Sustainable Biomimetics: A Discussion on Differences in Scale, Complexity, and Organization Between the Natural and Artificial World

Valentina Perricone, Carla Langella, and Carlo Santulli

Abstract Biomimetics emerges as an effective approach to identify functional bio-inspired solutions for the development of original design applications. This approach does not necessarily result in sustainable products and processes, which are frequently made of petroleum-based materials fabricated with non-renewable and high-energy consuming technologies. Nevertheless, the inspiration from nature has a great potential in terms of sustainable innovation, taking into consideration not only analogies but also the differences between the natural and artificial world. In this regard, the present contribution aimed to highlight the differences between biological and human industrial systems in scale, complexity, and organization, encouraging new sustainable biologically inspired designs increasingly close to the construction law of organisms. The result of this comparison emphasized nature's intelligence concerning balanced source consumption and regeneration of ecosystems as well as the effective adaptation of organisms to natural cycles in time and space. A biomimetic approach that combines the use of bio-based materials with a coherent use of bioinspiration is here identified as a future sustainable and effective strategy to design a new human world, which does not impose on nature but is inspired and integrated with it.

Keywords Bioinspiration · Bio-based · Life cycle · Circularity · Heterogeneity · Organismal design · Waste valorization · Sustainable design

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F. L. Palombini and S. S. Muthu (eds.), *Bionics and Sustainable Design*, Environmental Footprints and Eco-design of Products and Processes,
https://doi.org/10.1007/978-981-19-1812-4_7

1 Introduction

Nature is the best source of inspiration for designing environmentally sustainable artifacts that are compatible with the complexity of the present world dynamics [1]. Design projects in collaboration with biology can offer a valuable contribution to the evolution of sustainable design culture, eco-oriented marketing strategies, and environmental awareness with novel conceptual tools inspired by nature and its resilience [2].

Design for sustainability seeks solutions to resolve problems with minimal environmental impacts. In this regard, the transfer of logics found in nature to solve similar problems could be very useful. Artifacts designed using biological structures, materials, and working principles as models are certainly more performing and respectful of earth resources and its limits since they refer to strategies selected by nature and validated by millions of years of evolution.

Humans have always been inspired by nature to design artifacts that satisfy their needs improving their life. Many of the important achievements in technology, design, and art have been generated by imitating biological models. However, only current conditions, in terms of knowledge and tools, allow the creation of products and artifacts that could conceptually and concretely reproduce some of the most complex biological qualities hidden in the natural world. Indeed, the intersection between the progress of contemporary biological knowledge, together with new production technologies, proposes innovative and unique perspectives on the relationship between design and biology.

The interdisciplinary approach that combines the understanding of the natural world with its abstraction and translation into technological applications is known as "Biomimetics" [3, 4]. The biomimetic approach is increasingly spreading within the design culture at different dimensional scales from the development of nanotechnologies to systemic urban design. The acquisition of the biomimetic paradigm offers a valuable opportunity to draw new principles, strategies, and logics to make more environmentally sustainable products. However, it is not certain that the inspiration or imitation of nature always results in an improvement of the environmental/eco-friendly performance.

Biomimetics is not always a synonym of sustainability. Frequently, it is exclusively used as a method to increase the functional efficiency of man-made products, relying on Darwinian principles of progressive organismal functional adaptation in response to external conditions and stress. Sometimes the application of biomimetic models even implies an increase in environmental or economic costs. In well-known biomimetic products, such as *Fastskin* fabric or *Velcro*, the functional efficiency does not coincide with the increase of environmental safety using eco-friendly materials and production processes. Polymer-based self-cleaning coatings based on the lotus effect can even affect the environmental impact at the last lifecycle stage when there is no compatibility in terms of recycling.

Nonetheless, the inspiration from nature has great potential in terms of sustainable innovation. It can lead to the generation of products in which the increased performance, material innovation, productive technologies, and reduction of lifecycle environmental impact converge in a synergic manner.

The logics observed in biology, such as time cyclicity, energy efficiency, recovery, and regeneration of waste, and its difference with the artificial ones can guide design projects toward new sustainability scenarios. The concept of degrowth is replaced by a principle of sustainable evolution in which people can rediscover more natural behavioral and consumption models in harmony with the environment. Therefore, biomimetics can also lead the industrial product dimension closer to the more natural needs of people and the environment with an outlook on a human-centered ecological transition.

