting cores, which is used in endoscopes to directly image internal organs. The use of capillary tube-based optical fibers is used for proteomic and genomic studies. Photonic crystal-based fiber optics is used to study light interactions. Fiber-optic biosensors (FOBS) work as a transduction element and depend on optical transduction mechanisms for detecting biomolecules. They are used for applications such as detection of pathogens, medical diagnosis based on protein or cell concentration, and real-time detection of DNA hybridization. Fiber-optic chemical sensors (FOCS) are used in sensing gases and vapors, medical and chemical analysis, marine and environmental analysis, molecular biotechnology, industrial production monitoring and bioprocess control, and automotive industry.

1.8.4 Application of Sensors/Actuators

1.8.4.1 Fibers as Electronic Devices/Wearable Electronics/Energy Materials/Sensors and Actuators

Wearable electronics is one of the widely spoken technologies in smart textile arena. The functionality of the fabric is due to the electronics and interconnections woven between them. Future generation of wearable electronics focuses on the systems to be worn directly on human body. Wearable electronic systems developed using conductive fibers have shown promising results. The technical possibility for building the electronic functions as integral part or on the surface of the fiber is scientifically proven. The development of soft and flexible fiber-based conductive and semiconductive materials is essential. Conductive polymeric fibers are one of the promising materials due to their extremely flexible nature. It also can be blended with variety of composite materials to achieve unique electronic, optical, electrical, and magnetic properties. Π-Conjugated nanoscaled organic molecules was investigated for sensors, transistors, flexible electronic devices, and field emission display in textiles [57]. Polyaniline and polypyrrole-based nanofibers show high conductivity properties at room temperature [58–60]. Poly-(3,4-ethylenedioxythiophene) (PEDOT) is one of the conductive polymers with high conductivity and solution process ability. The application of this polymer as electrodes for wearable capacitors or photodiodes is currently being explored. Carbon-based nanomaterials due to their intrinsic carrier mobility are used as channel materials in transparent electrode and field-effect transistors. Porous carbon materials like graphene, carbon nanotubes (CNTs), carbon fibers, and carbon aerogels are frequently used in wearable electronics due to their large specific surface area and better mechanical properties. Metallic nanoparticles or nanowires possess high conductivity and are very much suitable for wearable electronics. Metallic nanowires are used to develop fiber-based piezoelectric nanogenerator by coating silver on highly stretchable polyamide fabric [57]. Fiber-based electrodes made of CNTs, metals, or alloys like copper and stainless steel are light, foldable, durable, and flexible, thus more suitable for wearable electronics. Integrating sensors with conductive fibers in the fabrics can be used to monitor electrocardiogram (ECG), electromyography (EMG), and electroencephalography (EEG) [61, 62]. Fabric integrated with luminescent elements could be used for biophotonic sensing; shape-sensitive fabrics is used to sense the movement and used with EMG to obtain muscle fitness data. Integrated carbon electrodes in fabrics help to detect environmental features such as oxygen, salinity, moisture, and contaminants. Strain fabric sensing technology uses conductive yarns to record motion or flexing, pressure, and stretching or compression [63]. Merely conductive yarns of specific length are also used to make fabric antennas by stitching them together with nonconductive fabrics [64].

1.8.4.2 Fibers for Medical Compression

Compression garments are used to apply certain pressure on different parts of body. They are specially used for medical treatments, sports, and body shaping purposes. Medical compression garments are used to treat scars, muscular sprains, and low blood pressure and to quicken healing process for deep vein thrombosis patients [65]. Medical compression systems are usually made using fibers like polyester, polyamide elastane. Recent studies about application of shape memory fibers and alloys in the medical compression have gained attention [55, 66–69]. Shape memory materials are actuated using electrical current and body heat to provide compression effect. Segmented polyurethane-based shape memory fibers have shown promising results, and they have gained advantage over shape memory alloys due to their lightweight, flexibility, comfort, and easy actuation without any additional devices [70].

