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Review

Biomimicry in textiles: past, present and potential. An overview

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The natural world around us provides excellent examples of functional systems built with a handful of materials. Throughout the millennia, nature has evolved to adapt and develop highly sophisticated methods to solve problems. There are numerous examples of functional surfaces, fibrous structures, structural colours, self-healing, thermal insulation, etc., which offer important lessons for the textile products of the future. This paper provides a general overview of the potential of bioinspired textile structures by highlighting a few specific examples of pertinent, inherently sustainable biological systems. Biomimetic research is a rapidly growing field and its true potential in the development of new and sustainable textiles can only be realized through interdisciplinary research rooted in a holistic understanding of nature.

Keywords: biomimetics; bionics; biomimicry; textiles; fibres

1. INTRODUCTION

Animals, plants and insects in nature have evolved over billions of years to develop more efficient solutions, such as superhydrophobicity, self cleaning, self repair, energy conservation, drag reduction, dry adhesion, adaptive growth and so on, than comparable man-made solutions to date. Some of these solutions may have inspired humans to achieve outstanding outcomes. For example, the idea of fishing nets may have originated from spider webs; the strength and stiffness of the hexagonal honeycomb may have led to its adoption for use in lightweight structures in airplane and in many other applications. The term ‘biomimicry’, or imitation of nature, has been defined as, ‘copying or adaptation or derivation from biology’ [1]. The term ‘bionics’ was first introduced in 1960 by Steele [2] as, ‘the science of systems which has some function copied from nature, or which represents characteristics of natural systems or their analogues’. The term ‘biomimetics’ introduced by Schmitt [3] is derived from *bios*, meaning life (Greek) and *mimesis*, meaning to imitate [4]. This ‘*new*’ science is based on the belief that nature follows the path of least resistance (least expenditure of energy), while often using the most common materials to accomplish a task. Biomimetics, ideally, should be the process of incorporating principles that promote sustainability much like nature does from ‘cradle to grave’, from raw material usage to recyclability.

Although the science of biomimetics has gained popularity relatively recently, the idea has been around for thousands of years. Since the Chinese attempted to make artificial silk over 3000 years ago [5], there have been many examples of humans learning from nature to design new materials and devices. Leonardo da Vinci, for example, designed ships and planes by looking at fish and birds, respectively [6]. The Wright brothers designed a successful airplane only after realizing that birds do not flap their wings continuously; rather they glide on air currents [6].

Engineer Carl Culmann in 1866, while visiting the dissecting room of anatomist Hermann Von Meyer, discovered striking similarity between the lines of stresses (tension and compression lines) in a loaded crane-head and the anatomical arrangement of bony trabeculae in the head of a human femur. In other words, nature has strengthened the bone precisely in a manner dictated by modern engineering [7]. Arguably, one of the most well-known examples of biomimetics is a textile product. According to the story, George de Mestral, the Swiss inventor went for a walk in the fields with his dog. Upon his return, he noticed burrs stuck to his trousers and to his dog’s fur. Upon closer inspection of the burrs, de Mestral discovered their hook-like construction, which led to his invention of the hook and loop fastener, Velcro (http://www.velcro.com/index.php?page=company).

There are many more examples of inventions drawing their inspiration from biological systems. This review explores the field of biomimetics as it relates to textiles. The exploration begins with a general overview, followed by a historical perspective; it describes some ongoing efforts in biomimetic textiles. Finally, it explores the potential of use of biomimetic materials and products towards the attainment of sustainable textiles.

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2. TEXTILES: A NECESSITY OF LIFE

Almost every animal in nature has some sort of protective layer, be it bare skin, skin with feathers, hair, fur, scales, shell or hide. Often it is meant to protect against predators and/or the environment, provide comfort or improve the individual's aesthetic appeal (attractiveness). Prehistoric humans used leaves, tree barks, feathers, animal hide, etc., to protect against the environment and/or enhance their aesthetic appeal. Humans with highly developed brain and other anatomical features, during their evolution, found themselves inadequately protected from a variety of adverse environmental conditions. This led to the need for additional covering of the skin on parts of their bodies; ergo, clothing in different manifestations.

The practice of fashioning materials into clothing is arguably older than pottery and perhaps farming [8]. The oldest known fragments of a variety of textiles, found in Nahal Hemar (Dead Sea, Israel), are from the 7th millennium BC (the early Neolithic period), and those from Catal Huyuk (southern Anatolia, Turkey) from around 6000 BC [8]. The textiles found in both cases are mostly flax (or linen) with occasional use of other fibres. The sophistication found in the design of the oldest known fragments of woven fabric from the late Neolithic period recovered from a lakebed in Switzerland is astonishing and dates back to 3000 BC [8].

Over the years, clothing evolved to serve as an expression of culture and social status; it also plays a part in attracting or discouraging a mate. Throughout human history, textiles and clothing have been synonymous. The term 'textiles' is derived from the Latin word *texere*, meaning 'to weave'; in other words, the term textiles referred to woven fabrics only. The process of weaving involves interlacement of two pre-arranged orthogonal sets of 'long' and 'flexible' strands or yarns. The terms 'long' and 'flexible', today, imply yarns that are either assembled from fibres or are manufactured as continuous flexible strands.

Today's textiles include cords and ropes to fabrics manufactured through various technologies including weaving, knitting, non-wovens and combinations thereof. Textile structures are valued for their low weight, flexibility and extraordinary properties. Whether it is a protective turnout coat for the firefighter, a parafoil to drop thousands of pounds of supplies, a set of tyres mounted on the landing gear of the newest aircraft, the Teflon-coated Kevlar airbags used in landing spacecrafts on Mars or the super-absorbent diapers of your new born, all of these innovations are born out of high-performance materials and technologies as well as excellent engineering design with textiles. Needless to say, modern-day textiles are far more than just clothing. Indeed, more than 75 per cent of the fibres used in the USA in 2008 were in products other than clothing and home textiles [9]. In fact, a broader definition, which describes textiles as flexible products made primarily of polymeric (natural or man-made) fibres, is more appropriate today.

Most natural materials are polymers (proteins and polysaccharides), polymer composites and some minerals (e.g. Ca and Si). Few metallic elements are used both as structural (e.g. Zn or Mn in insect mandibles) and functional (e.g. Fe in red blood cells) materials [10,11]. To obtain a very wide range of functionalities, nature combines these materials in many shapes and forms, often in a hierarchical fashion. Textile structures are inherently hierarchical. Levels of hierarchy, however, vary. At the macro-level, a simple woven or knit fabric has three levels of hierarchy: fibre to yarn to fabric. However, as pointed out by Vincent [11], fabric is an assembled structure rather than a material.