The possibility of transferring from biology principles and logics to reduce the environmental impacts of artifacts is strongly linked to the relationship between the size scale of the inspiring biological system and the artificial one; particularly when physical effects are linked to size. For example, the inspiration of principles based on optical or hydraulic phenomena observed in different organisms oriented toward the use of climatic resources such as solar radiation or rainwater, e.g., light transmission enhancement of window-leaved translucent crystals [5] or water distribution ability of the thorny devil desert lizard through its skin interscalar spaces [6]. This transfer could be very complicated and sometimes result in a reduction of effectiveness. Hence, the evaluation of the effects and changes in scaling biological working principles to the final project dimension is crucial for any biomimetic transfer process success [7]. Nonetheless, the main differences in scale, complexity, and organization between organismal design and artifacts can also provide new design perspectives in the sustainability of man-made products and productive processes.

In this context, the present contribution aims to provide a critical discussion on a series of key concepts regarding lifecycle and characteristics in which the biological world differs from the artificial one, encouraging a new cutting-edge and sustainable biologically inspired design increasingly close to the construction law of organisms. Additionally, a series of experimental case studies is provided, in which design projects are oriented toward effective integration of natural concepts, materiality, and processes.

2 Life Cycles

In nature, each organism goes through a specific life cycle, i.e., a continuous sequence of changes during its life from a primary form (gamete) to the reproduction of the same primary form. These formal transitions may involve growth, asexual or sexual reproduction. In these cycles, all “waste” turns into nutrition for other cycles creating a complex interconnection. In the food web, organisms are connected by trophic linkages and levels (autotrophs and heterotrophs): there are hierarchical organizations and conceptual scales. The first level is composed of basal species, such as algae, plants, and other vegetables, which do not feed on any other living creature on the web. Basal species can be autotrophs or detritivores. Apex predators constitute the top level and are not eaten directly by any other organisms. The intermediate levels are composed of omnivores that feed on one or more trophic levels and are themself eaten, causing a trophic energy flow. In trophic dynamics, energy transfer from one level to another is a unidirectional and noncyclic pathway with a loss of energy from the base to the top. Each organism is also characterized by a unidirectional energy flow, which typically includes ingestion, assimilation, non-assimilation losses (excrements), respiration, production (biomass), and mortality [8]. Nonetheless, the energy loss is always balanced in time by trophic relationships and organismal life cycles.

Conversely, the flow of mineral nutrients is cyclic and represents the recycling system of nature. Mineral cycles include for example the carbon, sulfur, nitrogen, and phosphorus, which are continually recycled into productive ecological nutrition. This recycling is mainly regulated by decomposition processes and relies on the biodiversity of the food web.

In human industrial systems, recycling differs from the natural one in scale, complexity, and organization. The industrial recycling systems seem to work independently from the food web without considering the waste restitution to different trophic sectors as well as source and energy regeneration time. This together with the increasing greenhouse gases concentrations owing to human combustion of fossil fuels and ecosystem degradation lead the industrial and in general the human world to be based on competitive and parasitic processes toward natural ecosystems [9, 10]. Major lifestyle and conceptual productive systems changes are needed and inevitable.

In this context, the theme of environmental sustainability applied to the design culture raises important issues centered on the difficult relationship between human activities and nature's delicate balance. Biological systems survive because of their life adaption and evolutionary processes becoming an integrating part of their environment. Organisms use local resources to build themselves (e.g., skeleton, shells, etc.) and their constructions (e.g., nests, traps, etc.), all of which are capable of complete recycling with continuous reuse and regeneration of their waste materials. They can conduct dynamic and adaptive management of both material resources and quantities of energy used for vital functions. Consumption and regeneration are always in balance, waste disposal is not necessary because everything is re-used and reintegrated into natural cycles in time and space.

