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Review Article

Applied Biomimetics: A New Fresh Look of Textiles

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Biomimetics is a new research field that deals with extraction and imitation of functional principles of nature and applying them in engineering. Due to the perfection of structures and mechanisms found in the natural world, scientists came to the conclusion that these may constitute reliable sources of inspiration and viable solutions for technological problems they face today. Industrial applications have rapidly developed. Trying to synthesize all information about this extremely large field, with branches in biology, physics, chemistry, and engineering, soon I realised that an exhaustive study is merely a utopia. Despite all that, the beauty and perfection of "inspiration sources" which led to the fabrication of many biomimetic prototypes encouraged me to approach with thrill and enthusiasm this fascinating domain, not in general, but in a more specific field, the textile field. After a brief introduction to Biomimetics and a historical review of it, there are presented some of the most important biomimetic textiles innovations, among which I mention fibrous structures, multifunctional surfaces, thermal insulating materials, and structurally coloured materials.

1. Introduction

In recent years, Biomimetics has shown a surprising interest in a great variety of research fields. This is mainly due to the discovery of potential that mimicking functional principles of nature has in designing artificial structures and mechanisms. Although with a shy presence in the early 1990s, today's extensive research in Biomimetics is highlighted by the big number of publications that fill the pages of many important journals.

Trying to synthesize all information about this extremely large field, with branches in biology, physics, chemistry, and engineering, soon I realised that an exhaustive study is merely a utopia. Despite all that, the beauty and perfection of "inspiration sources" which led to the fabrication of many biomimetic prototypes encouraged me to approach with thrill and enthusiasm this fascinating domain, not in general, but in a more specific field, the textile field.

In everyday life, textiles are used for a multitude of purposes, among which I can mention the following: to highlight or to disguise the wearer, to make a statement or comment about them, to provide information about next season, to cover a floor, and many others. Textile manufacturers are aware of the requirements that a potential customer can have and they try to meet them. But, although widely used, many of the applications that textiles have are hidden from our eyes. I mean that the textiles used for building roads, tire manufacturing, spacecraft components, or even replacing human organs.

The multitude of domains using textiles led to strong growth of the industry and hence resource consumption, resulting in huge amounts of waste that are becoming increasingly difficult to remove. Faced with these problems and the negative effects that have affected the environment, we find ourselves in a position to rethink our strategies for production and investment in manufacturing technologies that are environmental "friendly." Since we reached the limits of nature's tolerance, we begin to ask serious questions about how we can continue to produce materials without destroying the planet.

Meanwhile, nature unfolded right before our eyes manufacturing processes that are highly superior to those that we invented, but without the use of toxic chemicals or inactive waste generation. Nature has solved many of the mechanical, structural, and energetic problems that scientists and engineers face today, developing methods of handling hydrogen, oxygen, and carbon to achieve their objectives, while people contracted the destructive power of oil.

Biomimetics aims to remedy this error by designing systems and products that have nature as a guide. The mentality to dominate or to "improve" nature has to change to a completely new approach: mimicking the functioning principle of it. Over a few decades of rapid development, Biomimetics has proven its necessity and practicability by designing a variety of new mechanisms and significantly improving the performance of existing mechanisms and machines.

2. What Is Biomimetics?

At first glance, Velcro and the Eiffel Tower have nothing in common, but the designers of both had the same inspiration source: nature. The two examples are successful applications of a new field known as Biomimetics—taking ideas from Nature. To withstand battle for survival, plants and animals have been "equipped" with sophisticated defence mechanisms that can give practical solutions to technical problems that scientists and engineers face today. It was found that nature's "inventions" are superior to those man-made and hence interdisciplinary teams (biologists, chemists, physicists, engineers, etc.) have been created in order to observe how nature solved a problem and then to imitate its principle, to obtain new products and features. This approach led to the development of a new branch of science: Biomimetics (or imitation of Nature).