The earliest fibres used in textiles were flax (or linen), hemp, nettle, willow, etc., found in the wild. Earliest evidence of the domestication of fibre, flax, comes from Iraq and is dated close to 5000 BC [8]. A more recent discovery of cotton yarn used to string copper beads in a Neolithic burial site at Mehrgarh in the Greater Indus area indicates the use of cotton fibre in the 6th millennium BC [12]. Evidence of the first use of wool is a bit murky, but is assumed to be around 5000 BC [8]. The earliest awareness of silk, the only fibre that is found as a long continuous strand in nature, comes from the Shahnshi province of China and dates back to the Neolithic period [8]. Until the early twentieth century and the invention and commercialization of regenerated fibres (rayons), these were the only available textile fibres. The introduction of a number of key manufactured fibres (polyester, polyethylene, polyacrylonitrile, polypropylene, etc.) followed at a relatively rapid pace. Since the introduction of nylon in the early 1930s, the search for even better (stronger, tougher, etc.) fibres has been on. In the late twentieth century, a new generation of polymeric and inorganic high-performance man-made fibres with exceptional properties was introduced [13]. These include various meta- and para-aramid (e.g. Nomex, Kevlar are DuPont registered trademarks), aromatic polyester (e.g. Vectran is a Kuraray registered trademark), ultra-high molecular weight polyethylene (e.g. Spectra is a Honeywell registered trademark), ceramic (Nicalon is a Nippon Carbon Co. registered trademark) fibres. Today, numerous man-made fibres are available in the inventory of a textile designer, which can meet exacting functional requirements for use in the home or in the next space exploration.

3. LESSONS FROM NATURE

For many reasons, textiles provide unique opportunities to emulate nature. The building blocks of every textile structure at the lowest level of hierarchy (nano to micro) are organic fibres, and many of these are natural. In addition, like many natural functional surfaces, the large surface area of fibrous textiles offers tremendous opportunities to functionalize them. All of these attributes lend textiles more to biomimetic concepts than others.

3.1. Diverse use of fibres

Nature is full of excellent examples of building with fibres. A more obvious example is in the cobwebs formed by certain species of spiders. These are made up of short irregular strands of fibres arranged almost randomly while the orb-webs made by other species of spiders are regular, elegant and elaborate.

Plants and trees provide other superb examples of fibrous structures. In many cases, the fibres are arranged or oriented in a particular manner to impart desired mechanical properties to the structure. A good example is the coconut palm (*Cocos nucifera*, Linn.) tree. The coir fibre derived from its seed husk is well-known and used in floor coverings, mattress fillings and others. Among other fibres found on a coconut palm, the layers of fibrous sheets in the leaf-sheath (base of the leaf stalk attached to the tree trunk) with fibres in the alternating sheets oriented nearly orthogonal to each other appear to be already in a woven structure [14] (figure 1). Interestingly, the leaf-sheath consists of three distinct types of multicellular fibres made of mostly cellulose and lignin arranged in a highly ordered structure. The mechanical properties of these three types of leaf-sheath fibres are vastly different from each other [14].

Wood and bamboo are excellent examples of natural fibrous composites with high work of fracture. Wood consists of parallel hollow tubular cells reinforced by spirally wound cellulosic fibrils embedded in a hemicelllulose and lignin matrix. The helix angle of the spiral fibrils controls various mechanical properties including stiffness and toughness of wood [16–19]. Bamboo is one of the strongest natural fibrous composites with many distinguishing features. It is a hollow cylinder with almost equidistant nodes. Bamboo also has a functionally graded structure in which fibre distribution in the cross section in the bamboo's culm is relatively dense in the outer region [20]. The chemical composition of bamboo is very similar to wood but its mechanical properties are very different. Wood tracheid and bamboo fibres [21,22] are both hollow tubes (or with a lumen) composed of several concentric layers and each layer is reinforced with helically wound microfibrils. The difference in properties originates from the number of fibre layers and microfibrillar orientation angles [21].

Nature also has an abundance of examples of responsive fibrous structures. Many plants are able to produce passive actuation of organs by controlling anisotropic deformation of cells upon exposure to moisture. Plant cell walls are made of stiff cellulosic fibrils embedded in a moisture-sensitive softer matrix consisting of hemicelluloses, pectin and hydrophobic lignin. The absorption and desorption of moisture by the plant cell wall matrix causes anisotropic deformation of the cell wall [23]. The orientation of the cellulosic fibrils in the cell walls as well as their stiffness is crucial in determining the degree as well as the direction of the bending actuation [24]. Pine cones are known to use this hygromorphic behaviour in distributing their seeds. Drying at ambient humidity causes a close and tightly packed pine cone to open up slowly owing to the bilayered structure of the individual scales [24,25]. The mechanism of pine cone opening relies on the humidity sensitive outer layer of the ovuliferous scales to expand or shrink in response to moisture in the atmosphere, while the inner layer remains relatively unresponsive [24]. News reports (http://news.nationalgeographic.com/news/2004/10/1013_041 013_smart_clothing_2.html) point to a recent effort at the University of Bath to develop a bilayer fabric, which reportedly opens up its pores in the presence of increased moisture (owing to perspiration in warm weather) and thereby promotes cooling.

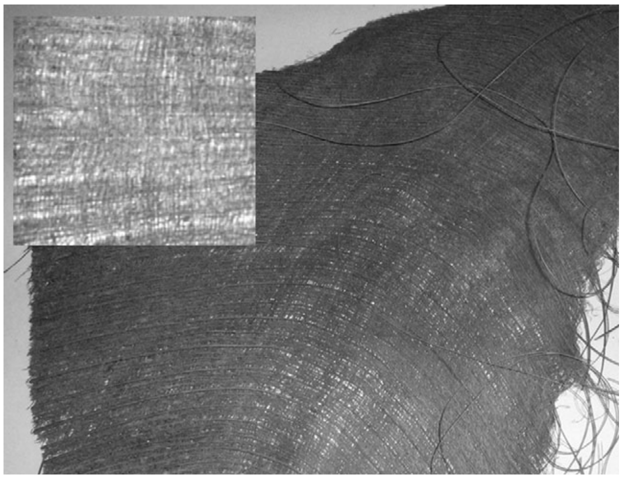

Figure 1. Photograph of coconut tree leaf-sheath. Inset is the inner mat of the leaf-sheath. With kind permission from Springer Science + Business Media [15, fig. 1*b*,*c*].

From plants to animals, one of the unique uses of fibres in structural construction is that of the skeleton of glass sponge *Euplectella* as reported by Aizenberg *et al.* [26] (figure 2*a*,*b*). The hierarchical structure is made of lamellar fibres of silica nanospheres at the nanoscale to rectangular lattice formed by rigid fibre-composite beams at the macroscale. The resulting remarkable truss-like cylindrical, skeletal structure made of the intrinsically low strength and brittle material, glass, is stable and is able to withstand tensile and shear stresses caused by currents while attached to the ocean floor. Interestingly, the structure is very similar to that of a triaxial fabric developed by Dow in 1969 to obtain a more 'isotropic' and stable structure appropriate for space applications [27].

For many years, traditional silk from *Bombyx mori* and *Antheraea pernyi* moths has been the only natural continuous fibre (filament) available in large quantities and valued by humans. It has been used for luxury fabrics and in technical applications, such as in parachutes, for its fineness, low weight, lustre, softness and strength. People have sought to mimic these fibres for ages [28]. The more recent interest in the study of spider silks is because of their unique combination of strength and toughness, which make them a model engineering material. Spider (Araneae) silks are protein-based biopolymer filaments with exceptional mechanical properties despite being spun at almost ambient temperature and pressure and with water as solvent [29]. It is an excellent example of nature's use of protein as an adaptable building material. The superior properties of these silks are attributed to their semi-crystalline polymer structure [30].