2.1 Use of Resources

Organisms adapt their design and functioning to local resources and environmental biotic and abiotic characteristics, creating cascades of nutrients at the end of their lifecycle. Conversely, biomimetic products and materials such as synthetic spider silk-like materials, mechanically and optically adaptive materials, self-healing elastomers and hydrogels, and antimicrobial polymers have often been made using petrochemical origin materials, which have devastating effects on terrestrial and ocean life other and furthermore an inherently toxic life cycle from production to the final disposal. Society increasingly pushes toward ecological transition resulting in a closer look at the development of sustainable polymers from renewable natural products or biomass. Diverse bio-based and biohybrid materials are rising as greener alternatives to their petroleum-based counterparts. In particular, bio-based materials consist of substances naturally or synthetically derived from living matters [11], whereas biohybrid or living building materials are based on microorganisms and used in construction and industrial design exhibiting biological functional properties [12]. Bio-based and biohybrid materials are therefore based on inert or active natural components that produce little or no waste using small amounts of energy and producing multifunctional and adaptable systems.

In the biomimetic field, the use of these materials is however limited due to their complexity. Particularly, the non-homogeneity leads to difficulties in experimental, computational, theoretical calculation, and predictability response of these materials. Moreover, they are difficult to manage and design at a molecular level. One of the most effective biomimetic material research projects refers to the optimization of crosslinking/networking processes, dynamic interactions, and self-assembly (or phase separation) of synthetic polymers [13].

Additionally, Ganewatta et al. [13] pointed out that natural polymers or bio-based compounds do not inevitably result in materials necessarily more sustainable than those based entirely on synthetic polymers. The overall sustainability of a material can only be assessed through a life cycle analysis that considers each stage's impact, such as pre-production, production, distribution, use, disposal, and end of life. A material that has a sustainable start in life, because based on highly renewable and easily accessible raw materials or not requiring energy-intensive processing and environmental emissions, may not be durable, well-performing, or need treatments that compromise recycling.

2.2 Time and Scale

Time is a crucial factor in nature. All organismal components and constructions in the natural world are at the right time biodegradable, becoming a source and food for other ecological chains. The degradability is a function of their time and utility. For example, the difference between a paper wasp and honeybee in constructions and material choices are related to the time of their social persistence. Social paper wasps live in brief annual communities and construct their nests using wood fibers (dead wood and plant stems) mixed with saliva resulting in a paper-like material, whereas honeybees build pluriannual colonies and use beeswax to construct high-resistant and durable nests. Materials and structural configurations differ in organismal design with different life perspective duration, besides protection needs. For example, bivalves that can have a relatively long survival time protect themselves with shell composed high-structured hierarchical ceramics [14]. The shell is realized by the continuous addition of materials necessitating constant strength throughout organismal life: any breaking or cracking will always constitute a point of weakness. Conversely, lightweight, and rapidly biodegradable polysaccharide-based materials are employed in seasonal cycles. For example, deciduous tree leaves quickly disintegrate after falling ending their function.

In this regard, one of the main human technology errors lies in the unbalanced connection between material choice and time of use in products and processes. Small scale disposable products, e.g., plastic bottles and flatware, have been made of materials that require 100–1000 years to degrade. This is an example that results in the need to use biodegradable materials with short disassembling and degradation time. On the contrary, fast biodegradability emerges as a paradox in the scale of architectural design, in which case the disposal time should be extended as much as possible since the structures are intended to last.

2.3 Use of Waste

Nature is based on completely zero-waste systems: the waste of one system becomes food for another. This smart cyclicity of nature is one of the most important logics to be transferred to the biomimetic design of artifacts. It induces the recovery and regeneration of material waste after production or consumption through reuse, recycle, or upcycling strategies. From this point of view, designers could be involved in the identification of waste types most suitable to be ennobled through bioinspiration. Biomimetic design can raise the final aesthetic, economic, ethical, and environmental value of wastes conceiving attractive and desirable products such as jewelry, furniture, and fashion accessories making upcycling processes convenient and profitable [15]. In this sort of project, designers are asked to analyze production processes, with particular attention to local activities, and to interpret waste transformed into resources in terms of technical characteristics, perceptive qualities, and processability. Thus, it is possible to identify new applications that maximize their potential by reducing their limitation impacts, transforming them into factors of specificity and originality [16]. In upcycling, biomimicry is an important added value in terms of marketing because it produces attractive and desirable products for the market and, therefore, economically viable. The increasing awareness of climate and environmental issues together with the impact of lifestyle on health and well-being leads people to choose what they perceive to be most natural and akin to their biological roots, preferring products that implement a biological factor in terms of raw materials or design inspiration. In a market that is progressively inclined to choose low-impact products, bioinspiration is proposed as an effective strategic vehicle to characterize, identify, and promote eco-sustainable products and eco-oriented innovation actions [17]. For these reasons, companies and commercial organizations are now aware of the great competitive potential of bioinspiration in terms of attractiveness, perceived value, and marketing, underpinning studies on bio-oriented entrepreneurship, referred to as biopreneuring [18], resulting in a biomimicry and upcycling synergy.

