Application of biomimicry in textiles

S. Das*, M. Bhowmick, S. K. Chattopadhyay and S. Basak
Central Institute for Research on Cotton Technology (ICAR), Adenwala Road, Matunga, Mumbai 400 019, India

doi: 10.18520/v109/i5/893-901

Nature has created excellent technologies around us, and as such, it is the chief mentor to humans on creativity and technology development. Nature uses fibre as a building block – natural structures like wood, bamboo, bone, muscle, etc. all have fibrous structure. Fibre spinning and weaving technologies are available in nature since time immemorial. Nature has also demonstrated sophisticated technologies useful in the development of technical textiles like functional surfaces, camouflage, structural colour, thermal insulation, dry-adhesion, etc. Thus, biomimicry can be an inspiration to develop innovative textiles. This article reviews some of the important technologies of nature relating to textiles.

Keywords: Biomimicry, fibres, spinning, textiles, weaving.

LIFE evolved on Earth about 3.8 billion years ago. A billion years of evolution resulted in the transformation from simple, single-celled prokaryotic cells such as bacteria to multi-cellular organisms. Arthropods, plants, fish, etc. evolved after a long process. Animals, plants, insects and microbes are still evolving to be compatible with nature. They have been trying to optimize every part of their body and every action they undertake to survive in nature, and the process is still ongoing. Evolution is a continuous process[1]. Over the years life has developed techniques such as structural strength, self-assembly, material recycling, self-cleaning, self-repair, energy conservation, drag reduction and dry adhesion to survive. These techniques have inspired humans to achieve outstanding outcomes. For example, the idea of weaving may have originated from the nest of a weaverbird, the strength and stiffness of the honeycomb structure may have led to its adoption for use in lightweight structures in aircraft and many other such applications[2]. Biomimicry is a word derived from the Greek words 'bios' meaning life and 'mimesis' meaning 'to imitate'. It is not new, as nature is the greatest teacher for the human race. The word 'biomimicry' has been popularized by the scientist and author Janine Benyus in her book *Biomimicry: Innovation Inspired by Nature*. Biomimicry has been defined in the book as a 'new science that studies nature's models and then imitates or takes inspiration from these designs and processes to solve human problems'. Benyus has suggested looking at nature as a 'model, measure, and mentor' and emphasized sustainability as an objective of biomimicry. Although the science of biomimetics has gained popularity relatively recently, the idea has been around for thousands of years[3,4].

There exist numerous examples of human learning from nature. Examples of bionics in engineering include the hulls of boats imitating the thick skin of dolphins. Leonardo da Vinci, for example, designed ships and planes by looking at fish and birds respectively. Invention of the radar seems to be related to the fact that some dolphins and bats have been using sound for communication and object detection for millions of years[5]. The flawless designs in birds have an enormous influence on the development of aviation. Indeed, the Wright brothers, regarded as the inventors of the airplane, used the vulture's wing as a model for building the wings of their Kitty Hawk plane[6]. Lifestyle, culture, and religion of early human civilizations were entwined with nature. These pre-industrial societies relied on nature to harvest crops, produce medicine, provide clothing, build shelter and clean up waste. In contrast, today's society depends on industrial manufacture[7]. Biomimicry will play a great role to achieve this.

Textiles are an indispensable part of human civilization. Humans have been using textiles from prehistoric age. Although more intelligent than animals, humans found themselves inadequately protected from a variety of adverse environmental conditions. The prehistoric humans used leaves, tree-barks, feathers, animal hides, etc. to protect themselves against the environment or enhance their aesthetic appeal. Fabrics were being produced long before the recorded history. Even 20,000 years ago, humans were twisting fibres together to make thread and string (the oldest preserved string is from Lascaux caves in France, aged circa 15,000 BC). The first garments made were probably string skirts, 'zostras', used to advertise a woman's fertility[8]. Egyptians made linen fabric around 5500 BC (ref. 9). Initially, humans started using textiles for protection purposes. Thereafter, textiles became fashion, art and design items.

This review explores the application of biomimetics in textiles. The exploration begins with a general overview, followed by a historical perspective – it describes some ongoing and future efforts in biomimetic textiles.

Learning from nature

Natural fibre – provider of structural integrity

We are bestowed with so many natural fibres. The common natural fibres from plants are cotton, jute, hemp,

---

*For correspondence. (e-mail: sekhar.tex@gmail.com)