1.8.4.3 Fibers for Health/Stress/Comfort Management

Fibers within the human body serve as an inspiration for development of different kind of advanced materials. Hollow fibers are used in artificial lung and blood vessels. There are several studies which focus on the production of artificial liver, pancreas, skin, muscle, and nervous systems. Lightweight, sweat-absorbent, and easy dry fibers are developed for sportswear application to keep the wearer feel comfortable during workout. Fibers that can retain heat allow the water vapor from the body to pass through and repel water and are developed to protect people from extreme cold weather conditions. Breathable shape memory polyurethanes fibers and films that can respond according to the microclimatic condition between the clothing and body of the wearer are used. Antibacterial fibers are used in clothing, hospital wear, and wound care bandages to prevent contamination and bad odors caused due to bacteria. Fibers used in comfort applications must have the following properties: absorption of sweat, high water absorbency/quick dry bacteria-free/moss-free, microbe controlling, insect/tick repellent, heat retention/storage, moisture retention, moisture absorption, coolness, tranquilizer moisture permeable/water repellent, deodorant, antibacterial, electric control, UV shielding, electromagnetic wave shielding, insulation, lightweight, fitness to skin, high touch, stretch, soil-free/soil release, and shape stability.

1.8.4.4 Fibers for Thermal Protection

Fibers used for flame and thermal protection play a vital role in providing protection to workers engaging in high temperature environments, military clothing, home furnishing materials, and building materials and for firefighters. The protective clothing made using these fibers must have insulation properties and dimensional stability. Flame-resistant viscose fibers are produced by doping the spinning solution before extrusion using phosphorus-based additives (Lenzing FR®), polysilicic acid, and clay nanocomposites (TENCEL®). Flame-retardant polyester and acrylics are produced using FR comonomers during copolymerization, introducing flame-retardant additives during extrusion and flame-retardant finishes. Aromatic polyamides and meta-aramid fibers are used for protective clothing for astronauts, tank crews, and fighter pilots. Nonwoven meta-aramids are used in thermal insulation and hot gas filtration purposes. Para-aramids are specifically used for ballistic and flame protection applications. Polyimide fiber is an aromatic copolyamide sold in the brand name P84®. It has Limiting Oxygen Index (LOI) of 36–38% and is used in the production of protective clothing, hot gas filtration, sealing materials, and aviation materials.

1.8.4.5 Fibers for Radiation Protection

The need for special protective clothing is inevitable to protect people exposed to radioactive rays, UV radiation, and electromagnetic radiations. Woven cotton, polyester/cotton, and polyester/nylon fabrics with twill and sateen weave and nonwoven fabrics are used to protect people from α, β, and γ radiation environments. The fabric acts as a barrier between human skin and nuclear radiation emitted from radioactive source. Closely woven fabrics made up of wool and polyester have high UV absorption and protect skin from UV-A and UV-B radiations. Humans are exposed to different kinds of electromagnetic radiation extending from 1 to 10 000 mHz emitted by various sources, for example, cell phones, microwave ovens, and radar signal communication systems. When exposed at higher levels, these waves will cause abnormal chemical activities in body that produces cancer cells. It also obstructs the capability of cells for regeneration of DNA and RNA. To tackle this problem conductive materials are used to shield electromagnetic and static charges. General textile fibers have sufficient resistivity to shield electromagnetic radiation. The resistivity required for dissipating and shielding electrostatic charges is achieved through conductive coatings on fabric, fibers doped with carbon black, carbon fibers, and metal fibers. The conductive fibers or yarns are incorporated in fabrics to produce conductive garments to resist static charges.