There are over 34 000 species of spiders and most are capable of spinning task-specific silk of varying mechanical properties [31]. Some spiders, specifically the orb-weaving *Araneid* and *Aloborid* spiders, have the ability to spin a variety of different silks depending

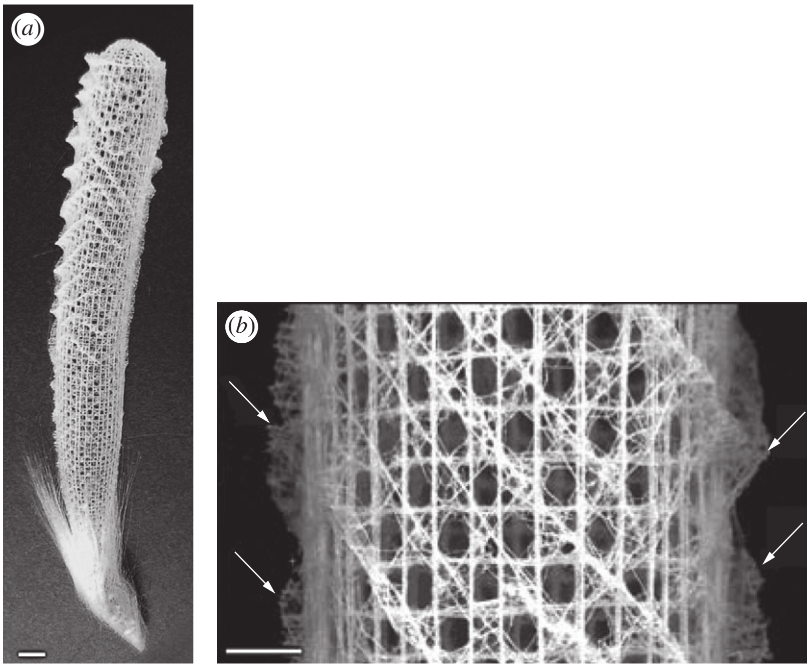

Figure 2. The mineralized skeletal system of *Euplectella* sp. showing (*a*) a photograph of the entire skeleton (scale bar, 1 cm) and (*b*) a fragment of the cage structure showing the square-grid lattice of vertical, horizontal and diagonal struts of the cylinder (scale bar, 5 mm). Adapted from Aizenberg *et al.* [26]. Reprinted with permission from AAAS.

Table 1. Range of properties of different types of spider silks and other fibres (adapted from [33–37]).

material	uses	strength (GPa)	elongation (%)	modulus (GPa)	energy to break (kJ kg^{-1})
cocoon silk (*Bombyx mori*)	cocoon	0.6	14	6	—
dragline silk (major ampullate)	dragline, frame threads	0.7–2.3	22–39	9.5–30	130–195
minor ampullate	dragline reinforcement	1	5	—	30
flagelliform silk	capture spiral within web	0.1–0.5	≤300	≤1	100
aciniform	envelop prey	360	46	0.6	—
aggregate	sticky silk glue for capture spiral	—	517	—	—
Kevlar		2.9–3.0	2.5–4.0	70–115	33
nylon		0.3–0.7	15–40	7–34	60
steel		1.5	0.8	190–210	0.76

on their need at a specific time [28]. Orb-weaving spiders use specialized abdominal glands to synthesize up to seven different protein-based silks and glues often simultaneously [29,30,32]. *Araneids*, it is hypothesized, produce the diverse silk properties by the expression of different fibroin genes [30]. Using the seven different silk glands, a typical *Araneid* orb-weaving spider produces different silk forms including: (i) the major ampullate, which is extremely tough and forms the primary dragline as well as the web-frame, (ii) the minor ampullate with high tensile strength and low elasticity used in web construction, (iii) the flagelliform (a viscid silk) which is highly extensible and forms the capture spiral, and (iv) the aciniform, which is the prey wrapping silk [30,31]. In short, orb spiders are capable of modulating silk properties ranging from low modulus highly extensible elastomers to high modulus, high tenacity and high toughness fibres.

There is great deal of similarity between the processes used to industrially produce many of the high-performance fibres and those used by spiders. In the case of spiders, the synthesis of silk protein(s) takes place in columnar epithelial cells and is secreted into a storage gland. The 'spinning dope' or the silk protein, in liquid crystal form is drawn down as it passes through ducts, from the glands to the spinnerets [29,33]. It has been shown that the silk becomes highly oriented as it passes down the ducts [29].

The dragline silk, the main structural web silk, has been the focus of numerous research investigations because it is among the strongest known fibres of any kind. It is the main component of spider webs, and also serves as the spiders' lifeline along which they swing and move. Typically, dragline silk has very high strength, high elongation and excellent toughness as seen in table 1.

Interestingly, one of the strongest fibres, Kevlar, a para-aramid, is stronger than the dragline silk but the silk is significantly more extensible and about five times tougher than Kevlar. Spider silk fibres are also thermally stable up to approximately 230°C. Cunniff *et al.* [34] reported two thermal transitions of dragline silk from the spider *Nephila clavipes*, one at −75°C, which is believed to represent the motion of amorphous regions of the fibre, and the other at 210°C being the glass-transition temperature.

A potential problem with dragline silk is that it contracts significantly when unrestrained and wetted. The wetting causes the length to shrink by more than half while its diameter more than doubles [38–41]. This phenomenon is known as supercontraction. Under restrained conditions, the supercontraction can generate stresses in the range of 10–140 MPa [38]. This finding has implications for the use of spider silk in applications where exposure to moisture is likely. To get around the problem, incorporation of the fibres in a water-resistant matrix or the development of methods to remove the water-sensitive sequence from the polymer itself has been suggested [39]. Interestingly, the minor ampullate silk does not show supercontraction.

Interestingly, the flagelliform silk, used in the capture spiral of the orb spider's web, is not sticky by itself. To provide stickiness, the spider uses other silks and glue [32]. The flagelliform silk has also been studied for its unique properties. This silk possesses exceptional stretch and recovery behaviour and is significantly tougher than Kevlar, bone and elastin [36,42]. These mechanical properties of flagelliform silk are believed to be derived from the amino acid sequencing and arrangement within the silk strands, which exhibit helical spring-like configurations [42]. These fibres possess considerable strength even though they exhibit elastomer-like extensibility.

Obviously, emulating the spider's silk and possibly its production method seem very attractive. The ability to produce natural protein fibres with tailorable properties in a 'green' process to replace the energy-intensive, often environmentally detrimental and non-recyclable fibres is definitely advantageous.

For reasons delineated above, dragline silk of the golden-orb weaver, *N. clavipes*, has attracted a great deal of research effort. Advances in biotechnology have opened up new, potential, pathways to extract, synthesize and assemble proteins in large scale for eventual production of silks. These proteins consist of various amino acids strung together by the organism in an exact sequence to produce specific characteristics. The amino acid sequences of a number of different proteins in silk fibres have been identified [36] and are known to form β-pleated sheet crystals. The exact amino acid sequence for the dragline silk of the araneid spider *N. clavipes* was found to be quite similar to that of silkworm moth silk produced by *B. mori*. The slight differences noted in the sequence, however, result in the drastic property differences observed [28,36]. Spiders draw fibres from a solution containing about 50 per cent protein in liquid crystalline form secreted and stored in a specialized sac [29,31]. The solution flows through a tapered duct and is drawn down using minimal forces as the fibre forms [29]. Vollrath & Knight [43] suggests that the thin cuticle surrounding the spider's duct acts as a dialysis system, which removes water and sodium ions; the change in the ionic composition converts the aqueous polymer dope into an insoluble protein fibre. This mechanism, it is believed, results in the strong and tough core and coat composite structure observed in spider-silk fibres [44]. This spinning mechanism of the spider may in fact influence the structure formation and the resulting high performance more than the sequence of amino acids [29,43].