ramie, sisal, etc. which are cellulosic in nature. Animal-based fibres are wool, silk, hair, etc. which are protein-based. Fibres are used for enhancing the strength and integrity of structures created by nature itself. Many natural structures are composite in nature, i.e. they are made of a combination of two or more materials that results in better properties than those made of a single component only[10]. Fibre is an important, strength-providing component of the composite material, because fibre is used as reinforcement material in polymer matrix composite so as to enhance the mechanical properties of the polymer. We have adopted the 'composite' material concept from nature in many man-made applications. Wood is one of the best example of natural composite material, consisting of cellulose fibres embedded in lignin matrix. Wood and bamboo also have fibrous structure providing strength, for which they are famous. Bamboo has a multi-scale, hierarchical and functionally graded structure. In macro-scale, the structure consists of a hollow tube with micron-scale fibre bundles that are organized into functionally graded structures. In micro-scale, the individual fibres are perfectly organized into fibre bundles in a lignin matrix. Researchers have found that the unidirectional, compact reinforcement of cellulosic fibres in lignin matrix is primarily responsible for the high strength of bamboo. Dry wood is primarily composed of cellulose, lignin, hemicelluloses, and minor amounts (5–10%) of extraneous materials. Cellulose, the major constituent is approximately 50% of wood by weight. During the growth of the tree, the cellulose molecules are arranged in ordered strands called fibrils, which in turn are organized into the largest structural elements that make up the cell wall of wood fibres[11]. The chemical structure of bamboo fibres is similar to that of wood. Their fibre length varies from 1 to 5 mm (with an average of 2.8 mm) and diameter from 14 to 27 μm with an average of 20 μm (ref. 12). In most cases, the fibres are arranged or oriented in a particular manner to impart the desired mechanical properties of the structure. Fibres can be a part of both the primary and secondary plant body. Fibres are primarily responsible for mechanical support for the tree being both hard and flexible, but when alive, they can also serve as a storage medium[13]. Some other natural composites are bone, teeth, dentin, cartilage, skin, mollusc shells, etc. where nature combines hard ceramic reinforcing phases with natural organic polymer matrices[14]. Another example is the bone, a highly complex and well organized organ that refers to a family of remarkable hierarchical structures with different motifs which are all constructed of a basic building block, the mineralized collagen fibril[15]. Reinforcing fibrous assemblies of peptides and proteins are the basic structure of biology, where they perform a variety of functions[16]. Skeletal muscle structures consist of hundreds of thousands, and sometimes millions of long and multinucleated fibres organized together in a particular direction by an extracellular matrix[17]. The protective grain layer gets its protective nature due to its fine, tough and fibrous structure[18]. Man learned from nature, even from the earliest times, the concept that combining materials could be advantageous. The procedures of wattle-and-daub (mud and straw) and 'pide' (heather incorporated into hard-rammed earth) building construction, still in use today, pre-date the use of reinforced concrete by the Romans that foreshadowed the pre-tensioned and the post-tensioned reinforced concrete of our own era[11]. Li *et al.*[19] copied the hollow, multi-layered and spirally wound bastfibre arrangement of bamboo structure and prepared a biomimetic reinforcing model, which is a double-helical structural model providing the optimum comprehensive mechanical properties.

We are aware that the prime needs of man are food, clothing, shelter and fuel. The word 'textile' comes from the Latin word 'textilis' and the French word 'texere'. Leaves from tree, tree barks, feathers, animal hide, etc. were used by prehistoric humans for protection from cold, heat, wind, etc. and clothing methods were used to enhance their aesthetic appeal[2]. From these materials, they learned that fibre is the basic unit of any protective gear. The earliest fibres used in textiles were linen, hemp, nettle, willow, wool, etc. Linen perhaps was the first textile to be manufactured by the Indians and Egyptians as early as 2800 BC. It was the Japanese who understood the weaving of linen, gold, silver and silk[20].

Fibre spinning

Nature is the inspiration for spinning continuous strands of synthetic fibres. Silk, one of the oldest known natural fibre to human civilization, is a continuous protein fibre produced by the silkworm. There are two main types of silkworm: mulberry silk (*Bombyx mori*) and wild silk, of which Tussar silk is the most important representative[21]. Very high quality silk fibre is also produced by some spiders belonging to the Arachnida family. There are over 34,000 species of spiders in nature and most of them are capable of spinning task-specific silk of varying mechanical properties[22]. Some spiders, specifically the orb-weaving Araneid and Uloborid spiders can produce silk fibres with very high mechanical properties. Orb-web-spinning spiders produce fibres with mechanical properties unmatched in the natural world and comparable with the very best synthetic fibres[23]. Spider silk is considered as a wonder fibre for its unique combination of high strength and breaking elongation. An earlier study indicated that the spider silk has strength as high as 1.75 GPa at a breaking elongation of over 26%. With toughness more than three times that of aramid, i.e. the industrial fibre used for making bullet-proof vests and other high-impact applications, spider silk spinning mechanism to be a mystery to the fibre scientists and hobbyists[24]. The man-made fibre spinning system is an imitation of the silk-spinning system. The history of the development of man-made fibre production tells us the story. The first patent for 'artificial silk' was granted in England in 1855 to a Swiss chemist named Audemars, who dissolved the fibrous inner bark of a mulberry tree, chemically modifying it to produce cellulose. He formed threads by dipping needles into this solution and drawing them out – but it never occurred to him to emulate the silkworm by extruding the cellulosic liquid through a small hole. After almost eight decades, in September 1931, the American chemist Wallace Carothers reported on research carried out in the laboratories of the DuPont Company on 'giant' molecules called polymers, particularly a polymer he referred to simply as '66', a number derived from its molecular structure. So, the 'Nylon' was born. Nylon was the first commercially successful fibre to be mass produced using the silkworm method of fibre production, i.e. melting the fibre and passing it at high pressure through a small orifice and then solidifying it[25]. Thereafter, several man-made fibres have been invented, e.g. polyester, polyethylene, polyacrylonitrile, polypropylene, Kevlar, etc. Today, numerous man-made fibres are available in the inventory of a textile designer, which can meet exacting functional requirements for use at home or in space exploration. This is all possible because nature has made silk first and shown us how to make a long continuous fibre. Kevlar fibres are made from lyotropic liquid crystalline polymer[26]. In nature, spiders and silkworms spin continuous fibres by liquid crystalline protein which is passed through their spinnerets. These fibres have high strength and toughness, which have attracted tremendous interests of researchers in various disciplines for a long time to learn the mechanism of silk spinning to produce artificial high-performance fibres resembling spider silk fibre[27]. Many attempts have been made to produce artificial spider silk by mimicking the spinning process of the spider. But so far a comprehensive understanding of the molecular processes which occur during spinning of protein fibres and the investigation of how the spinning conditions affect the properties of the final material are lacking. It is still a mystery how native silk fibres are produced with a minimal force by the spiders; unlike the man-made fibres formed from spin solution, which requires very high pressure or a large drawing force.