1.8.5 Applications of Integrated Products

1.8.5.1 Fibers for Tissue Engineering

Tissue engineering concept was born when several investigators realized that when cell are placed close enough to each other, they form structures identical with those formed by such cells in a living body. This, apparently, may be achieved thanks to signals that living cells can exchange with the neighboring ones. Various disciplines, such as materials science, cell biology, reactor engineering, and clinical research, are contributors of tissue engineering. Advanced tissue engineering involves the use of polymeric materials implanted at the defective site. The defective sites are usually supported by scaffolds. They provide the framework for the cells to attach, proliferate, and form results in the formation of extracellular matrix. Biodegradable natural and synthetic fibers as well as some nonbiodegradable polymeric fibers are currently used for tissue engineering. Polylactides, polyglycolides, polycaprolactone (PCL), and their copolymers have been often used for the preparation of scaffolds for cartilage tissue engineering. However, their hydrophobicity, the acidity of their decomposition products, and the self-acceleration of their degradation have constituted serious drawbacks. Chitosan and alginate are nontoxic, biodegradable, biocompatible polymer and does not have these disadvantages. The use of natural polysaccharide like alginates that are extracted from algae has shown promising growth in tissue engineering and wound dressing applications. Alginate fibers and dressings as wound care products are resistant to bacterial attack, antiviral, antifungal, nontoxic, high absorbent, hemostatic, non-allergic, breathable, biocompatible and can blended with medicines. Alginate nanofibers were produced by electrospinning technique in the presence of various synthetic polymers and/or surfactants and sometimes in combination with chitosan offer better cell adhesion properties [71, 72]. Bio-artificial scaffolds made of *Chlamydomonas reinhardtii* single-cell green alga mixed with fibrinogen have shown excellent in vitro biocompatibility and photosynthetic activity, and the algae survived for five days in vivo. These kinds of photosynthetic scaffolds can be implanted in full skin defects and can be used in the generation of chimeric tissue composed of mammalian and photosynthetic cells in vivo [73]. Chitosan, a unique biopolymer derived from chitin, exhibits outstanding properties along with excellent biocompatibility and biodegradability. Chitosan and its blends with sodium alginate, tropocollagen, cellulose, sodium hyaluronate, sodium chondroitin sulfate, poly(acrylic acid), and synthetic polymers like PEO,UMHMWPEO, PVA, PLA, and PVP are used to produce nanofiber mats for tissue engineering and wound healing applications [74]. Collagen fibrils and their networks form a highly organized 3D scaffold to surround the cells. It ensures structural and biological integrity of ECM. Collagen can form fibers with high tensile strength and stability. The hollow fiber made using collagen tubing is used for cell culture nerve regeneration [75]. The unique structure of silk, versatility in processing, biocompatibility, availability of different biomaterial morphologies, options for genetic engineering of variations of silks, the ease of sterilization, thermal stability, surface chemistry for facile chemical modifications, and controllable degradation features make silks promising biomaterials for many clinical functions. Silk fibrous materials are used as scaffolds for tissue engineering and sutures.

1.8.6 Sensitive and Smart Materials

1.8.6.1 Fibers with Conductive Properties as Industrial Materials

Conductive fibers are lightweight alternatives to heavy copper wiring in variety of areas where weight is a concern especially in aerospace technologies. Inherently conductive fibers include metallic fibers, carbon fibers, and conjugated polymeric fibers. Treated conductive fibers are conductive-filled fibers and conductive-coated fibers. Metallic fibers are developed from metals or metal alloys. These fibers have very high conductivity, but they possess low flexibility, stiffness, and high weight. Carbon fiber and its composites possess conductivity like that of metals with high strength, stiffness, and lower weight. Conjugated polymers like PEDOT fibers have high conductivity values from 150 to 250 s/cm. Polymeric fibers filled with conductive fillers like metallic powder, carbon black, CNT, graphene, or conjugated polymer powder are used as conductive fibers. The conductive fibers that can be produced by coating insulating materials with highly conductive materials, such as metals, metal alloys, carbon black, carbon nanotubes, and ICPs, are known as conductive-coated fibers. To apply metallic coatings, sputtering, vacuum deposition, electroless plating, carbonizing, and filling or loading fibers are the most extensively used methods. Potential applications of conductive fibers include power lines; aircraft and aerospace wiring systems; harnesses for automotive wiring; wires for missile guidance; electrotextiles for medical, military, and consumer applications; lightweight deployable antennas; thermal blankets and clothing; flexible keyboards; giant-area flexible circuits for energy harvesting; electrostatic charge dissipation; and battlefield monitoring and reporting of vital signs and wound locations on soldiers.

1.8.6.2 Memory Fibrous Materials

Smart textile is the development of textile having sensing, reacting, and adapting capabilities. Materials or structure that sense react to external stimuli or condition such as thermal, chemical, mechanical, or other sources. Shape memory material can move to temporary shape by external stimulus, and it can come back to its original shape with right stimulus. Memory materials include water vapor permeability textile, ventilation textile, medical textile, thermal protective textile, etc.