Biomimetics (also known as: bionics, biomimicry, or biognosis) is relatively young as a science of its own. It was originally listed in 1950 by the American biophysicist Otto Schmitt [1] who, through his doctoral study, developed an electronic circuit (Schmitt trigger) based on the operation principle of the nervous system [2]. The term "Biomimetics" is composed of two words derived from Greek: "bios" (meaning "life") and "mimesis" (meaning "to imitate") [3]. Although through his studies, Otto Schmitt has successfully transferred ideas from biology to technology (without his invention, Microsoft, Mac, or Google would not exist [2]); for a long time this science remained at an empirical stage. Ten years later, in 1960, medical doctor and US Air Force colonel Jack E. Steele introduced the term "bionic" in an international conference held at the military base Wright-Patterson Air Force Base in Dayton, Ohio (USA), with the theme: "Living Prototypes—the Key to New Technology." The term "bionics" is composed also by joining two words in Greek "*βίον*" and "bíon," pronounced [bi:on], meaning "unity of life" and the suffix "-ic," meaning "like," therefore "like life." In 1969, Schmitt used the term "biomimetic" in order to entitle one of his works [4], and in 1974 the word was first published in Merriam-Webster Dictionary, with the following definition: "*The study of the formation, structure, or functions of biologically produced substances and materials (as enzymes or silk) and biological mechanisms and processes (as protein synthesis or photosynthesis) especially for the purpose of synthesizing similar products by artificial mechanisms which mimic natural ones.*" [5].

3. Historical Review

Although only in the last century, Biomimetics has won a place among the sciences, its practice is as old as civilization. Since ancient times, man has been drawn to nature, carefully observed it, and tried to empirically imitate it. Fascinated by the flight of birds, people made wings as Icarus (Greek mythology) or Master Manole (Romanian mythology). They built primitive boats from hollowed trunks, noting that a tree floats on water. Following the discovery of Archimedes' law of floatation, the quality and efficiency of water transport were improved, and construction of ships experienced a great boom in antiquity and the middle ages. Effervescent era of Renaissance resumed with passion the study of nature, brilliant minds emerging, including that of Leonardo da Vinci. In a harmonious combination of technical innovations and their analogues existing in nature, the great artist and inventor sketched the first models of gliders, parachutes, and submersibles. A milestone in the history of Biomimetics was the development of mechanics, initiated by the work "The Mathematical Principles of Natural Philosophy," written by English physicist Isaac Newton (1642–1727), to which was added Hooke's law (Robert Hooke, 1635–1703), which is the base for rational design of mechanisms and machines.

Why did Biomimetics, with its long history, return to the attention of researchers in the early 1990s? In the past century, it was believed that the fundamentals of biology, a science more descriptive at that moment, were already settled. Nature's inventory was complete. The multitude of inferior and superior plants, as well as the variety of animals that walk, run, jump, crawl, swim, or fly have been listed, named, and classified. However many questions had found no answer. Only at the beginning of the last century, genetic problems, brain functioning, ways of communication in the living world, or environmental issues were elucidated. Although we experienced many successes in terms of knowledge and conservation of nature, scientific and technical advances that have marked recent decades proved that we are powerless and extremely vulnerable to earthquakes, typhoons, drought, how little we know about mechanisms of diseases, or how to use more from the brain capacity.

In technological field as well, a decline was encountered in the 1950s, facing the fact that devices and machines no longer respond to the necessities. Whatever their field of application, the tools used were accused of poor reliability, high volume, unnecessary complexity, and insufficient efficacy.

In many cases, the lack of satisfaction has proved fertile, driving scientific progress. This could be observed in the field of Biomimetics too, which encountered a considerable increase starting with the 1990s.

4. Biomimetic Textile Innovations

The natural world around us provides a multitude of examples of functional systems built with a minimum amount of materials. Over time, nature has evolved by adapting and developing sophisticated ways of solving problems. Just looking to nature, we can see many examples of fibrous structures, multifunctional surfaces, structural colours, materials with self-healing properties, thermal insulation, and so on, which can be excellent models of inspiration for future textiles.

This section presents an overview of current biomimetic textile innovations and the potential they offer in the development of textile products. In many ways, textiles offer unique opportunities to imitate nature. The base units of each textile structure at the most elementary level of the hierarchy (from nano to micro) are organic fibres, many of which are natural. In addition, like many natural functional surfaces, the textile surfaces also offer excellent opportunities for developing new functionality. All these allow an easier way to borrow the biomimetic principles in textile field than in other industrial areas.