By mimicking the spinning process of the spider, Spinox Ltd (Oxford University) has developed a biomimetic rig into which protein dope is fed and from which spun fibre is drawn. The biomimetic process at present typically suffers from severe die swell problems and fibres obtained by this process are more brittle and less stronger than spider silk. To combat the die swell problems, Spinox now wants to model the spinning process in the spider and compare it with the biomimetic ring to achieve internal draw down[28]. Spiders have silk-producing spinnerets consisting of a great number of nanoscale tubes (Figure 1), through which the spin solution can be extruded to form a bubble at the apex of each tube[29]. Surface tension of each bubble is so small that it could be spun into nanofibres by exerting a small force, either by the spider's body weight or tension created by the rear legs. To mimic the spinning process of the spider, the bubble-electrospinning process was developed to produce nanofibres. In this process polymer jets are ejected from the bubble formed from the highly charged aerated polymer solution. The charges get accumulated on the bubble surface in the presence of an electric field. Once the electric field exceeds a critical value needed to overcome the surface tension, a fluid jet is ejected from the apex of the conical bubble. Subsequently, the jet solidifies into a nanofibre[30].

Weaving

Weaving is a process by which threads or continuous strands of any substance are crossed and interlaced so as to be arranged into a perfectly expanded form, and thus be used for covering human or other bodies. The technology of weaving was invented many years ago. Fabrics were being produced around 20,000 years ago[31]. The baya weaver (*Ploceus philippinus*) is a weaverbird found across South and Southeast Asia. The male weaverbird constructs its nest using fibrous materials. They weave the leaves and other nesting materials to produce a strong nest. The baya weaver might be the possible inspiration for human weavers. The weaverbird nest is usually 15 cm long and 12 cm high and is often suspended from a branch. The weaverbirds weave the outer shell of the nest progressively, stage by stage. These include construction of the initial attachment, ring, roof, egg chamber, antechamber, entrance and entrance tube. The initial attachment is constructed by first holding the initial strip under its foot against a twig, then looping it back and alternately reversing the winding of the strip between the twig and the strip itself, which is similar to 'nippering' a knot, a type of fastening used today to lash

Figure 1. (Left) An electron microscope image of finger-like spinnerets of a spider. (Right) Biomimetic rig developed by Spinox.

two parallel ropes together. The initial attachment is then developed into a roughly vertical ring that provides the basic support for the whole nest (Figure 2).

On the basic support, the male weaverbird weaves its nest using a certain basic set of movements. The bird uses its beak to first seize a strip of nest material near one of its ends, then with a vibratory motion it pokes the end of the strip into the bulk of the nest. Once the strip sticks in the nest, it releases its grip, moves its head to the other side of the nest mass and grabs the end of the strip again and performs a similar action from the opposite direction of the nest. In this way it stitches its nest using its beak. The woven design of the entrance tube consists of interlacement of two sets of yarns at 45° angle, which provides the best resistance to the shear stress generated when the bird hangs from one side of the entrance at the bottom of the tube during nest-building. Weaverbird uses stitching, knotting and weaving actions during the building of its nest. In this way, its actions are similar to the weaving and knotting process adopted by human[32,33]. Thus observing the similarity in the weaving of present-day plain fabric, it can be inferred that the concepts may have developed by mimicking the construction mechanism adopted by the weaverbird.

Shark skin effect

Shark is one of the fastest swimmers in water. For swimming at great speed it is important to lower the frictional drag of the skin of the shark against water. So nature has provided it with such a technology and it has evolved over millions of years. The shark's skin protects it against biofouling and reduces the drag experienced as it swims through water. The skin of shark is rough and covered by minute placoid scales, also called dermal denticles. Under a microscope, it can be observed that the shark skin is covered with small *V*-shaped bumps made from the same material as its teeth (Figure 3). The scales are regularly aligned along the axis of the body; they are particularly small (0.2–0.5 mm), very fine and regularly spaced (30–100 μm) longitudinal ridges, similar to riblets[34].

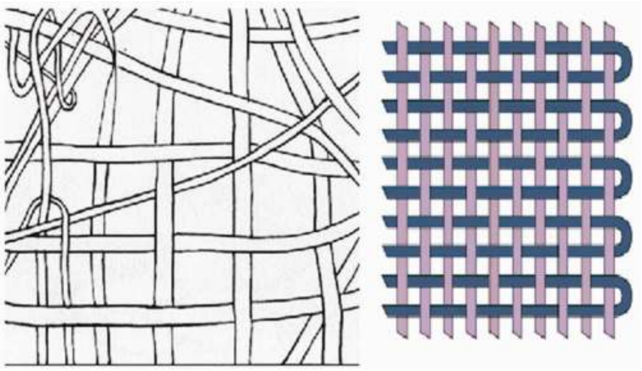

Figure 2. (Left) Weave structure of a weaverbird nest. (Right) plain weave structure.

Fast swimming produces vertical vortices or spirals of water, keeping it closer to the shark's body, thereby reducing the surface drag. These micro-scale ridges influence fluid flow in the transverse direction, thereby limiting the degree of momentum transfer. The ratio of scale height to tip-to-tip spacing has a critical role in reducing the longitudinal and transverse drags. A variety of shark skin mimicking engineered materials find a variety of applications, for example, riblets are fine, rib-like surface geometries with sharp surface ridges that can be aligned either parallel or perpendicular to the flow direction and might reduce drag[35].

