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Application of biomimicry for sustainable functionalization of textiles: review of current status and prospectus

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Abstract

With the increasing complexity of human lifestyles, the demand for functionalized or high-performance textile materials has seen a steep rise. However, the methods of producing thereof are still creating a negative impact on the environment. Although biomimicry is a possible means of catering for this demand, most of the emerging biomimetic technologies follow an unsustainable path, accentuated only on transferring functionalities of nature, by using chemical-intensive applications. Nevertheless, biomimicry holds promise in sustainable manufacturing, if toxic chemical usage can be reduced while structural applications are increased. This study reviews the possibilities of existing and futuristic textile technologies that could facilitate conscious biomimicking of functional textiles, rather than intense application of chemicals. A total of 283 research articles were initially obtained and screened to review the possibilities of combining biomimetic technologies with textile manufacturing technologies. Prospects of innovative textile technologies and additive manufacturing on the futuristic possibilities of structural mimicking of biological functionalities into textile materials are discussed comprehensively. Possible construction methods, including additive manufacturing and weaving in the micro/nano scale, are suggested for structural mimicking. It is also recommended to unfold the potential of biomimicry in producing functional textiles in order to alleviate the harmful impact already caused to the environment by the textile industry.

Keywords

biomimicry, sustainability, functional textiles, biostructures, additive manufacturing

Prehistoric human beings used to live tightly knit with nature, and they were exposed to it. To protect humans from their surroundings, they started using tree leaves, tree barks, feathers and animal skins as clothes.[1] These clothes simply ended up being soil at the end of usage, leaving no trace. Although the origin of textiles was based on this simplistic purpose, later, people started seeking more protection as well as solutions to functional challenges they were faced with.[1] Fashion and textiles has now become one of the most polluting industries on earth, causing adverse environmental impacts.[2] An annual global production of 80–100 billion garments[3] and the subsequent generation of textile waste has become an extreme environmental crisis to rival plastic pollution in the oceans. The overall annual worldwide consumption of apparel and footwear currently stands at approximately 62 million tonnes, and an estimated rise of 63% will bring this up to 102 million tonnes by 2030.[4] Moreover, the fashion industry consumes nearly 79 billion cubic meters of water and the carbon dioxide (CO_2) emissions from the industry alone are projected to be increased up to 2.8 billion tonnes per year by 2030.[4] This situation is fuelled by the "fast fashion" trend, which has significantly evolved over the past two decades. A fast fashion

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system combines two components: a highly fashionable product design with a short production and distribution lead-time.[5] Moreover, the changing dynamics of fast fashion have created an increasing number of fashion seasons and a ''throw away'' attitude among consumers.[6] Following traditional production and consumption trajectories, fashion's environmental footprint poses a threat to the planet on the key impact areas: water usage, CO_2 emission, chemicals usage and generation and disposal of waste.[4]

Usually textiles are made of natural fibers, synthetic fibers or a combination thereof. While most synthetic materials are inherently resistant to biodegradation,[7] textiles made of natural fibers will not readily decompose in a landfill either, because they too undergo numerous unsustainable processes from fibers to the final product.[8] They are often bleached, dyed, printed, scoured in chemical baths and myriad chemicals are used to impart special functionalities and finishes. Consequently, the originality of fabrics made out of natural fibers is lost, thus making it difficult to biodegrade, similar to fabrics made of synthetic fibers. Some of the major environmental impacts caused by textiles being highly intertwined with chemicals include, but are not limited to, the generation of effluents during production, ecotoxicity from washing and drying of textiles and dumping toxic waste substances.[9] Usage of chemicals in textiles that finally end up as waste somewhere on the planet is evidently an ever-increasing problem for humanity, which begs the necessity of sustainable systems and processes to overcome this problem. The role of irradiation of textiles has been studied, especially to mitigate the adverse outcomes of conventional textile dyeing.[10] The utilization of novel irradiation techniques, such as ultraviolet, microwave, ultrasonic, plasma and gamma radiations, has been indicated as a more sustainable means of dyeing over conventional wet processing methods.[11–16] However, such technological advancements are hardly seen to be practiced in mass-scale production.

Biomimicry: conscious emulation of nature

During 3.8 billion years of evolution, biological systems have perfected their crafts in terms of efficiency, innovation and sustainability through their own natural research and development.[17] More importantly, nature is home to limitless fashion, functionalities and smartness. These time-perfected systems hold promise in providing highly efficient systems and processes to tackle many resource and waste management problems humankind is burdened with today.[18]

Many researchers have already begun emulating nature. The shell of nacre has been studied in depth[19,20] and it has been attempted to replicate it using three-dimensional (3D) printing.[21] Tree leaves have inspired engineering deployable structures.[22] Although a multitude of terms are used to acknowledge this emulation process, such as bionics, biomimetics, biomimicry, biognosis and bio-inspired, the term ''biomimicry'' is typically repetitive in architecture and product design.[17,23–25] This emerging technology has found its use in many applications related to biology, physics, chemistry and engineering.[25] According to Benyus,[26] biomimicry is the ''conscious'' emulation of life's genius. In conscious biomimicry, no part of the mimicking process or product is problematic to the harmonious continuation of life. Therefore, conscious biomimicry is a sustainable way of deriving solutions for human problems, by emulating nature.

Technology transfer from biology to engineering must be systematic.[27] However, most of the emerging biomimetic technologies appear to translate the technology only, regardless of the sustainability considerations.[28] Chemical-intensive techniques have often been used in biomimicry, instead of exploring possibilities to mimic intricate structural designs that minimize the use of chemicals. The application of toxic chemicals to achieve desired functionalities hinders the concept of conscious biomimicry, as that pollutes the environment.