4.1. Fibrous Structures. Nature abounds with examples of structures made of fibres, one of the well known of these being the spider web. Depending on the species of spider that produce them (there are about 34,000 known species [6]), or the purpose for which they are made (there are over 130 cataloged models of webs), the spider web can be composed of short fibres with apparently no order or perfectly regular structures [7]. Other examples of extraordinary fibrous structures can be observed in plants and trees. Usually, the fibres are arranged and directed by a specific pattern in order to confer the desired mechanical properties. An interesting pattern is presented by the coconut palm. Its fibres are often used in carpets manufacturing, mattresses, and so on. The leaves that cover the palm's trunk are made of layers of fibrous sheets, orthogonally arranged like a fabric [8]. The coconut palm has three types of fibres, the interesting aspect of them being the significantly different mechanical properties of each type of fibres, depending on the position on the palm trunk [8].

Wood and bamboo are excellent examples of natural fibre composites with high strength. Wood is composed of parallel tubular cells reinforced with cellulose fibrils in a spiral wound, embedded in a matrix of hemicellulose and lignin. The winding angle of fibrils confers different mechanical properties of wood, such as stiffness and strength [9–12]. Bamboo is one of the strongest natural fibre composites with special properties. It has a tubular shape, with almost equally spaced components and very dense distribution of the fibres in the cross section, particularly on exterior [13]. Although it has a similar chemical composition to wood, the mechanical properties are quite different. The differences are due to the number and different arrangement of fibrous layers from their composition [14].

In nature, there are found also a wide variety of fibrous structures which respond to various stimuli. Most plants are able to passively action their organs by controlling anisotropic deformation of cells exposed to moisture. Cell walls of plants are composed of rigid cellulose fibres embedded in a softer matrix, sensitive to moisture, and composed of hemicelluloses, pectin and hydrophobic lignin. Absorption and elimination of moisture through cell walls determine their anisotropic deformation [15]. The angle and direction of bending are influenced by the mode in which the cellulose fibrils are oriented in the cell wall and on their rigidity [16]. The hydromorphic behaviour is well known at pinecones. In dry medium, the cone scales are closed protecting the seed, and when the humidity increases, the scales open due to the double layered structure in their composition [16, 17]. The operation principle of the pinecones consists in the moisture sensitivity of the outer layer of the scales (which expands or contracts depending on the humidity of the air), while the inner layer remains in the same position [16]. One of the successful biomimetic applications is based on this opening and closing principle of the pinecones. Centre for Biomimetics and Natural Technologies at the University of Bath (UK) produced a layered material whose pores open at high humidity, facilitating ventilation inside the product [18].

Composites are solid materials resulted through the combination of two or more substances in order to obtain a new substance with properties superior to those of the original components. An example is glass fibres, a synthetically made composite, which is often used for boats, fishing rods, bows, arrows, and other sport articles. Glass fibres are obtained by inserting very fine glass fibres into a polymer matrix, which can be liquid or with a jelly composition. When the polymer hardens, it results in a light, strong yet flexible composite. By changing the types of fibres or insertion polymer, a wide range of products can be obtained. Despite the stage of development we are at now, man-made composites are inferior to those observed at animals or plants.

At animals, instead of glass fibres or carbon fibres, a fibrous protein called collagen forms the basis of some composites which give strength to skin, intestines, cartilages, tendons, bones, and teeth. As an example, we can look at tendons who make the connection between muscles and bones. Tendons are extraordinary materials not only due to their fibres strength, but also because of the remarkable way in which the fibres are woven together. The forearm tendon is a bundle of twisted cables, very similar to those used in suspension bridges. Each cable is, in turn, another bundle of thinner twisted wires. Each of these wire is a thin bundle of twisted molecules.

The study conducted by Aizenberg et al. [19] on siliceous sponge *Euplectella aspergillum* presents one of the most beautiful natural structures. The skeleton of this sponge consists of very fine long fibres and silicon spiculi, plaited into a lace-like complex. The hierarchical structure is made of laminated fibres of silica nanospheres that are ordered in a rectangular rigid web. Although it is made of a brittle material (glass) with low strength, the cylindrical skeleton structure is very stable and able to withstand strong currents from the sea bottom. Inspired or not by this structure, Dow NF and Tranfield G [20] designed a similar triaxial fabric for space applications.