2.4 Production

Nature has been criticized for not producing enough and too slowly for the industrial productive standards, which conversely require efficient, rapid, precise, calculable processes and results. The productive scale and time of human technology seem not to be comparable with natural ones. This assumption seems to be true when a ceramic object produced at 1000 °C is compared with the productive time of a bivalve shell. However, the advantages in terms of time and efficiency are taken less for granted considering that a ceramic industry requires materials extracted from worldwide caves, which need to be imported and processed at high temperatures, pressures, and energies and furthermore must be transported and delivered to clients [19]. In nature, local extraction is part of the productive process and energetic costs are notably reduced.

Organisms produce biomaterials at local pressure and temperature conditions using locally available raw materials; in industrial production, artificial temperature and pressure conditions are often obtained by using great amounts of energy as well as raw materials generally transported from remote locations. Hence, the comparison between the natural and industrial production scale processes leads to another quantitative aspect. The number of natural creations depends on physical forces respecting the environmental carrying capacity in a potentially infinite cycle, while industrial processes are based on high-energy loss and resource depletion.

3 Biological Versus Artificial

During millions of years, organisms evolved complex shapes, structures, and processes generally tending to optimize the cost-benefit ratio and minimize energy and materials to be used for their construction, development, and maintenance. In a constructional perspective, they respond to principles of lightness, resilience, flexibility, resistance, and efficient logics oriented to ensure the high performance of organisms in their environment. Organisms are in this respect of particular interest for design, architects, civil engineers, and many other technical disciplines since they provide new technical and sustainable methodological strategies that can be transferred based on analogies as well as differences between the natural and technical world.

In particular, numerous differences emerge in the comparison between organismal design and human artifacts and technologies, which can lead to a change in perspective and to a design possibility and sustainability expansion.

A primary concept of sustainability emerges in terms of energy and productive processes: humans consume a vast amount of energy (60% of the time) to develop numerous diverse materials with novel properties; whereas organisms invest minimum energy (5% of the time), using few materials and synthetic processes, wherein energy contribution is high, and utilizing more structural organization (e.g., hierarchy, strategical porosity, textures), wherein energy is negligible [20]. In this regard, Vincent et al. [20] stated that “instead of developing new materials each time we want new functionality, we should be adapting the materials we already have”. Analogies and differences in scaling between organisms and artifacts can encourage cutting-edge, sustainable, and biologically inspired designs increasingly close to the construction law of organisms. The solution lies in the identification of functional strategies and properties that can add mechanical resistance and multi-functionalities to materials that have been already developed.

Numerous are the interesting differences between natural and artificial materials that can lead to other interesting insights regarding sustainability. Firstly, the genesis of biological structures is not based on a mere assembly of parts, rather it consists of a continuous growth process, i.e., a self-assemble automatism that generates structures with full functionality and integrity at all different stages of life. Secondly, organisms use basic, autochthonous, and sustainable materials that require neither excessive energy-consuming methods for their realization (working at environmental temperature and pressures) nor long-distance transportation. Lastly, biological structures are perfectly integrated into their environment and continuously interact and react to its biotic and abiotic components. In addition, many other functional features characterize biological structures, such as heterogeneity, anisotropy, hierarchy, modularity, adaptability, self-healing, and multifunctionality, which are still needed to be explored in-depth and employed as technical solutions.

3.1 Heterogeneity

Heterogeneity is a widespread characteristic in natural materials (e.g., soils, geological formations, biological tissues) occurring at different scales: from molecular to macroscopic. Organisms are characterized by a remarkable material and geometrical differentiation of their structural components as well as local adaptations of their physical and chemical properties.