Biomimicry in textile applications

Among many biomimicry applications, textile engineering has gained much significance, given the increasing number of realms it is being used for. The role of textiles in day-to-day life has seen a drastic transformation demanding special functionalities. Polar bear-inspired winter clothes[23,25] or solar-thermal applications,[29] lotus leaf-inspired self-cleaning fabrics,[30] rose petal-inspired superhydrophobic surfaces,[31,32] butterfly wing-inspired structural colors,[24,33] shark skin-inspired drag-reducing fabrics and[34–36] anti-microbial surfaces[37–39] are just a handful of functionalized textiles from a plethora of bio-inspired examples. However, chemical-intensive applications can be commonly found in those. For example, coating techniques to create one-level hydrophobic surfaces are usually sol–gel, dip coating, self-assembly, electrochemical and chemical/physical vapor deposition.[40] Sol–gel preparation can include organotriethoxysilanes,[41] colloidal silica particles and fluoroalkylsilane, and hydrolysis and condensation of alkoxysilane compounds,[42] zinc oxide nanorods[43] or many other chemical-intensive methods.[40]

There has also been a direct procedure described for creating stable superhydrophobic coatings from polyelectrolyte multilayers using a layer-by-layer self-assembly technique to create a poly(allylamine hydrochloride)/poly(acrylic acid) (PAH/PAA) multilayer.[44] Subsequently, silica nanoparticles had been deposited on that surface followed by modifying the surface with a chemical vapor deposition of (tridecafluoro-1,1,2,2-tetrahydrooctyl)-1-trichlorosilane. Creating two-level hydrophobic surfaces also uses different techniques using chemical treatments. Similarly, the mimicking of the rose petal for hydrophobicity and low adhesion also involves chemical treatments. Bhushan and Her[32] used various masses of *n*-hexatriacontane coatings on a microstructure to mimic the same. Mimicking of shark riblets to impart drag reduction and anti-microbial properties follows a similar trend. Commercially produced anti-fouling surfaces by Sharklet Technologies, Inc., are flat polydimethylsiloxane elastomer or acrylic film (Flexcon, Spenser, MA), either cast against nickel shims or embossed with an inverse Sharklet™ micro-pattern.[38] It is noteworthy that, currently, the trend of using special chemical coatings is rapidly growing and the global market for nano coatings alone is estimated to increase to 14.2 billion US dollars by 2019.[45]

Methodology

The outcome of this paper was based on a comprehensive literature review to seek an answer to the main research question on how existing and futuristic textile technologies could facilitate conscious mimicking of nature rather than intense application of chemicals to produce functional textiles. This main research question was further divided into sub-research questions as follows.

i How has biomimicry been used in achieving textile functionalities by promoting structural mimicking rather than chemical-intensive applications?
ii How could existing textile technologies and textile structures further facilitate structural mimicking to achieve textile functionalities without or with less use of chemicals?
iii How could emerging technologies facilitate environmentally responsible mimicking?

In order to answer the main and sub-research questions, a literature review was conducted in three phases as follows.

Review of advanced textile functionalities that have already been achieved by mimicking biological structures

Research articles in which biomimicry is used in achieving textile functionalities were initially selected for screening. The literature search was conducted using Scopus, ScienceDirect and Google Scholar databases to obtain peer-reviewed scholarly literature. The search was conducted using a combination of keywords: biomimicry, biomimetics, functional textiles, sustainable biomimicry, sustainable textiles. There were 231 papers obtained from the initial search and the initial selections were made based on the broad focus of this paper: the application of biomimicry in achieving textile functionalities. In total, 81 papers were selected for the review. Only structurally mimicked textile applications were considered for further review.

Review of existing textile technologies and fabric structures that would be applicable in structural mimicking

Scanning electron microscopy (SEM) images of those already identified biostructures were selected from the published literature and investigated to identify the possibilities of mimicking those as textile structures. In this regard, existing textile technologies as well as woven and knitted textile structures were carefully reviewed and compared with the selected biological structures to investigate the potential of structural mimicking.

Emerging technologies that would facilitate mimicking textile structures to achieve desired functionalities

Futuristic manufacturing technologies were reviewed to explore the possibilities of using those in structural biomimicking in textiles. The literature concerning existing and futuristic textile technologies was searched using Scopus and Google Scholar databases using the following keywords: innovative textile technologies, novel textile technologies, additive manufacturing (AM), 3D printing, nano-weaving and micro-weaving. Out of the 52 research articles obtained through the initial search, 10 promising research articles were selected based on the potential of those technologies to structurally mimic biological structures. Possibilities of sustainable functionalization of textiles were evaluated based on the selected innovative technologies and chosen biological structures.