For a long time, the only natural source of continuous fibres, available in large quantities, was provided by the silkworms Bombyx mori. The filaments were used for luxurious fabrics and technical applications (e.g., for parachutes) because of their qualities: smoothness, lightness, luster, softness, and strength. In addition, other insects too (such as butterflies, moths, and spiders) produce silk, but spider silk exhibits much better properties (unique combination of strength and elasticity). The list with the remarkable properties of spider silk is very long, among which the most important characteristics are resistance (a yarn of one micrometer in diameter is five times stronger than a steel yarn of the same thickness), flexibility (stretches up to four times its length), and lightweight (a thread long enough to circle the globe on the equator would weigh 320 g) [21]. Since spiders are difficult to keep in captivity (to harvest fibres), people have long studied them in order to mimic the principle by which they weave their webs [22]. The spider web is composed of filaments of biopolymer based on protein (keratin) which, although spun at ambient pressure and temperature and with water as solvent, presents outstanding mechanical properties [23] due to semicrystalline polymer structure [24].

So far there have been cataloged over 34,000 species of spiders, most producing webs for different uses (for catching prey—web-type structures; for protection and conservation—cocoon structures; for escaping from predators and transport—parachute-type structures), with different mechanical properties [6]. Spiders, such as those from the Araneid and Uloborid species, weave a diverse variety of webs depending on their needs at a given time [22]. For this purpose, they use the abdominal glands to synthesize, often simultaneously, over seven different types of silks and protein-based glues [23–25].

Many industrial processes for the production of high-performance fibres are similar to those of the spider. In spiders case, the silk is produced by the spinneret glands (up to 1,000 glands), located in the ventral part of their abdomen. The abdomen (the most voluminous part of spiders body) has no limbs or other attachments, except the spinnerets onto which are the orifices of spinneret glands. The ducts of these glands open through the orifices of spinnerets. The spinnerets (3 or 4) are mobile tronconic formations, having numerous pores. Silk threads coming out from these orifices are woven and positioned as desired with their feet claws. The fibres are drawn by means of a calamistrum (a kind of comb), located at the cribellum top. Finer fibres are braided around the thicker ones. Through spinnerets, the spider can control and change the production mechanism, the diameter, strength, and elasticity of the fibre in order to obtain the desired characteristics, but without modifying the chemical structure [23–26]. The complexity of these organs for the production of fibres, as well as the properties of the resulted web, could not be reached by modern technology.

Many efforts have been made in order to obtain synthetic protein fibres inspired by silk of spiders and worms, with customized mechanical properties that have an important potential for several civil, military, and medical applications. For civil applications, these kinds of fibres can be used in ropes, fabrics, or filtering systems. Antiballistic and strong light-weight gear, parachutes, and harnesses could be some of the uses of protein-based fibres for military applications. For medical purposes, protein-based fibres could be very good alternatives for artificial ligaments and strong suture threads.

Another natural fibrous structure was discovered recently in gecko feet that allows it to attach (dry adhesion) and move on very smooth surfaces (even upside down) [27, 28]. The skin from this lizard's foot consists of a hierarchical structure of filaments with spatula-shaped setae (around $2 * 10^{12}$ filaments/cm^2), of about 100 nm [27]. This complex structure uses a relatively simple adhesive mechanism based on physical bonds of van der Waals type between the filaments and the surface. Each filament can withstand a force of 20 μN, resulting in an adhesion force of 10 N for an aria of 100 mm^2 from lizard's foot [27]. There have been discovered however species of lizards whose bonding strength can reach 100 kPa [29]. Although these powerful forces can make it difficult for lizard to move, it uses a unique way of moving by curving its toes in order to eliminate the contact forces with the surface [27–29].

Reproducing the gecko adhesive system would bring many benefits in textile applications. Some of the top areas in which it may be used are medicine (replacing the suture fibres to close wounds, at adhesive bandages and transdermal delivery systems, in hernia repair, in laparoscopic surgery) and aerospace and diving (for shoes and gloves from aeronautical costumes, adhesives for emergency interventions underwater) [30–32].

So far, several attempts were made to imitate the dry adhesion principle of gecko. Although this seems simple at first, manufacturing a very dense fabric surface consisting of millions of nanofibres proved to be quite complicated. The first challenge was to develop fibres whose length is long enough to enable the contact with the surface (often irregular on a microscopic level) with which the adhesion is desired [33]. This raises a second issue; namely, the longer the fibres were, the more they tended to tangle with each other [33, 34]. In addition, if the spacing between the fibres is too small, the intermolecular forces determine their bonding [29]. Theoretical and experimental studies concluded that the solution to these problems lies in the development of surfaces with high ratio between fibre length and the distance between them, to obtain a satisfactory adhesion [34].