Being based on biological matter, bio-based materials are generally characterized by a high heterogeneity (Fig. 1), which limits their application, particularly on large scales (e.g., building construction). Indeed, this characteristic determines notable complexity and limits in experimental, computational, theoretical calculation, and predictability response of these materials. Nonetheless, the non-homogeneity of these materials can be valorized and enhanced in some design projects, generating multiple unique features, such as light effects and transparencies, multisensorial connotation, colorful effects, thickness differentiation, and singular textures (see sector 5). On the other hand, geometrical heterogeneity combined in an organized structure (achieved for examples with controlled porosity configuration) might also result in some benefits, such as crack propagation blunting and energy dissipation in bone ceramics [21].

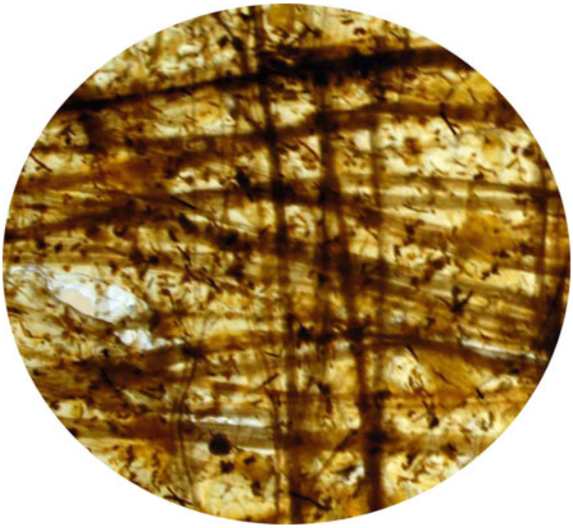

Fig. 1 Bio-based composite material heterogeneity. Bioplastic matrix based on starches and waste liquid from buffalo mozzarella production and hemp fibers. Retrieved from: https://www.hybriddesignlab.org

3.2 Anisotropy

Anisotropy derives from the uneven distribution and organization of materials; thus, each direction in the material has different properties and behavior. In nature, the anisotropic feature is generally exploited by combining different structural organizations that can result in emerging properties, e.g., movements, and lead to lightweight and efficient structures: e.g., the cellulose fiber orientations determine the shape and kinematics of plant cells and tissues as well as the anisotropic trabecular architecture resisting to predicted directional stresses [22]. Indeed, organismal design is adapted to forces that very seldom have the same intensity in all directions; therefore, it generally requires an adapted anisotropy. This stands for diverse natural structures: two examples are body tissues, where anisotropy is required for repair purposes [23], and rice leaves, where directional forces are related to water surface tension [24].

3.3 Hierarchy

Organisms are characterized by a multilevel organization from nano-to macroscale (Fig. 2). Increasingly sophisticated intelligence emerges from hierarchies, leading to different emerging functional properties. Emergent properties of a system arise from the interactions of its interrelated elements and cannot be reduced to or derived from the sum of the single element properties. Emergence is related to hierarchical organizations and occurs at all scales in nature, mainly: atoms, molecules, cells, tissue, organs, systems, organisms, populations, communities, ecosystems [25]. All these elements together determine unique properties and behaviors non-deductible

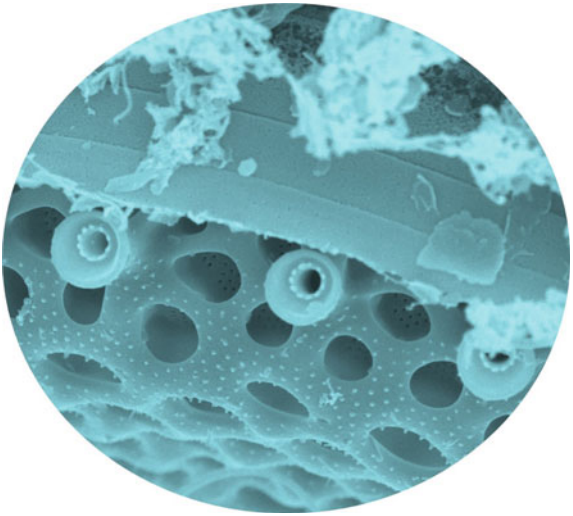

Fig. 2 Hierarchical porosity in diatom valves. SEM Micrograph made by Valentina Perricone at Stazione Zoologica Anton Dohrn, Naples, Italy

by a single component. For example, different organs constitute an organism that interacts with the environment trying to preserve itself and reproduce; while different organisms constitute a community that interacts and creates a stable environment for its members. The properties emerging from the organism and community are not deducible from their single constituents. Material science is currently working with hierarchical controlled gradients and configurations at a different scale to create high-performance materials with unique emerging properties (e.g., micro- and nano-structured materials to create structural colors). Numerous studies have been carried out at nano- and microscale, however, the introduction of these structural materials on large scales, such as building construction, is still very challenging [26].