1.8.7 Advantages of Fibrous Materials

Fibrous materials have been used from many centuries in the application of clothing and other utilitarian products. Natural fibers are abundantly available in different geological locations with various altitudes in the world, and they are easily processable. Synthetic fibers can be produced with customized parameters according to specific end use without much trouble. The revolutionary breakthrough of research in science and technology in the twenty-first century leads to the use of both natural and synthetic fibrous materials in vivid multidisciplinary applications, owing to their several advantages. This is the era of synthetic fibers now, and it offers platform to tailor their properties suitable to put them into proper end use. Synthetic fibers can be produced into micro-, macro-, and nano-sizes with novel functionalities, which is reliable to produce in mass with low material cost. Fibers do offer several advantages over other materials such as lightweight (less density), superior stretch ability, toughness (e.g. regenerated spider silk), high tensile strength (e.g. silk), high specific surface area, vibration damping capability [77], energy storage ability [78], super absorbency [16] and memory behavior (e.g. shape or stress memory) [79, 80], self-healing [81], biodegradability [82], biocompatibility (e.g. tissue engineering and implants) [83, 84], insulation capability [33], chemical inertness, antimicrobial [85], flame retardancy [86], biomimicking [87], etc. These several advantages of fibrous materials enable one to make them into substrates by traditional textile processing technologies such as weaving, knitting, nonwoven webs, and braiding due to their excellent flexibility and strength. These substrates made from fibers have been employed into various multidisciplinary areas including electronics, construction, power harvesting, aerospace, medical, transportation, and industrial high-performance materials. Both natural and synthetic fibers are needed in daily life to the human being, and smart fibers are considered as futuristic material to prepare well for needs of tomorrow's challenging and sustainable days. Hence fibers play a very vital role in fulfilling our requirements on this planet.

References

1 Denton, M.J. and Daniels, P.N. (2002). *Textile Terms and Definitions*, 11e. Manchester: The Textile in Institute.

2 Morton, W.E. and Hearle, J.W.S. (2008). *Physical Properties of Textile Fibers*, Woodhead Publishing in Textiles. England: Woodhead Publishing Limited.

3 Collier, B.J., Bide, M.J., and Tortora, P.G. (2009). *Understanding Textiles*, 7e. Pearson/Prentice Hall.

4 Houck, M.M. (2009). *Identification of Textile Fibers*, Woodhead Publishing in Textiles. Cambridge: Woodhead Publishing Limited.

5 Blackburn, R. (2005). *Biodegradable and Sustainable Fibers*, Woodhead Publishing Series in Textiles. Woodhead Publishing.

6 Mishra, S.P. (2000). *Fiber Science and Technology*. New Delhi: New Age International (P) Limited.

7 Saville, B.P. (1999). 3 - Fiber dimensions. In: *Physical Testing of Textiles*, 44–76. Woodhead Publishing.

8 Hearle, J.W.S. and Backer, P.G.S. (1969). *Structural Mechanics of Fibers, Yarns, and Fabrics*. Wiley-Interscience.

9 Hu, J.L. (2004). *Structure and Mechanics of Woven Fabrics*, Woodhead Publishing in Textiles. CRC Press; Woodhead Publishing.