Various methods to spin artificial spider silk have been explored. These include conventional wet spinning of regenerated dragline silk obtained through forced silking [45] and reconstituted *B. mori* fibres [46,47], solvent spinning of recombinant spider silk protein analogue produced via bacteria and yeast cell cultures doped with chemically synthesized artificial genes [35], and spinning of silk monofilaments from aqueous solution of recombinant spider silk protein obtained by inserting the silk-producing genes into mammalian cells [48]. In general, such manufactured fibres have properties close to those of spider silk. The results generally suggest that it should be possible to manufacture fibres with properties comparable to dragline silk with the optimization of the spinning process.

Another recent discovery involves natural fibrous structures on gecko feet, which give them the ability to stick (dry adhesion) to and move along very smooth surfaces, often upside down [49,50]. The skin on a gecko's feet consists of a hierarchical structure of rows of setae, and spatulae (figure 3*a*,*b*). The footpad of a gecko is covered with very high density (about 5000 mm^{-2}) of tiny fibres (setae). Furthermore, each seta branches into hundreds of spatulae with dimensions of approximately 100 nm (figure 3*b*) [49]. The complex structure uses a relatively simple mechanism of adhesion using van der Waals forces. Simply put, when two surfaces come in intimate contact with each other, considerable van der Waals forces can be generated [51]. Results of direct setal force measurements attribute the adhesion to van der Waals forces rather than suction, friction or electrostatic forces. The tiny fibre ends (spatulae) allow relatively unconstrained local deformation which is required to generate intimate contact with surfaces having local irregularities. Each gecko foot-pad seta can resist an average force of 20 μN, resulting in an adhesive force of 10 N for a foot pad area of approximately 100 mm^2 [49]. Some gecko species have adhesion strength capabilities as high as 100 kPa [52]. Although such strong adhesive forces would make the movement of the gecko difficult, this lizard has developed a unique way of walking by curling its toes for attachment and peeling during detachment to eliminate the forces between its foot and the surface, thereby enabling it to move with ease [49,50,52].

Since this discovery, many attempts have been made to construct the surface structure of gecko feet into a man-made material in order to achieve dry adhesion. The task seems to be simple in that it requires fabrication of millions of tiny densely packed nanofibres standing up on their ends on a substrate much like flocked fabric surface. Needless to say, it turns out to

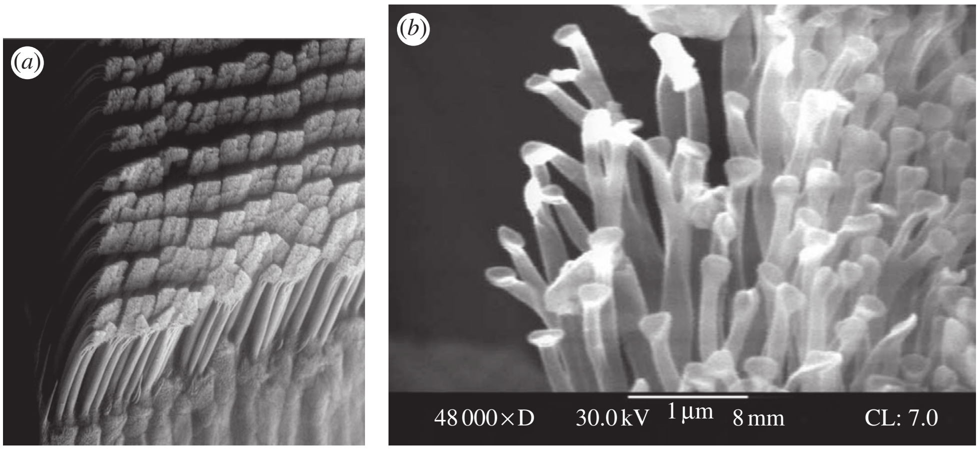

Figure 3. (*a*) Standard electron microscopy (SEM) image showing rows of setae on the bottom of a gecko's foot; (*b*) SEM image of spatulae on a gecko's foot. Adapted from Autumn *et al.* [49]. Reprinted by permission from Macmillan Publishers Ltd: *Nature* [49], copyright © 2000.

be lot more complicated. The first challenge is to ensure that the tiny fibres are of sufficiently high aspect ratio in order to be able to make contact with the contacting surface, which is often microscopically irregular [53]. The need for high aspect ratio leads to the second challenge in that the fine fibres tend to collapse and stick to each other leading to matting and entanglement [53,54]. Additionally, if the spacing between adjacent fibres is too small, the intermolecular forces acting between the fibres lead to bunching [52]. Theoretical analyses as well as experimental data point to the need for high modulus fibres of high aspect ratio with small inter-fibre spacing to achieve good adhesion [54]. Synthetic gecko foot fibres have been created using various materials and techniques. These include, for example, nanomoulding using silicone [55,56], polyimide [55], polyvinylsiloxane [57] and polyurethane, photolithography using polyimide [58], carbon nanotubes [59] and polyurethane [54]. The reported adhesion strength in many of these cases exceeded that of gecko feet. Some of the most impressive results, arguably, are those obtained when carbon nanotubes are used as hairs. Independent reports by Ge *et al.* [60] and Yurdumakan *et al.* [61] claim that carbon nanotube-based gecko tapes can support significantly higher stresses than those supported by gecko feet.

3.2. Functional surfaces

Natural surfaces offer examples of remarkable diversity of properties. Much like dry adhesion of gecko feet, examples of lack of adhesion in nature, in particular on plant surfaces, have attracted considerable scientific attention. Plants have evolved over the last 460 Myr to adapt to their natural environment. The surface structures of plants consist of many different cell types, cell shapes and cell surface structures, resulting in a huge variety of plant surfaces observed today. To create a protective barrier, plants have developed a continuous extracellular membrane or cuticle. The cuticle of most plants is made of a polymer, cutin, and soluble lipids. The water repellency and self-cleaning properties of many plant surfaces have been attributed to not only the chemical constituents of the cuticle covering their surface, but more to the specially textured topography of the surface [62–64]. In addition to the lipids that are incorporated into the cuticle of the plant, the textured surface topography is the result of distribution of small three-dimensional crystals of the epicuticular waxes (lipids). It is these surface structures that provide the model for superhydrophobic textiles [65].

While hydrophobicity is present in numerous plant surfaces, the superhydrophobic[1] (and self-cleaning) behaviour of lotus (*Nelumbo nucifera*) leaves has drawn iconic interest. Water drops on lotus leaves bead up with a high contact angle and roll off, collecting dirt along the way, in a mechanism known as self-cleaning. Plant leaves, in general, possess textured surfaces with hierarchical micrometre- and nanometre-sized structures [62,66,67] and show superhydrophobic behaviour. The first structure is the basic micro-level mound-like protrusions consisting of papillose epidermal cells. The secondary structure consists of nanoscale branch-like growths occurring on the epidermal cells as shown in figure 4*a*,*b* [68,69]. This is important for superhydrophobicity, as is the low-surface energy epicuticular wax found on lotus leaves. The micrometre-sized (5–9 μm diameter) papillae trap air when they come into contact with a water droplet. The roughness of the papillae leads to a reduced contact area between the surface and a liquid drop (or a contaminant particle) and helps create what has been called a re-entrant surface [70]. The droplets rest only on the top of the epidermal cells, and as a consequence, dirt particles can be picked up by the liquid and carried away as the liquid droplet rolls off the leaf. This occurs because there are only weak van der Waals forces between the leaf surface and the dirt particles, whereas stronger capillary forces exist between the water droplet and the dirt [65]. It is not clear if the surface geometry (bumps and hairs) or compositional (lipids) effect plays a more important role in the observed superhydrophobicity or the so-called 'lotus effect'.