In the beginning of mid-1980s, vinyl-film saw-tooth riblets were applied to the hulls of racing boats. They have also been used on hulls of ships. They find applications in aircraft industries for reducing drag. Another large, commercially used riblet technology is to reduce drag in liquid flow through pipes[36]. Probably, the most successful commercial application of riblet surface morphology is in Fastskin swimwear technology (Speedo, Inc.) developed in 2004. A drag reduction by several per cent was observed compared to other race suits in a static test. This mimicking of micro features of shark scales is used for designing swim suits with new fibres and weaving techniques[37,38]. The shark skin also impedes bacterial growth, thereby acting as antibacterial fouling surface inhibiting the growth of microorganisms on such grooved surface. Mimicking shark skin, a product called Sharklet was manufactured by Sharklet Technologies. It is a sheet of plastic with a microscopic texture that impedes the growth of bacteria. It is being manufactured for use in hospitals, restaurants, and other places where the potential spread of bacterial infections creates a hazard.

Coating surfaces with Sharklet is seen to greatly reduce the growth of bacterial colonies, due solely to the nano-scale structure of the product. The topography of Sharklet,

Figure 3. (Left) SEM of shark skin and (Right) Fastskin Fsii (FS2) swim suit, mimicking shark skin.

having ‘ridge’ and ‘ravine’ like qualities creates mechanical stress on the settling bacterium, a phenomenon known as mechanotransduction. The theory is that nanoforce gradients caused by variations in topographical features will induce stress gradients within the lateral plane of the membrane (plasma membrane) of a settling cell or microorganism during initial contact[39].

Hook-and-loop fastener

Hook-and-loop fasteners are generally made of two strips, one with ‘loops’ that ‘hook’ onto the other strip. When the two components are pressed together, the hooks catch in the loops and the two pieces fasten or bind temporarily. The hook-and-loop fasteners have been used for just about every conceivable application where a temporary bond is required. It is especially popular in clothing where it replaces buttons or zippers, as a shoe-fastener, in hand bags, etc. The hook-and-loop fastener was invented by Swiss engineer, Georges de Mestral in 1941 (ref. 40). There is a story behind this invention. One day when he was returning from a hunting trip with his dog in the Alps, he observed the burrs (seeds) of burdock that kept sticking to his clothes and his dog’s fur. He examined the seeds under a microscope, and noticed that they contained hundreds of hooks which could fasten with loops, such as clothing, animal fur or hair (Figure 4). He was inspired by this and invented hooks-and-loop fastener. Mestral saw the possibility of binding two materials reversibly in a simple fashion, if he could figure out on how to duplicate the hooks and loops. This inspiration from nature or the copying of nature’s mechanisms is viewed by some like Steven Vogelor Werner Nachtigall as a key example.

Dry adhesion gecko-feet

The gecko has a unique clinging ability; it can create dry adhesion using its amazing feet. Several creatures, including insects and spiders, have also developed unique clinging ability. Geckos, in particular, have developed the most complex adhesive structures capable of smart adhesion with the ability to cling to different smooth and rough surfaces, and also detach at will. Their feet contain millions of very fine hairs which can create dry adhesion to smooth and rough surfaces. These animals make use of about three million microscale hairs (about 14,000 mm^{-2}) that branch off into hundreds of nanoscale spatulae. This hierarchical surface construction provides the gecko the adaptability to create a large real area of contact with surfaces. van der Waals forces are the primary mechanism utilized to adhere to surfaces, and capillary forces are a secondary effect that can further increase the adhesion force[41]. The foot of a Tokay gecko (*Gekko gecko*) has about 5000 setae mm^2 and can produce 10N adhesive force with approximately 100 mm^2 of pad area[42]. Despite such strong adhesive forces which would hinder the movement of the gecko, this lizard has developed a unique technique 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. Scientists have been inspired by the clinging ability of geckos and many attempts have been made to construct the surface structure like gecko feet with man-made materials in order to achieve dry adhesion. Synthetic gecko foot fibres have been created by nanomoulding using silicone, polyimide, polyvinyl siloxane and polyurethane and carbon nanotubes[43,44]. A team of polymer scientists and a biologist at the University of Massachusetts Amherst have developed artificial Geckskin, Crosby has reported that ‘Our Geckskin device is about 16 inches square, about the size of an index card, and can hold a maximum force of about 700 pounds while adhering to a smooth surface such as glass’[45].

Figure 4. (Left) *Arctium lappa*, the capitula surrounded by an involucre made out of many bracts, each curving to form a hook, allowing them to be carried long distances on the fur of animals. (Right) Velcro, the brand name for fabric hook-and-loop fasteners, which is a biomimic material of *A. lappa*.

Lotus effect

Lotus effect observed in nature: Evolution has optimized the wettability of different animal and plant surfaces for different purposes. The wetting nature of different natural surfaces ranges from hydrophilic to super hydrophobic. Some of the natural surfaces are so hydrophobic that water droplets can roll over them without wetting the surfaces. The classic example of this kind of surface is the lotus leaf surface and the phenomenon it is called ‘lotus leaf effect’ (Figure 5). Other examples of such surfaces are rose petals, duck feathers and butterfly wings. The super-hydrophobicity of their surfaces generates self-cleaning properties, i.e. when the water droplet rolls over the surface, it takes away all the dirt on the surface, i.e. it self-cleaning. To investigate the reason for the lotus leaf effect, the surface of lotus leaf was observed under electron microscope. Though to the naked eye, lotus leaf is clean and smooth, on a nanoscale it is not so. On the contrary, it is rough due to papillose epidermal cells that form the papillae or microasperities. In addition to the microscale roughness, the surface of the papillae is also rough. The nanoscale roughness is created by three-dimensional epicuticular waxes, which are long-chain hydrocarbons that are hydrophobic. So the lotus leaf surface basically consists of systematically arranged three-dimensional nipple-like structures made of nano-sized wax crystal forms, which are no greater than a few nanometres in size, but are water-repellent[46]. This super-hydrophobicity of a surface is dependent on two important factors. First, a low surface energy and chemical composition of the solid surface and secondly, a high degree of surface roughness. This rough structure on the surface of the lotus leaves causes a reduced contact area with water. The water penetration is prevented by the presence of the hydrophobic nano-sized wax crystals[47]. As a result, the water forms droplets and rolls over the surface.