Results

In order to answer the formulated research questions, a comprehensive literature review has been conducted and the results obtained were categorized in to three main themes: review of structural mimicking applications in achieving textile functionalities; review of current textile technologies and textile structures to investigate the possibility of supporting responsible biomimicry; and the possibilities of incorporating

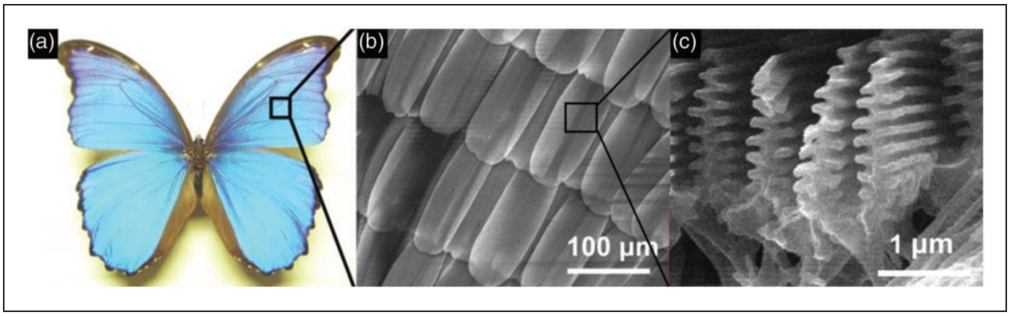

Figure 1. (a) Typical Morpho butterfly (*Morpho didius*). (b) Scanning electron microscopy image of the scale. (c) Scales covered with ridges whose lateral profile has the typical "Christmas tree" shape (adapted from Dumanli and Savin[50]; color online only).

emerging manufacturing technologies to enhance responsible biomimicry in the textile industry. The results are discussed in detail in the following sections.

Conscious mimicking for textile applications

Butterfly wings represent a complex biological structure. This biological structure has been mimicked to produce structural colors of butterfly wings in textiles, which can be considered as a breakthrough study at a time when the outcome of textile wet processing has become a global issue of concern. Structural colors of butterflies and moths are an outcome of a multitude of physical mechanisms, including multilayer interference, diffraction, Bragg scattering, Tyndall scattering and Rayleigh scattering.[46] Morphotex®, invented by the Japanese fiber company, Teijin Fibres Limited, Osaka, Japan, is a structurally colored fiber that uses no dyes.[47] It was inspired by the *Morpho* butterfly (*Morpho didius*), whose wing-scales exhibit a unique metallic blue color, as illustrated in Figure 1(a). This highly reflective iridescent blue color is due to the coherent scattering in the periodic arrays of scales,[48] as shown in Figures 1(b) and (c). Even though these periodic structures usually produce colors with high dependency on the angle of reflection, the specific *Morpho* butterfly's multilayer surfaces that exhibit a distribution of tilts with respect to the substrate of the scales make the characteristic blue color less angle dependent. A second layer of periodic ridges above the iridescent layer emphasizes the effect[49] and the outcome is the complex optical response of the combination of multilayer interference, diffraction, scattering and pigment-induced absorption to produce its singular, angle-independent brilliant blue color.[50] This has even inspired innovations beyond textiles, to even designing smart windows and buildings.[51]

Pinecone scales hold seeds within their folds when the surrounding environment is humid. When the air is dry, a part of the scale shrinks, causing the scales to open up and release the seeds.[52] Inotek™, a bio-responsive fiber that reacts to humidity levels in a micro-climate, has recently been invented and patented,[53] mimicking this concept of the "pinecone effect." It is common knowledge that natural fibers such as cotton[54] and wool[55] absorb moisture well and swell as a result. However, Inotek™ fibers behave in exactly the opposite way, shrinking in volume as the humidity increases. Microscopic air pockets open up in fabrics made using these special fibers, thus increasing their breathability. This process is reversible, causing the microscopic air pockets to close as the humidity in the micro-climate decreases, thus giving the fabric an adaptive breathability. The effect is primarily due to the structure of special bi-component fibers used with an eccentric core–sheath arrangement with polymers of contrasting moisture regains.[56] In the eccentric core–sheath configuration, the force generated by the higher shrinking polymer is not equally balanced by the lower shrinking polymer, so the forces are resolved by the curling of the fiber into a helical shape. The yarns spun from these special fibers will therefore be able to curl and uncurl reversibly with humidity changes. Nike has been successful in creating a fabric with adaptive breathability, the Nike AeroReact™, mimicking the pinecone effect using a special bi-component yarn, as mentioned above, to control the porosity of the fabric.[57] At different stages, Nike's AeroReact™ fabric opens up with increasing humidity.

With the energy crisis in the 1970s, scientists studied Avians and Nekton to observe their drag-reduction mechanisms to mimic them in transportation modes.[36] Sharks have been the particular focus of ample research,[58–61] given their multi-purpose skin, famous for drag reduction and the biofouling protection effect. These effects are credited to the special placoid scales on sharks (also called dermal denticles or skin teeth) formed as small riblets in the direction of fluid flow.[53] It is also believed that sharks could bristle these riblets at high swimming speeds (or that the scales might erect passively at high speeds).

The role of these special riblets in reducing the increased drag in turbulent flow is twofold, firstly by

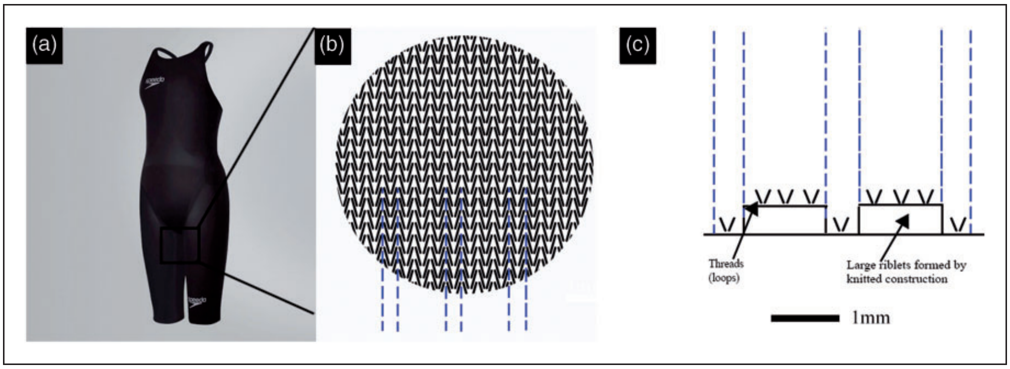

Figure 2. Speedo FastSkin® swimsuit and (b) stretched swimsuit close up. (c) Schematic showing apparent hierarchical riblet structure formed by threads (adapted from Bhushan[64]).