[1]A surface with a high advancing water contact angle, typically 150° or higher, and a very low contact angle hysteresis (or a very low sliding angle), typically below 15° is considered superhydrophobic.

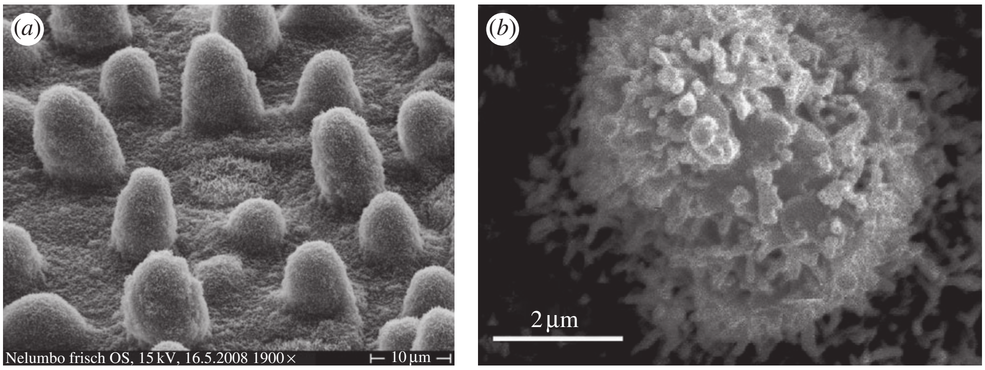

Figure 4. (*a*) SEM image of the surface of a lotus leaf showing papillae and epicuticular wax. Reprinted from Koch *et al.* [65]. Copyright © (2009), with permission from Elsevier. (*b*) SEM image showing the surface characteristics of a single papilla constituting the surface of a lotus leaf. Reprinted with permission from Sun *et al.* [68]. Copyright © American Chemical Society (2005).

Superhydrophobic surfaces have important technical applications such as antifogging and self-cleaning coatings, microfluidics, etc. Superhydrophobicity in textiles is important in applications such as outdoor clothing, carpets, architectural fabrics, etc. The importance of water repellency in textiles was recognized long before biomimetics became popular and is highlighted by the excellent two-part review by Schuyten *et al.* [71] published in 1948.

The approaches to engender the lotus effect on surfaces in general and textiles in particular fall into two categories. The first approach involves creating nano-/microscale surface topography [68,72–74] and the second approach consists of lowering surface energy by chemical modification [75,76]. In fact, surface texture modification in conjunction with surface chemistry modification has been used to create surfaces that can support a robust composite (solid–liquid–air) interface and in turn behave superhydrophobically and/or superoleophobically [77,78].

In a 2006 paper, Gao and McCarthy presented a practical and simple way of imparting superhydrophobicity to a textile surface. The process involved simple silicone-coating of two polyester fabrics containing conventional (coarser) and micro- (finer) fibres, respectively, using a method described in a patent of 1945 [79]. The finer topography of the microfibres fabric reportedly produced water repellency superior to that of lotus leaf [76].

In a recent paper, Choi *et al.* [80] reported a simple dip-coating of extremely low-surface energy flurodecyl polyhedral oligomeric silsesquioxane (POSS) molecules on commercial fabrics to engender significant water repellency. They define two critical parameters, namely fibre radius and fibre spacing as dominant parameters in determining fabric-wetting behaviour. Their data demonstrate biaxial stretching (to control fibre spacing) as a means to control the wetting characteristics of fabrics. The same group earlier demonstrated superoleophobic behaviour of an electrospun fibreweb of ploy(methyl methacrylate) blended with flurodecyl POSS [70]. Plasma coating of fluropolymers on nonwoven fabrics has proven more beneficial for liquid repellence than in the case of woven fabrics because of surface hairs in non-wovens [75]. Hoefnagels *et al.* [81] report covalent bonding of silica particles onto cotton fibres and subsequent chemical modification through dip-coating in polydimethylsiloxane to obtain a superhydrophobic surface. Recently, the same group reported applying relatively larger sized (approx. 800 nm) silica nanoparticles onto woven fabrics followed by surface perfluorination to achieve superoleophobicity [82].

Similar to the lotus leaf, taro leaf, rice leaf, duck feathers, legs of water striders, butterfly wings and many others show notable superhydrophobic behaviour. Besides being hydrophobic, duck feathers (and those of other water birds) also exhibit good thermal-insulating properties. However, when they are excessively wet, the feathers tend to clump together, hold water (thereby becoming heavy) and do not insulate as effectively. Details of bird feather morphology and the hierarchical network formed by barbs and barbules have been investigated, to understand their hydrophobic behaviour [83,84]. Liu *et al.* [84] attempted to develop a durable, potentially self-cleaning, superhydrophobic surface treatment for soft textiles based on their understanding of duck feathers. They assert that duck feathers exhibit highly ordered and hierarchical branched structures built around a micro-sized backbone. Branches of various sizes of a duck feather are made up of micro-sized tomenta. These tomenta in turn have nanoscale undulates on the surface as shown in figure 5*a*,*b*. The water repellency of the bird feather in general is attributed to the trapped air space in the multi-scale texture formed by the barbs, barbules and tomenta with nano-sized grooves, forming an air cushion at the feather–water interface thereby keeping the feather from being wet [83,84].

Liu *et al.* [84] emulated the microstructures of the duck feather on cotton and polyester fabrics. They applied chitosan, a naturally derived polymer, on the fabric surface using an appropriate precipitation method to form nanoscale surface roughness. The chitosan was seen to form nanoscale flower-like structures on the polyester fabric, whereas on cotton, a more even coating was observed. The fabrics were further modified with a silicone finish to achieve lower surface energy. They reported significant improvement in water repellency as a result of the treatments.