Characteristics of hydrophobicity and lotus effect: The primary parameter that characterizes wetting of a surface is the static contact angle, which is defined as the angle that a liquid makes with a solid. The contact angle depends on several factors, such as the surface energy, surface roughness and its cleanliness. If the value of the static contact angle is $0° \leq \theta \leq 90°$, the liquid wets the surface, whereas if the liquid does not wet the surface, the value of the contact angle will be $90° \leq \theta \leq 180°$. Surfaces with high surface energy, formed by polar molecules, tend to be hydrophilic, whereas those with low energy and built of non-polar molecules tend to be hydrophobic. Surfaces with a contact angle less than 10° are called super hydrophilic, while those with a contact angle between 150° and 180° are called super hydrophobic. Wettability of a surface mainly depends on two factors: (i) the surface free energy, and (ii) the surface roughness. The self-cleaning property of a surface depends on its smoothness – extremely smooth surfaces show a reduced soiling behaviour, because the particles have only low mechanical hold and can be removed either by air or liquid. When overlapping structures with dimensions of a few micrometres and superposed structure of 50–100 nm are applied to surfaces, and if the chemistry of the surface is hydrophobic, a real self-cleaning effect can be achieved. The effective surface contact area of dirt particles is extremely minimized by the surface structure and thus, adhesion is very low. When a drop of water rolls over such a surface, dirt particles are removed. Because of the roughness of the surface and the low contact area, the adhesion energy of the particle to the solid surface is very low[48].

Figure 5. Lotus effect on the surface of a lotus leaf (left) and hydrophobic surface (right).

Lotus effect mimicry in textiles: Natural lotus effect phenomenon is useful as far the application in textile materials is concerned. If this can be imitated in textile materials, then it can produce a whole range of products like umbrella, rainwear, carpets, upholstery, protective clothing, sportswear, automotive interior fabrics, etc. and even self-cleaning garments. In this regard, the first patent was filed on hydrophobic textiles in 1945; an alkyl silane was used in hydrophobic textile materials[49]. Hydrophobic properties of a surface can be achieved by the use of nonpolar hydrophobic agents such as paraffin wax, silicones, silanes and fluorinated polymers[50]. However paraffin wax, silicones and silanes only make the textile surface waterproof, which is uncomfortable in the case of apparels. A variety of fluorine-based polymers are popular for this purpose because of their high water and oil resistance, organic solvent resistance and lubricity. Because of these advantages, fluoropolymers have been used in the textile industry since the 1960s (ref. 51). The lotus effect phenomenon was first studied by Dettre and Johnson in 1964 using glass beads coated with paraffin or PTFE telomer. They created a microscopic rough surface to generate the hydrophobic surfaces and developed a theoretical model[52]. Recent approaches to this kind of finishing include achieving nano–microscale surface topography by nanoparticles attached to the fibres that increases surface roughness. Silicate and fluorocarbon nanoparticles are used in commercial level for this purpose. It has been reported that the super hydrophobicity can be achieved on cotton fabric using a homogeneous silica–copper hybrid nano-composite[47]. Joshi *et al.*[53] used nanosilica and nanoclay along with a surface tension lowering agent to get a lotus effect on cotton fabric. Lauryl acrylate has been used as hydrophobic monomer and malic anhydride as reactor to produce durable, nonfluro hydrophobic finish on cotton fabric[54]. Ramaratnam *et al.*[54] reported the preparation of ultrahydrophobic polyester textile surface using a mixture of polystyrene grafted layer with silver nanoparticles. Here grafting lowered the surface energy of the substrate and nanoparticles increased roughness of the surface[55]. Plasma etching at different atmospheres also provides hydrophobic rough surface. In this regard, Twardowski and Makowski[56] reported that super hydrophobicity can be achieved on polyester fabric using the argon plasma etching method. Researchers have prepared hydrophobic etched polypropylene by argon atmosphere plasma treatment in the presence of polytetrafluoro ethylene gas. The hydrophobicity of electrospun PVA fabrics can be achieved using SF6 plasma treatment. The application areas of these fabrics are biomaterial, filtration and medical devices[57]. Recently, hydrophobic textiles have been made by etching titanium dioxide-coated layer of the fabric with CF4 plasma treatment[58].

Camouflage

Nature is a deadly battlefield of hide-and-seek between prey and predator. Both try to conceal their identity or visibility from each other so that they can survive. Some animals have developed special skills to hide in the environment they live by having special colours, texture and patterning on their bodies that help them to conceal their presence. This phenomenon of blending with the environment is called camouflage. So, camouflage plays a vital role in the struggle of surviving of living beings. There are many ways to camouflage. They vary from species to species. The most common techniques are: (i) crypsis, where the animal blends with the background; (ii) disruptive coloration; (iii) self-decoration with materials such as twigs, sand, or pieces of shell from their living environment; (iv) changing skin pattern and colour, and (v) Mimesis. The most common camouflage technique, however, is by changing the skin colour. The skin colour, texture and patterning are important for concealment. But most of the camouflage techniques get nullified by movement of the species. Hence, 'active' camouflage is more effective. Some animals achieve active camouflage by both colour change and counter illumination. One of the examples of such type of camouflage is that of the coleoid cephalopods (octopus, squid, cuttlefish). They can easily hide themselves in colourful coral reefs, temperate rock reefs, kelp forests, sand or mud plains, seagrass beds and other environments by rapidly adapting their body pattern. Although most examples of animal camouflage involve body colouration or patterning, decorator crabs in the brachyuran superfamily Majoidea (majoids) are a large and diverse group of crabs, best known for a distinctive form of 'decoration' camouflage. They attach materials from the environment to specialized hooked setae on their body[59–61]. Humans have tried to use this kind of camouflage from prehistoric times.