hindering the cross-stream translation of the stream-wise vortices in the viscous sub layer and, secondly, the shear stress and momentum transfer are reduced by elevating the high-velocity vortices above the surface.[62] Lee and Lee[63] experimentally determined that most of the stream-wise vortices interact only with the tips of the riblets (small surface area), thus preventing them from interacting with the valleys of the riblets. Moreover, the spaces between the dermal denticle ribs in the micro-pattern are such that microorganisms find it impossible or difficult to adhere to the sharkskin, thus preventing biofouling.[64]

Subsequently, this structural geometry in nature has been mimicked in designing drag-reducing surfaces in many applications.[34,60,65] Given that 90% of the swimmer's power output is spent overcoming aero/hydrodynamic resistance, application of this concept in swimwear provides a competitive edge to swimmers.[35] Some of the most popular swimsuits produced mimicking this technology are the Speedo® LZR (Speedo® Fastskin Series), Blueseventy® Pointzero3 and TYR® Sayonara. Foster et al.[66] concluded that the introduction of new swimsuits caused performance enhancements in freestyle swimming and also that the most likely cause for the said improvements is the reduction in cross-sectional area of the swimmer presented in the water and of the drag coefficient. Mimicking this concept in textiles by Speedo® is noteworthy, since they have incorporated the riblet structure into the fabric itself (i.e. the effect is built/knitted into the material) rather than using chemical-intensive processes to achieve the effect. This is notable progress made in the direction of mimicking a biostructure in a purely structural sense (Figure 2(a)). This special structure of Speedo® Fastskin employs the riblet geometry in two different scales: the macro level or the larger riblets are created by the aligned ''legs'' of knitted loops of the fabric structure, whereas the comparatively smaller riblets are a result of the individual threads used to knit the loops.[64] In a way, the design can be thought of as micro-riblets on macro-riblets, as shown in Figures 2(b) and (c).

Two thirds of the world's population currently lives in areas that experience water scarcity for at least one month a year.[67] Therefore, efficient water-harvesting systems have become an important direction of research. Nature has evolved and perfected the craft of surviving in the harshest of environments. Plants such as Namib Desert grass (*Stipagrostis sabulicola*), Canary Island pine (*Pinus canariensis*), bayberry/candleberry (*Myrica arborea*), etc., and animals such as the Black Beetle (*Onymacris unguicularis*) are some of the best examples of time-perfected fog harvesting, that is, harvesting water from the surrounding air. These biostructures provide insight for efficient artificial fog harvesting systems. Among the fog harvesting beetles in the Namib deserts, the Black Beetle (*Onymacris unguicularis*) is one of the most common.[68] Its surface is covered with micro-scale nubs, the tips of which are weakly hydrophobic while the surface of the top (front) fused ''wings'' (elytra) is covered with a wax layer. This makes it more hydrophobic than the nubs. This microstructure allows adsorbing and coalescing water droplets on the less hydrophilic nubs. When the droplets reach a threshold size, they lose adhesion and roll along the shell due to the hydrophobic wax.[69]

The ability of *Stipagrostis sabulicola* to transport collected fog water toward the plant base with a minimal loss (by droplet scattering) is attributed to the two different kinds of surface roughness. The first is the highly irregular surface caused by prickle hair and platelet-like wax structures, as shown in Figures 3(c) and (d). They prevent the premature shedding of collected water droplets that are too small for the downslide. Secondly, grooves along the axes of the leaves ensure a guided downslide of large enough drops, thus minimizing loss by droplet scattering.[70] These biological structures, combined with the advanced water-harvesting strategies from the needle-shaped leaves of the