Biomimetic synthetic fibres inspired by gecko were so far created from various materials, using different production technologies. Among them we mention modelling at nano level using silicon [35, 36], polyimide [35], polyvinyl siloxane [37] and polyurethane, photolithography using polyimide [38], carbon nanotubes [39], and polyurethane [34]. Many of them have reached a superior adhesion force compared to the natural model of inspiration, among which carbon nanotubes used as hairs presented the best results [40, 41].

4.2. Multifunctional Surfaces. Natural surfaces represent a rich inspiration source in terms of remarkable diversity of their outstanding properties. As mentioned above, the dry adhesion of gecko has been widely studied, leading to better biomimetic applications than their natural model. However, the researchers' attention is also directed to low-adhesion surfaces, such as those of plants. Their surface is composed of several types of cells, with different shapes and structures of the surface; that confers special properties to plant. In order to provide a protective barrier, the plants are covered with an extracellular membrane (cuticle). In most plants, the cuticle is composed of a mixture of polymer (cutin) and soluble lipids. In some studies, it was concluded that the hydrophobic properties and self-cleaning properties of plants are due to not only the chemical constituents of the cuticle covering them, but also the special topographic texture of the surface [42–44]. Besides lipids incorporated into the plant cuticle, surface topography is composed of three-dimensional epicuticular wax crystals whose model inspired the superhydrophobic textile surface structure [45].

Many plants and animals present hydrophobic surfaces due to microscopic roughness. They are characterized by a static contact angle greater than 150° and a low hysteresis angle that allows a water droplet to roll on a surface with an inclination of less than 10° [42]. In the study conducted by Neinhuis and Barthlott [42], there have been presented static contact angles of two hundred of hydrophobic plant species. Most of them showed a contact angle greater than 150° and therefore were classified as superhydrophobic. The morphological characteristics of the leaves of these plants are due to a hierarchical structure composed of convex to papillae epidermic cells, with a very dense arrangement. All known crystal forms were found on superhydrophobic leaves, whose sizes range from 0,5 μm to approximately 20 μm in length [43].

Reproduced by nanotechnology, these superhydrophobic and self-cleaning properties have been developed as biomimetic technological innovations and patented under the "Lotus effect" label. Textiles with these properties are used for outerwear, carpets, materials for constructions, and so forth. The importance of superhydrophobicity for textiles has been highlighted long before Biomimetics became known, through the work of Schuyten et al. [46] published in 1948.

The possibilities to create the "Lotus effect" textiles have known two approaches so far: the first consists in achieving a surface roughness at nano- or microscale [47–50] and the second involves reducing surface energy by chemical modification [51–54]. After a study by Gao and McCarthy (published in 2006), there have been made superhydrophobic polyester textiles by coating them with silicone, using a method described in a patent from 1945 [55]. The topography of these fabrics conferred them a better property of repelling water than lotus leaves [40]. Hoefnagels et al. [56] have developed a superhydrophobic surface made of cotton fibres covered with silicon particles which was then chemically modified by immersion in polydimethyl siloxane. In order to obtain a superoleophobic structure, the same group of researchers coated a fabric with silica nanoparticles (of about 800 nm), after which it was treated with a fluorine-containing compound [57].

Although the lotus leaves are the most popular due to their superhydrophobicity, nature abounds in such models, among which we can mention rice leaves, duck feathers, water spider legs, wings of butterflies, and many others. Studies on duck feathers showed that in addition to their water-repellent property, they are very good thermal insulators. This is due to the morphology of the feather and to the hierarchical network composed of barbs and barbules [58, 59]. Water repellency is caused by the air trapped into the microtexture of the feather, forming air "cushions" at the contact interface between the feather and water [58, 59]. Trying to imitate this model, Liu et al. [59] have developed a surface treatment for conferring superhydrophobic property for delicate cotton and polyester fabrics. For this purpose, the surface of the material was covered with chitosan, by a precipitation process to form roughness at nanolevel. Polyester material showed a more pronounced roughness than cotton, on the surface of which a smoother coating was formed. The materials were then treated with silicone to reduce the surface energy [59].