10 Yang, Q.X. and Li, G.Q. (2014). Spider-silk-like shape memory polymer fiber for vibration damping. *Smart Materials and Structures* 23 (10).
11 Haigh, H.S. (2009). Speciality fibers. *Journal of the Textile Institute Proceedings* 40 (8): 794–813.
12 Das, T. and Ramaswamy, G.N. (2006). Enzyme treatment of wool and specialty hair fibers. *Textile Research Journal* 76 (2): 126–133.
13 Vineis, C., Aluigi, A., and Tonin, C. (2011). Outstanding traits and thermal behaviour for the identification of speciality animal fibers. *Textile Research Journal* 81 (3): 264–272.
14 Prahsarn, C., Klinsukhon, W., Padee, S. et al. (2016). Hollow segmented-pie PLA/PBS and PLA/PP bicomponent fibers: an investigation on fiber properties and splittability. *Journal of Materials Science* 51 (24): 10910–10916.
15 Tallury, S.S., Behnam, P., Melissa, A.P., and Richard, J.S. (2016). Physical microfabrication of shape-memory polymer systems via bicomponent fiber spinning. *Macromolecular Rapid Communications* 37 (22): 1837–1843.
16 Kim, G.H., Youk, J.H., Kim, Y.J., and Im, J.N. (2016). Liquid handling properties of hollow viscose rayon/super absorbent fibers nonwovens for reusable incontinence products. *Fibers and Polymers* 17 (7): 1104–1110.
17 Beskisiz, E., Ucar, N., and Demir, A. (2009). The effects of super absorbent fibers on the washing, dry cleaning and drying behavior of knitted fabrics. *Textile Research Journal* 79 (16): 1459–1466.
18 Lee, T.W., Han, M., Lee, S.E., and Jeong, Y.G. (2016). Electrically conductive and strong cellulose-based composite fibers reinforced with multiwalled carbon nanotube containing multiple hydrogen bonding moiety. *Composites Science and Technology* 123: 57–64.
19 Schmidt, M.A., Argyros, A., and Sorin, F. (2016). Hybrid optical fibers - an innovative platform for in-fiber photonic devices. *Advanced Optical Materials* 4 (1): 13–36.
20 Xi, P., Tianxiang, Z., Lei, X. et al. (2017). Fabrication and characterization of dual-functional ultrafine composite fibers with phase-change energy storage and luminescence properties. *Scientific Reports* 7 (1): 1–9.
21 Meng, Q.H., Hu, J.L., and Yeung, L. (2007). An electro-active shape memory fiber by incorporating multi-walled carbon nanotubes. *Smart Materials and Structures* 16 (3): 830–836.
22 Meng, Q.H. (2009). The influence of heat treatment on the properties of shape memory fibers. II. Tensile properties, dimensional stability, recovery force relaxation, and thermo mechanical cyclic properties. *Journal of Applied Polymer Science* 111 (3): 1156–1164.
23 Meng, Q.H. (2007). Morphology, phase separation, thermal and mechanical property differences of shape memory fibers prepared by different spinning methods. *Smart Materials and Structures* 16 (4): 1192–1197.
24 Meng, Q.H., Hu, J.L., Zhu, Y. et al. (2007). Polycaprolactone-based shape memory segmented polyurethane fiber. *Journal of Applied Polymer Science* 106 (4): 2515–2523.
25 Pan, N. and Gibson, P. (2006). *Thermal and Moisture Transport in Fibrous Materials*. Cambridge: Woodhead Publishing Limited.

26 Kajiwara, K. (2009). Synthetic textile fibers: structure, characteristics and identify cation. In: *Identification of Textile Fibers* (ed. M.M. Houck), 68–87. Cambridge: Woodhead Publishing Limited.

27 Hess, K. and Naturwissenschaft, H.K. (1944). Over-long-term interferences and micellar fiber refinement in fully synthetic fibers (polyamides and polyesters). *Journal of Physical Chemistry* A193 (171): 196.

28 Hearle, J.W.S. (1958). You have full text access to this content fringed fibril theory of structure in crystalline polymers. *Journal of Polymer Science* 28 (117): 432–435.

29 Hearle, J.W.S. (1963). The fine structure of fibers and crystalline polymers. I. Fringed fibril structure. *Journal of Polymer Science* 7 (4): 1175–1192.

30 Kozasowski, R.M., Mackiewicz-Talarczyk, M., and Allam, A.M. (2012). 5 - Bast fibers: flax A2 - Kozłowski, Ryszard M. In: *Handbook of Natural Fibers*, 56–113. Woodhead Publishing.

31 Roy, S. and Lutfar, L.B. (2012). 3 - Bast fibers: jute A2 - Kozłowski, Ryszard M. In: *Handbook of Natural Fibers*, 24–46. Woodhead Publishing.

32 Roy, S. and Lutfar, L.B. (2012). 4 - Bast fibers: ramie A2 - Kozłowski, Ryszard M. In: *Handbook of Natural Fibers*, 47–55. Woodhead Publishing.

33 Koh, E. and Lee, Y.T. (2017). Antimicrobial activity and fouling resistance of a polyvinylidene fluoride (PVDF) hollow-fiber membrane. *Journal of Industrial and Engineering Chemistry* 47: 260–271.

34 AATCC (2013). *Fiber analysis: qualitative.*

35 Edward, L.G. (1966). *Natural and Manmade Textile Fibers: Raw Material to Finished Fabric*, 1e. New York: Duell, Sloan and Pearce.