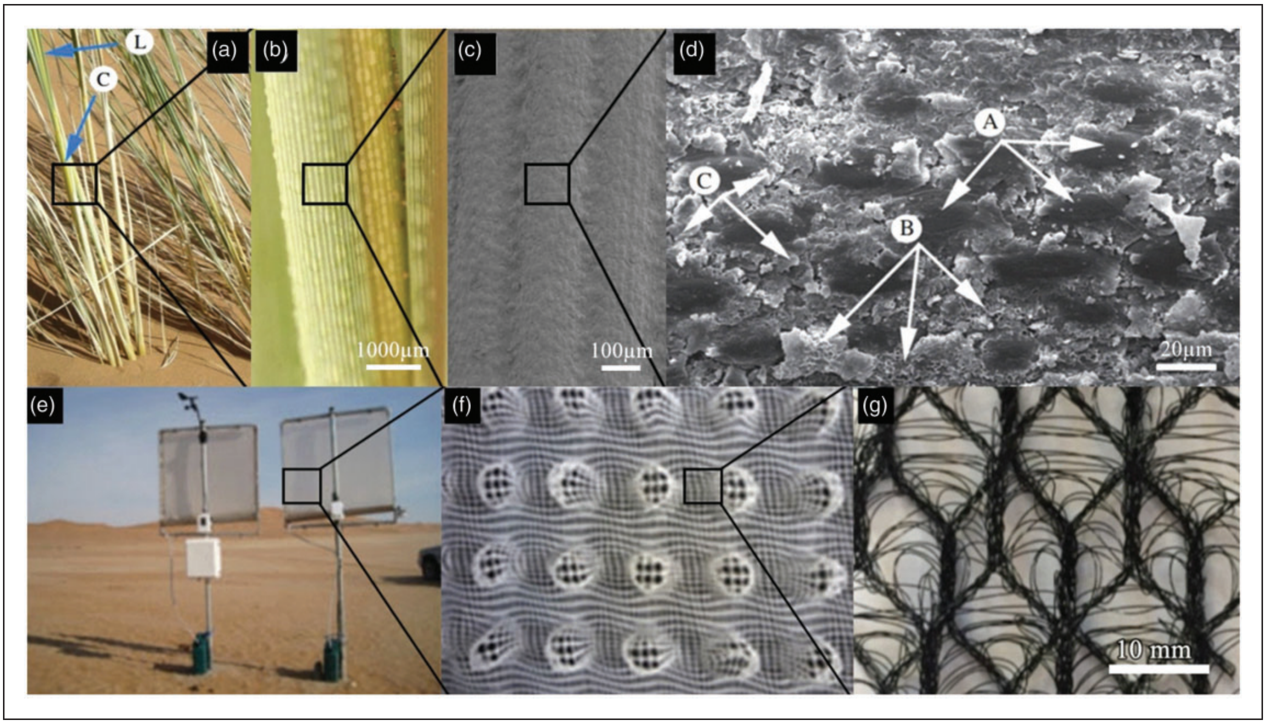

Figure 3. (a) Young tussocks *of S. sabulicola*. C: culms; L: leaves. (b) Drops on involute leaves of *S. sabulicola* after a fog event. (c) Scanning electron microscopy (SEM) image of the abaxial leaf surface. (d) SEM image of the surface of *S. sabulicola* featuring (A) prickle hairs, (B) putative wax platelets with microcrystalline structure and (C) putative wax platelets without microcrystalline structure (adapted from Roth-Nebelsick et al.[70]). (e) Fog collectors in the Namib Desert. (f), (g) Close up of views of the three-dimensional spacer knitted textile (adapted from Sarsour et al.[72] and Fernandez et al.[71]).

Pinus canariensis and *Epiphytic bromeliads* for their harvesting as well as evaporation preventing mechanisms, have collectively inspired the 3D spacer knitted fog collector known as "FogHa-TiN" (Figure 3(e)). FogHa-TiN can harvest fog water in an efficient manner while withstanding wind velocities of up to 100 km/h and ultraviolet radiation. Therefore, it is suitable for harsh environmental conditions in a desert, such as intense sunlight and desert storms.[63] This porous structure is spacer knitted using synthetic monofilaments of different thicknesses and is deployed in two orientations.[71] The outer surfaces are honeycomb structures knitted with a finer monofilament, while the spacer thread connecting the two honeycomb structures on either side of the 3D fabric is knitted with a thicker monofilament.[72] This special construction is illustrated graphically in Figures 3(f) and (g).

Prospects of available textile technologies in conscious biomimicry

Although sharkskin has been structurally mimicked into textile materials to impart drag reduction, its anti-microbial property has not. The spaces between the dermal denticle ribs in the micro-pattern are such that microorganisms find it impossible or difficult to adhere to the sharkskin, thus preventing biofouling.[72] Researchers have developed synthetic anti-fouling surfaces or thin films rather than textile materials, mimicking this concept. Sharklet™ Micro-pattern by Sharklet Technologies, Inc., is one of the most commonly seen synthetic materials. Its structure consists of obround ribs of 2 μm width occurring in a periodic micro-pattern. This periodic micro-pattern has diamond-like shapes formed of the said obround ribs spaced 2 μm apart, as shown in Figure 4(a).[73] These miniature dimensions make it difficult to mimic those patterns in textiles with the existing technologies. However, weaving or knitting technologies alone can make comparable patterns in macroscale on textile surfaces. Figures 4(b) and (c) are two such fabric samples knitted in a comparable 3D structure to Figure 4(a), while Figures 4(d) and (e) are commercially available comparable knitted articles.

In principle, these structures when woven or knitted in the correct dimensions could exhibit the same functionalities. The problem, however, lies with the incapability of existing knitted or woven fabric technologies to produce such intricate shapes. On the contrary, structurally mimicked fibers and fabrics such as Inotek® fibers, Speedo FastSkin® and Morphotex fabrics have already been developed using existing textile