Examples of aerodynamic shapes with low drag are abound in natural fliers and swimmers. From birds to

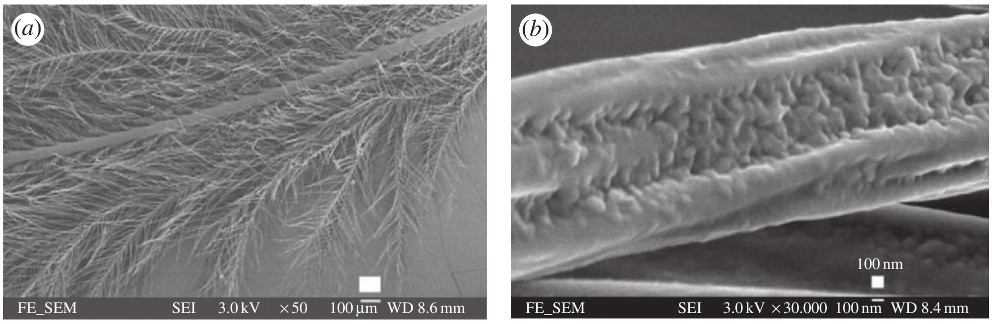

Figure 5. (*a*) FE-SEM image showing hierarchical structure of duck feather (scale bar, 100 µm) [84]; (*b*) FE-SEM image of tomenta of a duck feather (scale bar, 100 nm) [84]. Reprinted with permission from IOP Publishing.

ocean animals, nature has optimized shapes and surfaces to lower aero- and hydrodynamic drag. Most animals have evolved over millions of years to optimize body design and skin for efficient locomotion in water with minimal drag. The drag force that acts to hold swimmers back and slow them down can be broken down into three different types: skin friction drag, form drag and wave drag. The form drag (also known as pressure drag) depends mostly on the shape of the body. Skin friction drag is the force a fluid exerts on a surface in the flow direction and is a result of the no-slip condition at the boundary layer [85,86]. Flow across this boundary can be either laminar (smooth) or turbulent (rough). For increased speed in the water, laminar flow is desired [87]. Skin friction drag alteration in nature follows two basic strategies: (i) maintain a laminar flow through use of smooth surfaces and/or (ii) alter body smoothness to establish a favourable turbulent flow [87]. Wave drag, the third component of drag, occurs only near the surface, where the pressure surrounding the moving swimmer sets up a wave system.

Humans are not efficient swimmers, for their shapes are *not* well suited to rapid travel through water. For humans, swimming is a learned trait. Swimming style is vital to a swimmer's speed, but beyond that, it is important to lower the skin friction drag experienced by swimmers. Human quest for greater speed has led to the examination of examples in nature [87–90]. The movement of sharks in water, and in particular, the structure of their skin, has been of interest. Sharks, on the one hand, are an excellent example of a super-predator with the ability to swim at great speeds and manoeuvre swiftly in water. Humans, on the other hand, are not as graceful in water and this has led to the examination of sharks' speed and agility in water.

The skin of most types of sharks is covered by tiny (0.2–0.5 mm) hard tooth-like three-dimensional placoid scales, also called dermal denticles. The denticles have very fine and equi-spaced ridges and are aligned along the body axis. These tiny riblets of denticles vary in terms of number, size and shape depending on the sharks' age and species (figure 6) [88,92].

These riblets exhibit an overall parallel pattern, facing from head to tail on the shark skin in an interlocking fashion. In some areas of the shark, these riblets converge while in others they are found to diverge, which results in varying water flow patterns around the shark in these different regions [90]. Riblets are known to channel water through the small vales they create, which speeds up the flow of the water over the surface of the skin, resulting in the reduction of the turbulent skin friction drag [92]. Laboratory experiments on riblets have shown a reduction of skin friction drag of almost 10 per cent [89]. The drag-reducing potential of riblets is influenced by the sharpness of riblet edges, their optimal height protrusion into the surrounding sea water and the spacing between individual riblets [93]. Very thin, vertical riblets result in the greatest amount of drag reduction. Sharp, triangular ones create intermediate level of drag reduction. Broad, tortuous riblets result in the lowest amount of drag reduction [59]. Bechert *et al.* [88] provide a detailed explanation of the fluid mechanics of drag reduction resulting from shark riblets.

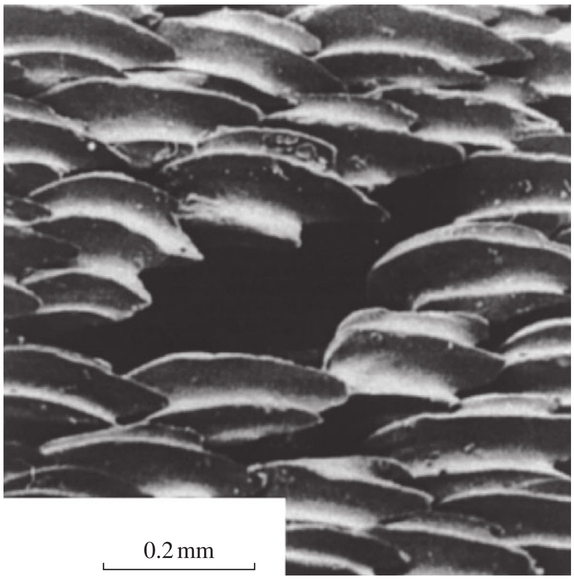

Figure 6. Image of denticles and riblets of a great white shark scale. Adapted from Bhushan [2] with scale images originally obtained by Reif [91].

For obvious reasons, the ultimate focus of research studies has been to imitate the surface morphology of shark skin in applications such as in swimwear and skin designs of long-range aircrafts as well as sea-faring vessels. Indeed, a riblet skin produced by 3M company has been used in Stars and Stripes, the America's cup champion racing yacht (http://www.nasa.gov/centers/langley/news/factsheets/Riblets.html). Probably, the most well-known commercial application of riblet surface morphology is in Fastskin swimwear technology (Speedo, Inc.). It was reportedly claimed that a 7.5 per cent reduction in drag would be experienced by the swimmer as a result of wearing the suit [94]. However, direct measurement of drag values at different speeds found a statistically insignificant drag reduction of 2 per cent using a Speedo Fastskin suit [94]. In another study on the efficacy of using Fastskin, no evidence of physical or physiological benefits of wearing these suits was reported [95]. Besides swimwear, materials mimicking sharks' skin have been suggested for applications that include aircraft skin and interlining of fluid-transport pipelines, to name a few.

3.3. Thermal insulation

The thermal-insulating property of duck feathers is attributed to the trapped air in their nanoscaled and hierarchical structure. Synthetic alternatives to down have been attempted, but their insulating capabilities do not match those of natural feathers [96]. Bonser *et al.* evaluated the mechanical properties of duck and geese down feathers. The influence of moisture on the mechanical properties of duck feathers has been reported as nominal [97]. Penguins live in extremely cold weather and have the ability to dive deep into the water without trapping any air in their coat to avoid creating positive buoyancy. Dawson *et al.* [98] investigated the coat of the penguin using a heat transfer model to show no convective heat loss with minimum radiative heat loss. They attribute the behaviour entirely to the structure of penguin afterfeather (figure 7), a collection of barbs (about 47) attached at the bottom of the feather. Du *et al.* [99] used a Monte Carlo simulation method to examine the heat transfer through the penguin coat and attributed the superior insulating properties to the fineness of the barbules in the feather as the major factor.

Thermal insulation mechanism of polar bear fur has been a subject of debate for some time. Polar bear pelt, an excellent natural insulator, allows the animal to survive arctic cold. Polar bears are known to appear black when illuminated by ultraviolet (UV) lights despite their white appearance to the human eye [100]. In addition, it is impossible to view a polar bear through an infrared camera because of very low heat loss through their pelt. The mechanism of low UV reflection is thought to be related to the thermal behaviour of bear pelt and has been a subject of research. The polar bear hair is hollow with foam-like substance in the middle [101]. Before Koon [102] published data on poor fibre-optic transmission behaviour of polar bear hairs, it was proposed that the bear hairs act like fibre-optic transmitters that allow the capture of incident sunlight and the heat is transferred to the black skin [103]. Koon's data showed that the polar bear hair is indeed a poor wave guide and that it may simply absorb UV light. Stegmaier *et al.* [101] reported the development of a solar thermal collector, based on the supposed solar function of the polar bear fur and skin, with high light-transmission capability using a spacer fabric with translucence coatings on both sides.