36 Lawrence, C.A. (2010). *Advances in Yarn Spinning Technology*. Cambridge: Woodhead Publishing Ltd.

37 Mahadevan, M.G. (2009). Textile spinning, weaving and designing. In: *Chandigarh*, 1e. Abhishek Publications.

38 Vasudeo, K.M. (2013). *Fundamentals of Yarn Winding*. New Delhi: Woodhead Publishing.

39 Ormerod, A. and Sondhelm, W.S. (1995). *Weaving: Technology and Operations*. Manchester: The Textile Institute.

40 Abhijit, M. (2017). *Principles of Woven Fabric Manufacturing*. Boca Raton, FL: CRC Press.

41 Belal, S.A. (2009). *Understanding Textiles for a Merchandiser*, 1e. Dhaka: BMN3 Foundation.

42 Chandra, R.S. (2012). *Fundamentals and Advances in Knitting Technology*. New Delhi: Woodhead Publishing India Pvt.

43 Spencer, D.J. (2001). *Knitting Technology*, 3e. Cambridge: Woodhead Publishing.

44 Albrecht, W. and Fuchs, H.W. (2003). *Nonwoven Fabrics*. Weinheim: Wiley-VCH.

45 Gürses, A., Açıkyıldız, M., Güneş, K., and Gürses, M.S. (2016). *Dyes and Pigments*. Switzerland: Springer.

46 Fu, J. (2013). *Dyeing: Processes, Techniques, and Applications*. Hauppauge, NY: Nova Science Publishers, Inc.

47 Clark, M. (2011). *Handbook of Textile and Industrial Dyeing*. Cambridge: Woodhead Publishing.

48 Arthur, B.D. (2001). *Basic Principles of Textile Coloration*. Bradford: Society of Dyers and Colorists.

49 Trotman, E.R. (1975). *Dyeing and Chemical Technology of Textile Fibers*, 5e. London: Griffin.

50 Kate, W. (1997). *Fabric Dyeing & Printing*. Loveland, CO: Interweave Press.

51 Yohanan, P. (1990). *Dyeing and Printing: A Handbook*. London: Intermediate Technology.

52 Thakur, S., Jahid, M.A., and Hu, J.L. (2018). Mechanically strong shape memory polyurethane for water vapour permeable membranes. *Polymer International* 67: 1386–1392.

53 Jahid, M.A., Hu, H.L., and Zhou, H. (2018). *Smart Textile Coatings and Laminates*, Chapter 6, 155–173.

54 Jahid, M.A., Hu, J.L., Wong, K.H. et al. (2018). Fabric coated with shape memory polyurethane and its properties. *Polymers* 10: 681.

55 Nayak, R. and Padhye, R. (2015). *Garment Manufacturing Technology*. Sawston, Cambridge: Woodhead Publishing, an imprint of Elsevier.

56 Koncar, V. (2016). *Smart Textiles and Their Applications*. Duxford: Woodhead Publishing.

57 Horrocks, A.R. and Anand, S.C. (2016). *Handbook of Technical Textiles*, 2e. Cambridge: Woodhead Publishing in association with the Textile Institute, Woodhead Publishing is an imprint of Elsevier.

58 Meng, Q. and Hu, J.L. (2008). A temperature-regulating fiber made of PEG-based smart copolymer. *Solar Energy Materials and Solar Cells* 92 (10): 1245–1252.

59 Zhu, Y., Hu, J.L., and Yeung, K.W. (2009). Effect of soft segment crystallization and hard segment physical crosslink on shape memory function in antibacterial segmented polyurethane ionomers. *Acta Biomaterialia* 5 (9): 3346–3357.

60 Jang, S.Y., Seshadri, V., Khil, M.S. et al. (2005). Welded electrochromic conductive polymer nanofibers by electrostatic spinning. *Advanced Materials* 17 (18): 2177–2180.

61 Huang, K., Wan, M., Long, Y. et al. (2005). Multi-functional polypyrrole nanofibers via a functional dopant-introduced Process. *Synthetic Metals* 155 (3): 495–500.

62 Huang, J. and And Kaner, R.B. (2004). Nanofiber formation in the chemical polymerization of aniline: a mechanistic study. *Angewandte Chemie International Edition* 43 (43): 5817–5821.

63 Zeng, W., Tao, X.M., Chen, S. et al. (2013). Highly durable all-fiber nanogenerator for mechanical energy harvesting. *Energy & Environmental Science* 6 (9): 2631–2638.

64 Coosemans, J., Hermans, B., and Puers, R. (2006). Integrating wireless ECG monitoring in textiles. *Sensors and Actuators A: Physical* 130: 48–53.

65 Custodio, V., Herrera, F.J., Lopez, G., and Moreno, J.I. (2012). A review on architectures and communications technologies for wearable health-monitoring systems. *Sensors* 12 (10): 13907–13946.