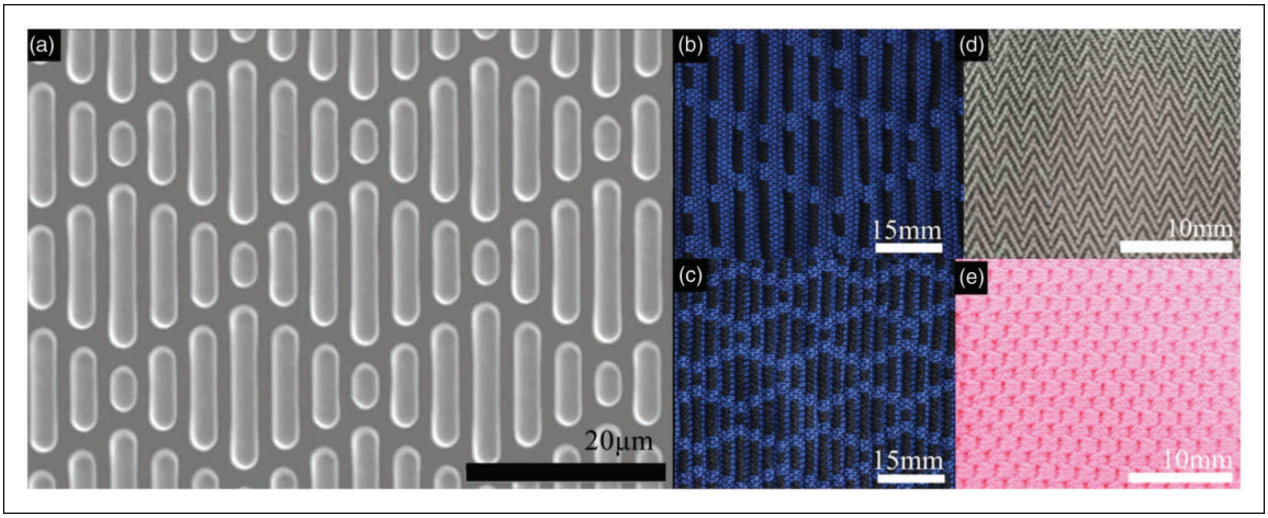

Figure 4. (a) Scanning electron microscopy image of Sharklet AF topography molded in Polydimethylsiloxane (adapted from Callow and Callow[73]). (b), (c) Knitted fabrics following the three-dimensional (3D) microstructured pattern of (a). Commonly found (d) knitted and (e) woven fabrics with comparable 3D structures to (a).

technologies, as widely discussed in the preceding sections. It is therefore evident that mimicking biological structures in a purely structural sense does not always involve highly intricate articles but rather a conscious connection made between the technology available and the biological functionality being mimicked. For example, if a leaf were to be observed carefully, it would have two sides with different functionalities as well as textures and appearances. Existing woven and knitting technologies facilitate fabrics being developed having entirely different properties on either side. A woven double cloth, which is a single piece of fabric consisting of two separate fabrics simultaneously woven but interconnected at predefined binding points, is one of the most common ways to achieve this. The cross-section of a woven double cloth is graphically illustrated in Figure 5(c).

Another different technique is to use a warp knitting machine with two sets of knitting needles (double needle bar), each capable of knitting different structural patterns simultaneously into a single fabric. This provides more flexibility in design than a woven double cloth. For example, the two fabrics could be joined simply at one edge to make a double width fabric or at both edges to produce a tube with two sides having two different functionalities. Moreover, a specialty yarn can be used joining the two fabrics to produce a 3D spacer warp knitted fabric. Double needle bar warp knitting and a 3D knitted spacer are graphically illustrated in Figures 5(a) and (b), respectively. Adding more to the design capability, guide bars available on these machines could facilitate localized effects on either side of the fabric, mimicking different functionalities on the two sides of a leaf. Moreover, the plating technique in weft knitting could also be used, to feed two different yarns at different feeding angles to appear on either side of the fabric separately. Other 3D knitted effects facilitated by stitch holding, loop transferring and racking, relief jacquard, etc., or specialty knits, such as fleecy, plush and velvet, are also available to structurally mimic biostructures. With the development of technologies such as conductive yarns, these technologies have limitless capabilities. However, a conscious connection between technology and biomimicry is still missing.

Producing levels of intricacy such as the Sharklet™ micro-pattern in Figure 4(a) is a possibility, with the conceptual frameworks such as nanoweaving technologies based on voltage-induced actuation force,[74] which overcomes the probable failures of micro/nano filaments. Such micro or even nano structures produced employing weaving technologies using micro or nano filaments are advantageous in many other engineering applications. These woven structures increase strength and flexibility and, at the same time, the pore size and uniformity can be controlled by varying the weaving density.[74]

Use of emerging technologies for conscious biomimicking of advanced textile structures

The properties of the output of a textile can be easily manipulated by varying the sublevel building block: fibers/filaments in addition to the macro levels; weaving, knitting, etc. By changing the fiber diameter, raw material as well as its cross-sectional shape yield useful effects. Advanced technologies allow reducing the diameters of textile fibers to a few nanometers, which

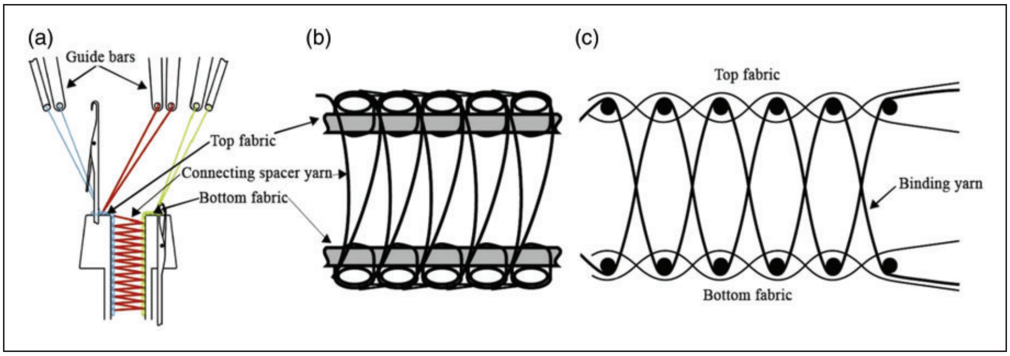

Figure 5. (a) Schematic of a double needle bar warp knitting machine. (b) Cross-section of a three-dimensional knitted spacer. (c) Cross-section of a woven double cloth (adapted from Wulfhorst et al.[75]).