Human civilizations have adopted camouflage techniques, mostly for hunting or military purpose. But camouflage has also influenced other aspects of society, for example, arts, popular culture and design. Throughout the 18th and the 19th centuries, due to the prevalence of non-accurate weapons on the battlefield, military clothes included bright and high-contrast colour arrangements to enable distinction between different units. However, with the growing use of accurate weapons, since 1880s, adoption of some form of camouflaging the soldiers in the battlefield was introduced. Beginning with the British Armed Forces, various other militaries changed the colours of their clothing predominantly to ones that blended in, more with the terrain, such as khaki or olive drab. That was the reason why olive green shaded hues became significant in military clothing. Camouflage fabrics are used for hiding soldiers and military equipment, and now are one of the main components of warfare. The main functional requirement for such fabrics for military use includes not only the physical aspects like resistance to various environmental conditions, water, wind, fire, heat and specific battlefield threats, but also the camouflaging requirements[62,63]. The major design requirement of a camouflaged fabric is to obtain a colorimetric match to its anticipated surrounding. This match needs to cover both the visible and other colours of the spectrum, as is used in silicon-based surveillance sensors, such as image intensifiers, low-light TV, and both near and infrared (IR) devices. Modern camouflaged garments should be able to provide protection not only in the visible range, but also in a wide spectral range, including UV, near IR, far IR, radar and acoustic ranges. The camouflaging technique uses chosen shapes and colours to produce perfect harmony with the surrounding. The modern military forces use combat uniforms, that not only break-up the outline of the soldier during the daytime, but also provide a distinctive appearance that makes it difficult to detect them with light amplification devices, such as night-vision devices[64]. Nanotechnology has made it possible to develop military clothes that can change pattern and colour with the change in environment. 'Chameleonic' camouflage allows the soldier to become a mirror of his surroundings[65]. Currently, conventional colour and pattern type of camouflage is used by the infantry in reconnaissance and infiltration operations. The modern dismounted soldier may be carrying any or all of a night-vision sight and/or goggles, thermal-imaging sight, personal role radio and combat net radio, laser rangefinder, laser designator and laser weapon pointer, noise cancelling unit, IR and visible beacons, electronic countermeasures, global positioning and/or blue force tracking and camouflaging should be effective against all of these[66]. To hide in near-IR light, low-emissivity paints are used in fabrics that emulate the near-IR reflection of vegetation, rocks, sand and soil of the intended environment. The 'MAYA' suit imitates its intended environment by specially designed shapes, shades and colours. The texture of the suit also disrupts the revealing contours of a human body.

The 'MAYA' suit has multispectral properties and provides protection from visual detection, day and night vision devices, and thermal sensors and cameras. It also has two-side camouflage for different battlefields[67]. An object can be effectively concealed from electromagnetic radiation detection by placing a reflecting or absorbing surface on it. Conventional radar absorbing materials (RAMs) exhibit excellent absorbing properties. But they have limitations due to their dimensions, high weight and limited mobility. There is a need to develop new RAMs on a flexible substrate for achieving the desired absorbing properties. Textile fabrics with thin polymer composite films can help in this regard[68]. Recently, an Australian company has claimed that it has developed a line of anti-shark wetsuits that will repel sharks or camouflage a swimmer, based on scientific studies on the sense of sight of Sharks[69].

Conclusion

Human beings have been using textiles since prehistoric times for protecting their body from nature's adversities, and for fashion purposes. The basic building block of textiles is fibre. Nature provides us with many natural fibres sourced from plants and animals. Nature uses fibre from nanoscale to microscale to build the body structure of the living species. Natural structures like wood, bamboo, bone, skin, mollusc shells, etc. are fibre-composite structures. In nature, fibres are used in diverse applications. Silkworm and some spiders can spin continuous fibres and baya weavers can weave their nests. Some multi-fictional natural surfaces are also available in nature. Rough surface of shark skin facilitates reduction in drag force and lotus leaf has a unique self-cleansing property. Different animals, insects and fishes use the camouflage technique by changing their skin colour and pattern. These techniques have not only been adopted by humans, most notably by the military and hunters, but have also influenced other aspects of the society, for example, arts, popular culture and design. Nature is like a vast technological book that provides us lessons several sophisticated techniques to use fibre as a building block.