Regarding the surfaces with low friction resistance we can also seek for inspiration if we study birds, or even fish. Their special shape allows efficient movement through air or water, with minimal energy wasted through friction. It is known that water exerts a drag resistance on a swimmer. This resistance can be divided into three types: skin friction resistance (represented by the force exerted by a fluid in the opposite direction of the movement of the body [60, 61]), the resistance due to the shape of the body, and the resistance due to waves (which occur at the water surface, when the pressure around the body in motion produces waves).

Because of the shape of the body, humans are not suited for rapid motion in water, but this can be improved by a certain swimming style or by reducing the friction resistance between water and the skin. To eliminate these impediments, once again researchers turned their attention to nature [60–63]. The inspiration was not hard to find, since they found that sharks are the most rapid creatures in water, relative to their size. This is due to special texture of their skin surface. The shark skin is covered with three-dimensional hard scales (0.2–0.5 mm) in the form of teeth, called dermal denticles. These denticles have longitudinal ridges on their surface oriented along the body axis, varying in number, size, and shape depending on the age and shark species [60, 64]. Although the overall model shown by these ridges is parallel, however, in some areas of the body, they tend to close or to move away from each other which influences the friction with water [63]. Laboratory tests have shown that these arrangements of dermal denticles reduce friction at a rate of about 10% [61]. Friction reduction potential is influenced by the sharpness of the edges of ridges and by optimal ratio between the height and the distance between ridges [65]. A comprehensive study on how water friction is reduced by denticles was presented by Bushnell and Moore [60].

For obvious reasons, studying and mimicking shark skin morphology have important contribution to biomimetic innovations like swimming suits and surface structures for planes and ships. 3M Company used this principle for the construction of Star & Stripes yachts, who won the America's Yachting Cup. However, one of the most popular commercially available innovation inspired by sharks is Fastskin swimming suit (Speedo, Inc.), which seems to reduce water friction at a rate of 7.5% [66].

4.3. Thermal Insulating Materials. As mentioned above, the duck feathers present thermal insulation properties, attributed to "cushions" of air formed within the hierarchical nanostructure. Although numerous efforts have been made to achieve the performance of duck feather in terms of insulation, artificial replicas were not as expected [67].

Another model that has attracted the attention of researchers is the penguin feathers. In the 1990s, a team of researchers from the University of Reading, UK, have shown interest in penguins ability to survive in extreme conditions. Penguins have to withstand low temperature for 120 days (during the incubation period of the egg), with a thermal gradient of about 80°C, to a layer of feathers that has only 2 cm. In addition to thermal insulation, penguin feathers are also waterproof. Studies by Dawson et al. [68] showed that these properties are due to the special construction of the feathers. Their main shaft, called rachis, is flexible yet very strong. From this shaft rows of overlapping barbs emerge. They form the flag, or the flat side of the feather. Barbs are joined together by means of hundreds of tiny barbules which are provided with hooks (barbicels) and can easily attach to each other like a "zipper." On the underside, along the rachis, there is a groove. This simple element of feather's structure brings resistance to the shaft, allowing it to bend and twist without breaking. Under the waterproof layer of feathers there is a thick layer composed of soft feathers, called down. The down is formed of about 47 barbs, with an average length of 24 mm. Each barb is coated with about 1,250 barbules, who are about 335 μm long. These structures contain air spaces of approximately 50 mm in diameter, which create a high insulation surface [68].

The properties of thermal insulation and impermeability of the penguin feathers are obtained by varying the air volume incorporated. Attempts to mimic this feature in order to obtain innovative textile materials led to the development of a textile system characterized by its variable geometry; some research in this direction was carried out by N & MA Saville Associates. Other biomimetic innovations designed on the same principles are GoreTex clothing products, with changing thermal insulation Airvantage Adjustable Insulation [69]. They are based on the existence of an inflatable room between two layers of fabric.

Thermal insulation mechanism of polar bears was also a subject of study for a long time. Polar bear fur is a great insulator, allowing them to survive in the cold arctic. According to some studies [70], it was found that their fur appears completely black illuminated with UV light, and with an infrared camera polar bears are nearly invisible due to minimal heat loss through the fur. The hair from which the fur is composed has a tubular form, filled with a foamable material [71]. Initially, it was thought that polar bears hair acts as an optical fibre that captures sunlight and then sends it to the black skin underneath [72]. Koon's study [73] showed that polar bear hair is a weak waveguide absorbing UV light. Inspired by these functions, Stegmaier et al. [71] have developed a solar thermal collector with high transmission capacity composed of a layered textile material, coated on both sides with a translucent film.