in turn allows their use in a multitude of disciplines. Commonly used fibers usually have a circular or a nearly circular cross-section. Although methods to produce fibers with complex cross-sections are currently available, there are limitations in terms of the level of intricacy of the cross-section as well as the fineness of fibers. AM, among other innovations, is a technology that holds promise with regards to overcoming the said limitations.[76] Rapid production of microstructured monofilaments by heat drawing of additive manufactured polymer preforms can produce intricate and complex geometries to be readily accommodated to filament cross-sections. Here, a preform is firstly 3D printed, with a complex cross-sectional shape, but comparatively large in dimension. The cross-section of this ''parent preform'' can be of virtually any level of intricacy, as defined by the 3D printer's resolution. It is subsequently drawn to a micro filament while retaining the shape of the parent preform. Meanwhile, this technology, in general, also eliminates the need for infrastructure otherwise needed in conventional technologies. The modern trend seems to displace traditional manufacturing, given these benefits, coupled with reduced waste, parts count, lead-times and, in particular, its transformative customizability.

Figure 6 shows microstructured monofilaments manufactured by heat drawing additive manufactured polymer preforms. This technology can be further developed to improve the accuracy of the cross-section of the filament to the parent perform as well as further reduce the dimension by tenfold or more.[76] Therefore, it opens up new possibilities to structurally mimic amazing geometries in nature in textile materials. For example, it will be possible to produce fibers with a cross-section in the shape and dimension comparable to Figure 1(c). With such specialty fibers coupled with technical possibilities to weave/knit microstructures using these specialty microfilaments, the result is a comparable replica of the butterfly wing with structural colors. A filament with ridges of thickness and spacing of about 2 μm could similarly be produced with various diameters. For these specialty filaments, the theory of the anti-microbial property could be applicable. Microbes would find it impossible to adhere to a surface created with these specialty filaments, using textile technologies such as weaving or knitting, thus making it an anti-microbial two-dimensional (2D) assembly. The anti-microbial functionality is therefore structurally integrated into the fabric. This technology will essentially have limitless possibilities in the sustainable development of biomimetic textile structures.

In addition to the AM of fibers/filaments, AM is becoming a viable solution for producing textiles or apparels now, especially given the advantages in terms of the intricacy and complexity of designs. AM textiles have already gone into mass production[77] and special, high-performance materials such as biomimetic heart valves[78] and stab resistant textiles[79] have also been produced in niche. A structure with virtually any complexity can be produced with AM technologies. However, more connections need to be made and more research needs to be carried out to coalesce biomimicry with this infinitely complex design/manufacturing capability.

Three-dimensional printing can be classified into stereolithography (SLA; 3D systems), inkjet printing (Z Corporation), selective laser sintering (EOS GmbH), fused deposition modeling (Stratasys) and laminate object manufacturing (Cubic Technologies), out of which, SLA and inkjet printing are high-resolution methods, that is, these methods have a minimum feature size of 50 μm. These technologies hold the potential to be the future of structural biomimicking of textiles, with emphasis on the design complexity of biological structures found in nature, otherwise impossible to mimic, using conventional textile technologies. For example, the microstructure on the *Stenocara gracilipes* (also known as the Fogstand beetle) is capable of extracting water from desert fogs. Its texture is intricate, and the structure is in the range of a few microns or even at the sub-micron level.

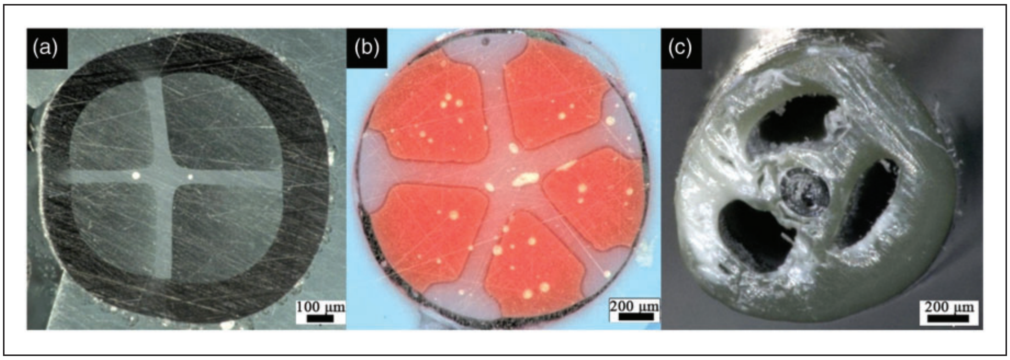

Figure 6. Microstructured monofilaments produced by heat drawing additive manufactured polymer preforms (adapted from Toal et al.[76]).

Researchers have already attempted 3D printing of sharkskin for its drag-reduction property. Wen et al.[80] attempted to 3D print sharkskin denticles at the micron scale but had to rescale the original model by magnifying the original design 12.4 times to create denticles of 1.5 mm in length. The limiting factor was the resolution of the 3D printer, an Objet Connex500 available at the time (Stratasys Ltd, Eden Prairie, MN, USA). However, Bhushan and Caspers[81] have recently 3D printed sharkskin using SLA and inkjet printing (ProJet 3510SDprinter) on a micron scale and have achieved micron-range 3D assemblies. Analogously, the required micron resolution of the novel 3D printing technologies will soon be realized, thus opening up an entirely novel domain of research with respect to additive or rapid manufactured biomimetic materials for special functionalities. Therefore, it is expected that this paper will be a precursor for further research in the said futuristic domain.