---

1. http://www.bbc.co.uk/nature/history_of_the_earth (accessed on 13 January 2014).
2. Eadie, L. and Ghosh, T. K., Biomimicry in textiles: past, present and potential. An overview. *J. R. Soc. Interface*, 2011, **8**, 761–775.
3. Goss, J. M. A., *Biomimicry: Looking to Nature for Design Solutions*, Master's thesis, Columbian College of Arts and Science, Washington, DC, USA, 2009.
4. Czyzewski, A. M. and Barron, A. E, Protein and peptide biomimicry: gold-mining inspiration from nature's ingenuity. *AIChE J.*, 2008, **54**, 2–8.
5. http://en.wikipedia.org/wiki/Leonardo_da_Vinci (accessed on 13 January 2014).
6. http://www.natureandbiomimetics.com/6.htm (accessed on 13 January 2014).
7. http://lcs.syr.edu/centers/sustainableengineering/modules/10-17_Cattano.pdf (accessed on 13th January 2014).
8. http://nrvaug.org/images/history/timelin3.pdf (accessed on 13 January 2014).
9. Jenkins, D., *The Cambridge History of Western Textiles*, Cambridge University, 2003, pp. 30–33.
10. Campbell, F. C., Structural composite materials, Copyright, Ohio, 2010, pp. 31–52.
11. Harris, B., *Engineering Composite Materials*, The Institute of Materials, London, 1999, pp. 5–31.
12. Lipp-Symonowicz, B., Sztajnowski, S. and Wojciechowska, D., New commercial fibres called 'bamboo fibres' – their structure and properties. *Fibres Text. East. Eur.*, 2011, **19**, 18–23.
13. Lev-Yadun, S., Plant fibers: initiation, growth, model plants and open questions. *Russ. J. Plant Physiol.*, 2010, **57**, 305–315.
14. Lakes, R., *Composite Biomaterials. The Biomedical Engineering Handbook*, Boca Raton, FL, USA, 2000, 2nd edn.
15. Zheng, W., Zhang, W. and Jiang, X., Biomimetic collagen nanofibrous materials for bone tissue engineering. *Adv. Eng. Mater.*, 2010, **12**, 451–466.
16. MacPhee, C. E. and Woolfson, D. N., Engineered and designed peptide-based fibrous biomaterials. *Curr. Opin. Solid State Mater. Sci.*, 2004, **8**, 141–149.
17. Mendias, C. L., Regulation of the structure and function of skeletal muscle and tendon, Thesis, The University of Michigan, USA, 2007, pp. 3–4.
18. http://www.wollsdorfleather.com/aus/service/downloads/structure_of_leather.pdf (accessed on 12 Febrarury2014)
19. Li, S. H., Zeng, Q. Y., Xiao, Y. L., Fu, S. Y. and Zhou, B. L., Biomimicry of bamboo bastfibre with engineering composite materials. *Mater. Sci. Eng.: C*, 1995, **3**, 125–130.
20. http://images.library.wisc.edu/HumanEcol/EFacs/MillineryBooks/MBE_llsworthTextiles/reference/humanecol.mbellsworthtextiles.i0009.pdf (accessed on 16 March 2014).
21. Mondal, M., Trivedy, K. and Kumar, S. N., The silk proteins, sericin and fibroin in silkworm, *Bombyx mori* Linn., – a review. *Caspian J. Environ. Sci.*, 2007, **5**, 63–76.
22. Gatesy, J., Hayashi, C. and Motriuk, D. W., Extreme diversity, conservation, and convergence of spider silk fibroin sequences. *Science*, 2001, **291**, 2603–2605.
23. Gosline, J. M., Guerette, P. A., Ortlepp, C. S. and Savage, K. N., The mechanical design of spider silks: from Fibroi sequence to mechanical Function. *J. Exp. Biol.*, 1999, **202**, 3295–3303.
24. http://web.mit.edu/course/3/3.064/www/slides/Ko_spider_silk.pdf (accessed on 16 March 2014).
25. Lewin, M. and Pearce, E. M., *Handbook of Fiber Science and Technology*, CRC Press, 1985, vol. 4, pp. 18–25.
26. Jassal, M. and Ghosh, S., Aramide fibres – an overview. *Indian J. Fibre Text. Res.*, 2002, **27**, 290–306.
27. Vollarath, F. and Knight, D. P., Liquid crystalline spinning of spider silk. *Nature*, 2001, **410**, 541–548.
28. http://www.maths-in-industry.org/miis/27/1/Silk.pdf (accessed on 17 March 2014)
29. Jinyou Lin, J., Wang, X., Ding, B., Yu, J., Sun, G. and Wang, M., Biomimicry via electrospinning. *Crit. Rev. Solid State Mater. Sci.*, 2012, **37**, 94–114.
30. He, J. H., Liu, Y., Xu, L., Yu, J. Y. and Sun, G., Biomimic fabrication of electrospun nanofibres with highthroughput. Chaos *Solitons Fractals*, 2008, **37**, 643–651.
31. http://nrvaug.org/images/history/timelin3.pdf (accessed on 19 March 2014).
32. http://www.cs.cmu.edu/afs/cs/academic/class/16741-s07/www/projects06/dineshproject.pdf (accessed on 19 March 2014).
33. Collias, N. E. and Collias, E. C., *Nest Building and Bird Behavior*, Princeton University Press, Princeton, 1984, pp. 3–85.
34. Lang, A. W., Motta, P., Hidalgo, P. and Westcott, M., Bristled shark skin: a microgeometry for boundary layer control? *Bioinsp. Biomim.*, 2008, **3**(9); doi:10.1088/1748-3182/3/4/046005.
35. Oeffner, J. and Lauder, G. V., The hydrodynamic function of shark skin and two biomimetic applications. *J. Exp. Biol.*, 2011, **215**, 785–795.
36. Dean, B. and Bharat, B., Shark-skin surfaces for fluid-drag reduction in turbulent flow: a review. *Philos. Trans. R. Soc. London, Ser. A*, 2010, **368**, 4775–4806.
37. Singh, A. V. *et al.*, Bio-inspired approaches to design smart fabrics. *Mater. Des.*, 2012, **36**, 829–839.