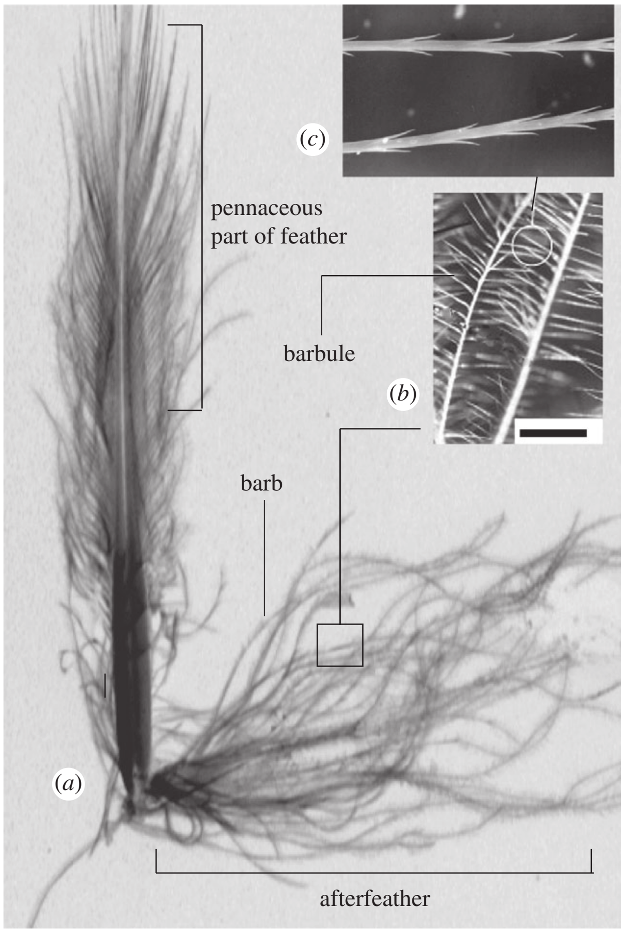

Figure 7. (*a*) Image of a penguin (*Pygoscelis papua*) feather including afterfeather (scale bar, 5 mm). (*b*) Optical micrograph of barbs from the afterfeather (scale bar, 500 μm). (*c*) Scanning electron micrograph of barbules (scale bar, 10 μm) [98]. Reprinted from Dawson *et al.* [98]. Copyright © 1999, with permission from Elsevier.

3.4. Optical systems

Nature has unique abilities to manipulate light. Most surfaces in nature are not just functional; they often produce brilliant, vivid and iridescent colours. Colour, of course, is an essential part of most textiles. Natural colours are often produced by a diversity of photonic structures that have evolved over millions of years to generate effects known as structural colours (in contrast to colour from pigments). Structural colours result from interference or diffraction, or selective reflectance of incident light owing to the physical nature of a structure. If these submicrometre structural variations are periodic with a periodicity of the order of the wavelength of light, they are often called biological photonic crystal structures. These biological structures suggest a new perspective on fine structure of fibres as well as higher level assemblies of fibres used in textiles. Examples of structural colours have been reported in a large number of species, including butterflies [104–107], bird [108,109] and beetles [84,110]. There is a vast body of literature on the structural colour in plants and animals. Srinivasarao [107], Parker [111], Tayeb *et al.* [112] provide excellent reviews of mechanisms of structural colour.

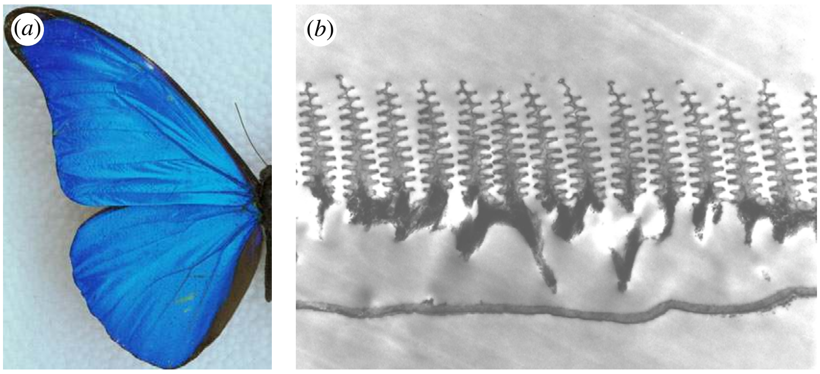

Figure 8. (*a*) Image of blue photonic butterfly wing. (Online version in colour.) (*b*) Transmission electron microscopy image of cross section through a butterfly's wing showing discrete multi-layers. Reprinted by permission from Macmillan Publishers Ltd: *Nature* [114], copyright © 2003. Image obtained from P. Vukusic, University of Exeter.

Excellent examples of biological optical systems and clues to their potential applications in textiles can be found in studies involving anatomical basis of photonic crystals in nature. Photonic crystals (also known as photonic band-gap materials) are periodic structures that have a band gap that forbids the propagation of a certain frequency range of light. As a result, photonic crystals always reflect only that specific band width (colour) of visible light [113]. Such structures are found in nature in butterfly wings, some plant species (bracts of edelweiss), marine creatures (e.g. brittlestar, *Ophiocoma wendtii*), opals [114], etc.

Butterflies probably exhibit the most interesting varieties of optical microstructures and have been studied extensively. In general, the butterfly wing consists of two or more layers of small scales formed over a membrane. Typically, there are two to three types of scales of about 200 μm long and 50 μm wide, arranged with an overlap much like roof shingles [107,115,116] (figure 8). The density of the scales varies from 200 to 500 mm^{-2}. The various colours produced are mainly owing to both pigmentary and structural colour production mechanisms. Most of the colours are produced by either thin film interference or diffraction [105,107]. The membrane of the wing usually contains the pigments melanin or pterins that accentuate the colour effects because of structural variations. In the case of *Morpho* butterflies, the metallic blue is produced by the elaborate structural features on the wings. The dark melanin present in the membrane absorbs the light that is not reflected to make the reflected colours appear bright [107,116].

A fibre manufacturer, Kuraray Corp., took inspiration from the ridge formation on the *Morpho*'s wing to create a polyester fabric with low reflectivity, but vivid coloration. This fabric was dubbed Diphorl and was manufactured using bicomponent polyester fibres of rectangular cross section. The fibres were spun from two polyester components of different thermal properties, which developed twist (approx. 80–120 twists per inch) upon heat treatment after weaving. It is claimed that the structure produces alternating horizontal/vertical alignment of surfaces to cause repeated reflection and absorption of the incident light in close proximity to each other, thereby producing brilliant colours [117]. Teijin Fibres Ltd of Japan began commercial production of a fibre called 'Morphotex' that claims to mimic the microstructure of *Morpho* butterfly wings and produce structural colour. The fibre made of either polyester or nylon has more than 60 laminated layers of nanometre dimension [118]. An exact replica of the *Morpho* wing structure was produced using atomic layer deposition of Al_2O_3 on real butterfly wing template [115]. Alternative methods of generating such fine nanoscaled structures in textiles need to be looked at.