Discussion

Textile structures are versatile, and are mainly based on weaving, knitting, braiding and nonwoven technologies. The beauty of these four technologies is that, separately or in different combinations, they can create an infinite number of surface geometries around specific requirements, which have not yet been fully explored by textile engineers and manufacturers. The building blocks of these technologies are synthetic or natural fibers. One of the predominant features of synthetic over natural fibers is that synthetic fibers can be altered according to material or geometry of the final requirement of the textile. Currently, there is a plethora of materials used for synthetic fiber manufacturing, such as polyester, nylon, spandex, rayon, Kevlar, Nomex, acrylic, etc. The geometries of these fibers can be changed cross-sectionally or linearly. Today, with the advancement in computing technology where computerized programs are used for patterning and creating form, the history of weaving, knitting, braiding and nonwoven technologies are poised for a progression that will create intricate surface geometries. Textile engineers equipped with this knowledge continue to explore possibilities of mixing and matching advanced technologies with existing textile manufacturing technologies to mimic complex geometries in nature, in a sustainable manner.

The examples discussed in the preceding sections are, however, just a few applications of biomimicry in textiles. Countless biological structures are still waiting to be discovered. The role of textile engineers is vital in this regard, making conscious observations and identifying as many biostructures with applicable functionalities as possible. At a time the textile and fashion industry is trying to join the circular economy,[65,66] textile engineers could create more value by interacting with the value chain as much as possible.[67]

The most commonly discussed biomimetic subject, *Nelumbo nucifera*, has a hierarchical nanostructure on a microstructure. The diversity of leaf surfaces is enormous, evolving for billions of years to suit necessary environmental interactions. Each of these biological structures may be a key to finding answers to the most severe complications humans face. Although humankind has progressed well from developing the Velcro™ technology in the 1950s, there is still progress to be made in biomimicking in textiles. As such, discovering and understanding as many biological structures as possible is a crucial part of this voyage. It is hoped that this work inspires scientists and engineers to question nature further in order to build complex systems with functionality and efficiency. Leaf cells make a photosynthesis powerhouse, whereas cellulose in combination with lignin makes a natural hard composite: wood. Dragline silk from spiders is five times stronger than steel and tougher than bulletproof Kevlar. The building blocks in nature have so been assembled to perfect their functionalities. That is why textile processing technologies offer analogies to natural growth

Table 1. Summary of current and suggested potential methods to create biological surface structures on textiles

Biological structure	Functionality	Current method	Suggested method
Shark skin	Anti-microbial effect	Polydimethylsiloxane elastomer or acrylic film based Sharklet™ micro-pattern	Nano/micro weaving with specialty nano/micro-filaments
Shark skin	Drag reduction	Knitted fabrics using micro and macro-riblets created by individual threads and knitted loop legs, respectively, when stretched	3D printing the riblets
Butterfly wing	Structural color	Alternate layers of nylon and polyester having different refractive indices	Using micro/nano filaments with intricate cross-sections by heat drawing of 3D printed foams
Microstructure on the Fogstand beetle	Fog harvesting	FogHa-TiN, 3D spacer fabric knitted with synthetic monofilaments of different thicknesses	Additive manufacturing of the intricate microstructure
Nanostructure on Taro leaf	Hydrophobicity	Sol–gel, dip coating, self-assembly, electrochemical and chemical/physical vapor deposition	Additive manufacturing of the intricate micro/nano structure

3D: three-dimensional.

processes and hold promise in ''successful'' biomimicry. Textile fibers can be filaments as tiny as a few nanometers. Larger components can subsequently be manufactured using many different methods to be finally assembled, following a sequence of processes. Moreover, the many different methods of fiber processing, fiber orientation and finishing at disposal make textile materials highly suitable for transferring biological functions to technical products, as clearly portrayed above in this paper. However, the capacity of technology has not yet been evolved to cater for the ever-growing demand for functionalized textiles and remains a niche. Analogous to the vastly miniaturized developments of modern electronics from vacuum diodes, transistors and integrated circuits to microprocessors, technology will be adequate in the near future to cater to the said demand. However, more and more connections need to be made between existing textile materials and biomimicry, while novel biological structures must be constantly sought. In summary, the suggested new methods that have potential to replace the current methods for the selected biological structures can be summarized as shown in Table 1.

The suggested 3D printing or AM methods in Table 1 could avoid chemical and energy-intensive manufacturing processes. Furthermore, this technology helps to manufacture complex designs with short lead-times, compared with the traditional manufacturing methods.[70] Even though chemical coatings are often employed to impart functional properties in textiles, those coatings hinder the biodegradability of textiles. Moreover, synthetic fibers are petroleum-based and are neither biodegradable nor renewable. However, biodegradable and renewable polymers such as polylactic acid (PLA) can be used to produce textile fibers/filaments. Therefore, PLA can be used as a feedstock for 3D printing structures in nature toward improving the environmental sustainability of the resultant textile material.

Conclusion

The functionalization of textile materials using biomimicry currently follows an unsustainable path, despite its prospects for sustainability. While more and more biostructures must be discovered for their special functionalities, efforts must also be made to pick up traits of the global trend of sustainability in mimicking those. Although technology is still evolving to cater this necessity, this study highlights that the basic framework is already available. This study also emphasizes that advanced weaving, knitting, braiding and nonwoven technologies and futuristic frameworks, such as AM, hold promise in realizing the true potential of biomimicry, with emphasis on the sustainability considerations. Some researchers have already started making promising connections between novel textile technologies and biomimicry to innovate in a truly sustainable fashion. However, further research is imminently essential in order to break the already set trend of unsustainable functionalization.

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