4.4. Structurally Coloured Materials. Nature presents unique abilities of manipulating light. Most natural surfaces, in addition to being multifunctional, have also magnificent aesthetic characteristics, producing bright, vivid, and iridescent colours. They are the result of complex photonic structures and are called structural colours. Structural colours are not due to the presence of pigments, but only to interference phenomena, diffraction, and selective reflection of incident light on the complex structure of the photonic material if its components have a periodicity equal to the wavelength of visible light [74].

Colour is one of the essential characteristics of a textile product and studying structural colours of nature could bring new perspectives of designing textile fibres and materials [75]. From a biological perspective, many studies have been made on a large number of species showing structural colour, among them the most significant are butterflies [76–79], birds [80, 81], and beetles [59, 82]. In order to explain the mechanism of structural colour production several studies were conducted, including those of Srinivasarao [79], Parker [83], and Tayeb et al. [84].

How biological optic systems could be a source of inspiration for potential applications in textiles can be extracted from the studies on photonic crystals in nature. These photonic crystals, also known as band gap materials, are periodic structures that cancel the propagation of light of a certain frequency; the reflected colour is only in the specific bandwidth [85]. Most common natural photonic crystals are present on the wings of butterflies, at some sea creatures (such as the starfish *Ophiocoma wendtii*), or opals [85].

Butterflies present perhaps the greatest diversity of optical microstructures, which led to their intensive study. From these studies, it appears that butterfly wings are covered with two layers of tiny scales, overlapped on a membrane. The average size of the scales is about 200 μm long and 50 μm wide [79, 86, 87]. Scales are completely transparent, while the wing membrane may contain pigments such as melanin or pterin. These pigments are designed to enhance the colours produced by light reflection on the scales microstructure [79, 87].

Inspired by scales structure of Morpho butterflies, Kuraray Corp. fibre manufacturer designed a polyester material with low reflectivity, but with intense colour. This material, called Diphorl, was made of rectangular cross section fibres. The fibres are spun from two types of polyester with different thermal properties who are heat-treated after weaving and produce some twists in the yarn (about 80–120 twists/inch). It is assumed that this structure produces alternative alignments on horizontal and vertical directions, causing the multiple reflection and absorption of incident light, thus producing bright colours [88].

Another company, Teijin Fibres Ltd from Japan, has developed a fibre called Morphotex, who is assumed to mimic the Morpho butterfly microstructure also and its structural colours. This fibre, with the thickness of about 15–17 μm, has a flat shape and is composed of 61 alternative layers of polyester and nylon, each of them with a thickness of about 70–90 nm. The thickness of the layers, their number, and different refractive indices (1.6 for nylon and 1.55 for polyester) of the polymers used give rise to structural colours [89].

5. Conclusion

Nature is an extremely vast database of structures and mechanisms that proved to be clearly superior to those man-made. There are numerous examples of fibrous structures, multifunctional materials, thermal insulating materials, structural colours, and many others that can serve as sources of inspiration for future sustainable textiles. In many ways, textiles offer unique opportunities to imitate nature. The base units of each textile structure at the most elementary level of the hierarchy (from nano to micro) are organic fibres, many of which are natural. In addition, like many natural functional surfaces, the textile surfaces also offer excellent opportunities for developing new functionality. All these allow an easier way to borrow the biomimetic principles of nature in textile field than in other industrial areas. As it could be seen from this paper, fibrous structures of bamboo and wood, spiders and silk worm, pinecones, and even tendons (to mention just a few of them) led to the development of impressive textile structures. Superhydrophobicity, self-cleaning, and drag reduction are some of the functionalities that have been successfully integrated in textile products. Thermal insulation properties of duck feathers, penguins, and polar bears also inspired some clothing articles for cold weather. The aesthetic aspect could not be neglected, especially when it comes to clothing, so researchers turned their attention to beautiful vivid colours of butterflies, birds, and beetles. Their structural colours conducted to fascinating textile fibres and fabrics that do not require dying to display a colour, their appearance being due to light phenomena at submicron level of their architecture. Seeing the increasing number of papers related to Biomimetics topic, it is more than clear that it presents a high potential for future development of engineering, in general, and of textiles, in particular.

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

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