66 Pacelli, M., Taccini, N., and Paradiso, R. (2006). Sensing fabrics for monitoring physiological and biomechanical variables: E-textile solutions. *2006 3rd IEEE/EMBS International Summer School on Medical Devices and Biosensors*.

67 Salonen, P. and Hurme, L. (2003). A novel fabric WLAN antenna for wearable applications. *IEEE Antennas and Propagation Society International Symposium. Digest. Held in conjunction with: USNC/CNC/URSI North American Radio Sci. Meeting (Cat. No.03CH37450)*.

68 Wang, L., Felder, M., and Cai, J. (2011). Study of properties of medical compression fabrics. *Journal of Fiber Bioengineering & Informatics* 4 (1): 15–22.

69 Kumar, B., Hu, J.L., and Pan, N. (2016). Smart medical stocking using memory polymer for chronic venous disorders. *Biomaterials* 75: 174–181.

70 Kumar, B., Hu, J.L., and Pan, N. (2016). Memory bandage for functional compression management for venous ulcers. *Fibers* 4 (1): 10.

71 Moein, H. and Menon, C. (2014). An active compression bandage based on shape memory alloys: a preliminary investigation. *Biomedical Engineering Online* 13: 135.

72 Zhu, Y., Hu, J.L., Yeung, K.W. et al. (2007). Effect of cationic group content on shape memory effect in segmented polyurethane cationomer. *Journal of Applied Polymer Science* 103 (1): 545–556.

73 Rinaudo, M. (2014). Biomaterials based on a natural polysaccharide: alginate. *TIP* 17 (1): 92–96.

74 Jeong, S.I., Krebs, M.D., Bonino, C.A. et al. (2010). Electrospun alginate nanofibers with controlled cell adhesion for tissue engineering. *Macromolecular Bioscience* 10 (8): 934–943.

75 Schenck, T.L., Hopfner, U., Chavez, M.N. et al. (2015). Photosynthetic biomaterials: a pathway towards autotrophic tissue engineering. *Acta Biomaterialia* 15: 39–47.

76 Croisier, F. and Jérôme, C. (2013). Chitosan-based biomaterials for tissue engineering. *European Polymer Journal* 49 (4): 780–792.

77 Chattopadhyay, S. and Raines, R.T. (2014). Review collagen-based biomaterials for wound healing. *Biopolymers* 101 (8): 821–833.

78 Deng, J., Ye, Z., Yang, Z. et al. (2015). A shape-memory supercapacitor fiber. *Angewandte Chemie International Edition* 54 (51): 15419–15423.

79 Narayana, H., Hu, J.L., Kumar, B. et al. (2017). Stress-memory polymeric filaments for advanced compression therapy. *Journal of Materials Chemistry B* 5 (10): 1905–1916.

80 Tonazzini, A., Stefano, M., Bryan, S. et al. (2016). Variable stiffness fiber with self-healing capability. *Advanced Materials* 28 (46): 10142–10148.

81 Emmert, M., Patrick, W., Miranda, R.G., and Doris, H. (2017). Nanostructured surfaces of biodegradable silica fibers enhance directed amoeboid cell migration in a microtubule-dependent process. *RSC Advances* 7 (10): 5708–5714.

82 Akbari, M., Tamayol, A., Bagherifard, S. et al. (2016). Textile technologies and tissue engineering: a path toward organ weaving. *Advanced Healthcare Materials* 5 (7): 751–766.

83 O'Connor, R.A. and McGuinness, G.B. (2016). Electro spun nanofibre bundles and yarns for tissue engineering applications: a review. *Proceedings of* *the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine* 230 (11): 987–998.

84 Korjenic, A., Zach, J., and Hroudova, J. (2016). The use of insulating materials based on natural fibers in combination with plant facades in building constructions. *Energy and Buildings* 116: 45–58.

85 Shukla, A., Basak, S., Ali, S.W., and Chattopadhyay, R. (2017). Development of fire retardant sisal yarn. *Cellulose* 24 (1): 423–434.

86 Zhang, K., Fan, L., Yan, Z. et al. (2012). Electrospun biomimic nanofibrous scaffolds of silk fibroin/hyaluronic acid for tissue engineering. *Journal of Biomaterials Science Polymer Edition* 23 (9): 1185–1198.

87 Weng, W., Chen, P., He, S. et al. (2016). Smart electronic textiles. *Angewandte Chemie International Edition* 55 (21): 6140–6169.