38. Craik, J., The Fastskin Revolution: from human fish to swimming androids. *Culture Unbound*, 2011, **3**, 71–82.
39. http://en.wikipedia.org/wiki/Sharklet_%28material%29 (accessed on 21 March 2014).
40. Ivanic, K. Z., Tadic, Z. and Anteomazic, M., Biomimicry – an overview. An Holistic Approach to Environment, 2015, vol. 5, pp. 19–36.
41. Bhushan, B. and Sayer, R. A., Gecko feet: natural attachment systems for smart adhesion – mechanism, modeling, and development of bioinspired materials. *Nanotribiol. Nanomech.*, 2008, **27**, 1073–1134.
42. Autumn, K., Liang, Y. A. and Hsieh, S. T., Adhesive force of a single gecko foot-hair. *Nature*, 2000, **405**, 681–685.
43. Davies, J., Haq, S., Hawke, T. and Sargent, J. P., A practical approach to the development of a synthetic Gecko tape. *Int. J. Adhesion and Adhesives*., 2009, **29**, 380–390.
44. Abbott, S. J. and Gaskell, P. H., Mass production of bio-inspired structured surfaces. *J. Mech. Eng. Sci*., 2007, **221**, 1181–1191.
45. http://phys.org/news/2012-02-gecko-feet-scientists-super-adhesive-material.html (accessed on 19th March 2014).
46. http://www.researchgate.net/publication/49580258_Self-cleaning_dirt_and_waterrepellent_coatings_on_the_basis_of_nanotechnology (accessed on 19 March 2014).
47. Berendjchi, A. and Khajavi, R., Fabrication of superhydrophobic and antibacterial surface on cotton fabric by doped silica-based sols with nanoparticles of copper. *Nanoscale Res. Lett*., 2011, **6**, 594.
48. Abbott, A. and Ellison, M., *Biological Inspired Textiles*, Cambridge, Woodhead Publishing, 2008, pp. 137–148.
49. Norton, F. J., Waterproofing treatments of materials. US Patent 2386259, 1945.
50. http://publications.lib.chalmers.se/records/fulltext/172069/172069.pdf (accessed on 16 April 2014).
51. Sayed, U. and Dabhi, P., Finishing of textiles with fluorocarbons. *Int. J. Adv. Sci. Eng.*, 2014, **1**(2), 1–7.
52. Barthlott, W. and Neinhuis, C., Purity of the sacred lotus, or escape from contamination in biological surfaces. *Planta*, 1997, **202**, 1–8.
53. Joshi, M., Bhattacharyya, A. and Agarwal, N., Nanostructured coatings for super hydrophobic textiles. *Bull. Mater. Sci.*, 2012, **35**, 933–938.
54. Prusty, A., Gogoi, N., Jassal, M. and Agrawal, A., Synthesis and characterization of non-fluorinated copolymer emulsions for hydrophobic finishing of cotton textiles. *Indian J. Fibre Text. Res.*, 2010, **35**, 264–271.
55. Ramaratnam, K., Iyer, S. K., Kinnan, M. K., Chumanov, G., Brown, P. J. and Luzinov, I., Ultrahydrophobic textiles using nanoparticles: lotus approach. *J. Eng. Fibres Fabrics*, 2008, **3**(4), 1–14.
56. Twardowski, A. and Makowski, P., Plasma treatment of thermoactive membrane textiles for superhydrophobicity. *Mater. Sci.* (*Medziagotyra*), 2012, **18**(2), 163–166.
57. Thongphud, A. and Paosawatyanyong, B., Improvement of hydrophobic properties of the electrospun PVA fabrics by SF6 plasma treatment. *Adv. Mater. Res*., 2008, **5**, 16–20.
58. Roach, P., Shirtcliffe, N. J. and Newton, M. I., Progress in superhydrophobic surface development. *Soft Matter*, 2007, **4**, 224–240.
59. Hultgren, K. and Stachowicz, J., Camouflage in decorator crabs. Integrating ecological, behavioural and evolutionary approaches. In *Animal Camouflage*, Cambridge University, 2011, pp. 214–216; www-eve.ucdavis.edu/stachowicz/papers/Hultgren_Stachowicz_2001_BookChapter.pdf
60. Hultgren, K. M. and Stachowicz, J. J., Evolution of decoration in majoid crabs: a comparative phylogenetic analysis of the role of body size and alternative defensive strategies. *Am. Nat.*, 2009, **173**, 566–578.
61. Merilaita, S., Visual background complexity facilitates evolution of camouflage. *Evolution*, 2003, **57**, 1248–1254.
62. Kovacevic, S., Schwarz, I. G. and Durasevic, V., Analysis of printed fabrics for military camouflage clothing. *Fibres Text. East. Eur.*, 2012, **20**, 82–86.
63. Stevens, M. and Merilaita, S., Animal camouflage: current issues and new perspectives. *Philos. Trans. R. Soc. London, Ser. B*, 2009, **364**, 423–427.
64. Osterman, D. P. and Glogar, M. I., The characteristics of olive green shade military clothes in nature surrounding. In 4th International Textile Clothing and Design Conference – Magic World of Textiles, Croatia, 2008.
65. http://www.textileconnect.com/documents/resources/Technical%20-Textiles%20Edited.pdf (accessed on 14 April 2014).
66. http://www.rusi.org/downloads/assets/swallow_RDS_feb2010.pdf (accessed on 14 April 2014).
67. http://www.exporterez.com/uploadimages/maya_art%20print.pdf (accessed on 14 April 2014).
68. Studynkova, Z., Kucera, F. and Jobanek, A., Preparation and properties of micro and nanofilled polymer composites on textiles. *Nanocon*, 2011, **9**, 21–23.
69. http://www.livescience.com/38350-anti-shark-wetsuits-inspired-by-nature.html (accessed on 14 April 2014).

Received 4 April 2014; revised accepted 28 April 2015