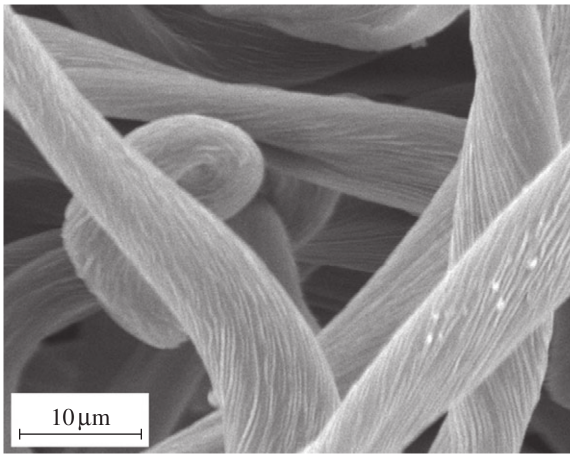

Figure 9. SEM image of the entangled fibrous structure found on edelweiss that protects the plant from harmful UV radiation [113]. Reprinted from Kertész *et al.* [113]. Copyright © 2006, with permission from Elsevier.

Advanced photonic structures are also found in plants. The woolly white filament covered bracts of the edelweiss plant (figure 9) possess special spectral behaviour that apparently protects the plant from harmful UV exposure at high altitudes. The white filaments on the bracts are hollow with fine nanostructures on the surface that can selectively couple the UV radiation in a guided mode along the fibre and dissipate the radiation harmlessly, while the visible part of the spectrum is mostly reflected or transmitted through the fibres [113].

3.5. Biomimicry and sustainability

Biomimicry, in its strictest interpretation, is the process of emulating nature's ways of finding a solution including 'designing' and 'making' with the least

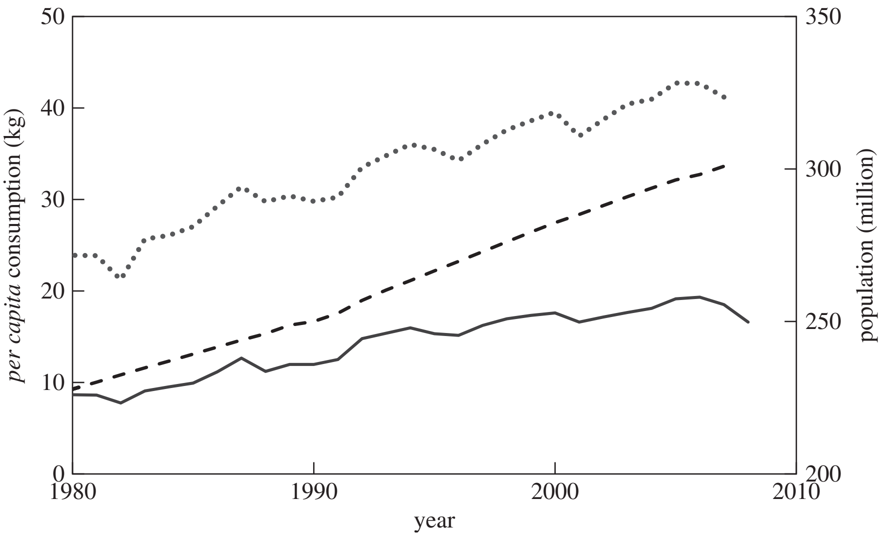

Figure 10. US fibre consumption (*per capita*) and population growth over the last three decades (US domestic consumption (mill consumption plus imports less exports of semi-manufactured and manufactured products)) [119–121]. Dotted line, all fibres; solid line, natural fibres; dashed line, population.

environmental impact. In fact, biological systems should be seen more as concept generators in terms of transfer of principles and mechanisms rather than something to copy, literally. Modern technologies have made it possible to design and manufacture products/systems that are based on nature. However, the process or the technology to do so has not always been purely eco-friendly. It is primarily because nature's implementation of a concept into a system is far different than that developed by humans. In nature, growth is the primary means of 'manufacture' rather than fabrication. The hook and loop fastener, Velcro, has been traditionally manufactured using nylon. The key ingredients are petroleum derivatives, with the usual environmental consequences of petroleum processing. If biomimicry is to be used as a new principle in designing textiles, sustainability must be part of it. Biomimetics can help us rethink our approach to materials development and processing and help reduce our ecological footprint. The history of textiles is full of continuous search for and invention of new fibre-forming polymers with unique and improved properties. The increase in world population coupled with increased standards of living has driven *per capita* consumption of fibres to levels that may not be sustainable. As an example, *per capita* consumption of textile fibres in the USA has grown from about 25 kg in the early 1980s to about 40 kg in 2008 (figure 10). The increasing demand for fibres is also driven by their new and innovative use in new and innovative products. Ideally, the increasing demand should be met largely by using renewable resources and through efficient recycling. Plants and animals in nature hold the key to this route.

The large array of polymeric fibres and other materials available to us often lead to blending or mixing of these fibres to develop a new product or improve an existing one. This makes it immensely difficult, at times, to eventually recycle the product. Use of limited variety of materials in nature makes it easier to recycle. With only two polymers (proteins and polysaccharides) in use, it is much easier for nature to separate and recycle. Biomimicry in textiles must also consider recyclability and aim at reducing the number of polymer types we tend to use in a product. Natural systems are inherently energy-efficient and adaptable. To be sustainable, textile fibres and products must emulate this feature as well.

The combination of biofibres, such as kenaf, hemp, flax, jute, henequen, pineapple leaf fibre and sisal, with polymer matrices from both non-renewable and renewable resources to produce composite materials that are competitive with synthetic composites requires special attention, i.e. biofiber–matrix interface and novel processing.

4. CONCLUSION

We began this review with the assertion that textile structures are similar in a number of ways to plants and animals found in the environment. The basic building block of textiles is fibres. Nature also makes extensive use of fibres, from nanoscale collagen fibres in tendons to microscale wood fibres. In nature, fibres are used in diverse applications, including terminal hairy fibres in gecko feet pads to high-tenacity spider silk. Furthermore, most natural surfaces are multi-functional. This is also desired in textile products: a natural interface between humans and their environment.

There is ample evidence to suggest that our ancestors looked to nature for inspiration to conceive new materials and devices long before the term biomimetic (and similar phrases) was coined. It is unclear what inspired prehistoric humans to invent the processes (i.e. spinning, weaving, etc.) to assemble fibres into clothing; it may have been an orthogonally interlaced thin and flexible biological structure like the coconut leaf sheath, or the nest of a weaver bird, or it may have been an invention of a contemporary genius. The fundamental practice of prehistoric humans to produce textiles from natural fibres has evolved into a vast array of modern energy- and resource-intensive technologies to make high-performance fibres and manipulate these fibres into complex textile structures for applications in civil construction, filtration, healthcare, etc., in addition to clothing.

Nature provides us with a plethora of techniques to build with fibres to achieve specific goals, and there is tremendous potential to learn from it. Understanding the structure–function relationships is key in developing textile products that are, for example, adaptive, thermo-resistant, superhydrophobic, or self-healing, examples of which are plentiful in nature. The obvious need for sustainability requires not just mimicking natural design but also the process. A few of these have been covered in this review. The field remains wide open for continuous scientific exploration. The concept of hierarchical structuring for the development of multi-functional materials through optimization at various scales is relevant for many of today's textile structures and applications. Transfer of a concept from natural to man-made is not trivial. However, as Vincent [11] noted 'there is a huge potential to obtain new or unusual combinations of material functions/properties by structuring a given material, rather than by changing its chemical composition'. In fact, textile fibre assemblies can readily provide an ideal test-bed for this concept.

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