3.4 Modularity

A common strategy of organismal design is modularity at different scales. Modules are functional units that generally implement and satisfy local needs with some degree of self-maintaining and self-controlled properties. For example, the liver system can operate controlling nutrients in the blood in relative independence from the central nervous system [27]. Moreover, the subdivision of the body in a series of segments is a common phenomenon in nature, known as metamerisms. An outstanding example is the subdivision of the worm body in multiple meters with a repetition of organs and muscles. Modules or segments have a proper problem-solving intelligence and are independent of external changing conditions. Modularity is also used in artifacts and their fabrication processes based on the assembling of units that provides differentiation of materials, reproducibility adaptability, and easy substitution. This is however based on inert modules that create a final configuration by a mere assembly

Fig. 3 Echinoid test tessellation. SEM Micrograph of *Paracentrotus lividus* ambulacral plates made by Valentina Perricone at Stazione Zoologica Anton Dohrn, Naples, Italy

of parts. There is often no intelligence, self-maintaining or self-controlled properties. Nonetheless, natural modularity can lead to functional strategies that can inspire effective biomimetic configurations. For example, diverse studies have been carried out on the modular structures that combine hard and soft materials (tessellations) that characterize numerous invertebrate and vertebrate biomaterials and structures (Fig. 3). The studies reported how tessellation can optimize mechanical configuration, e.g., maximizing mechanical material toughness with minimum expenditure of stiffness or strength [28].

3.5 Adaptability

Organisms and systems in nature vary their properties according to predictable external constraints to which they are subjected during growth and/or throughout their life cycle. For example, vertebrate bones are made of composite material (mainly hard hydroxyapatite and elastic collagen) creating a complex internal trabecular system that varies in porosity and orientation according to the main stress trajectories; this allows to create of an adaptive, lightweight, and resistant skeleton able to withstand both tensile and compressive internal and external forces.

Conversely, industrial products generally consist of repeated parts with identical properties that are not able to adapt, rapidly becoming waste. As stated by Oxman [29], design should create new concepts of formation, in which products adapt and perform, i.e., behave, rather than form and absolve a unique function.

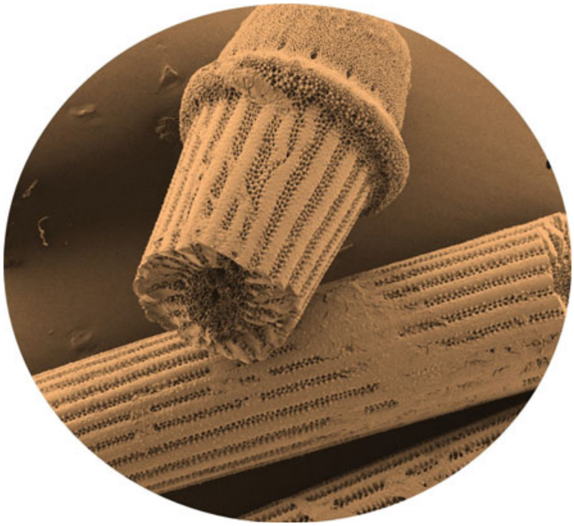

Fig. 4 Echinoid spines. SEM Micrograph of *Arbacia lixula* spines made by Valentina Perricone at Stazione Zoologica Anton Dohrn, Naples, Italy

3.6 Self-healing

In case of fractures, amputation, or damages, organisms adopt specific self-repairing, self-healing, and regeneration mechanisms. For example, rapid self-sealing and self-healing prevent plants from desiccation and infection. The repairing properties are frequently related to the damage extension as well as organismal component and complexity: sea urchins can repair their test (endoskeleton) only if the damage is circumscribed and can entirely regenerate their spines (Fig. 4), whereas sponges can completely regenerate from fragments or even single cells.

In material science, synthetically created materials have been developed with the ability to automatically repair damages. These materials are usually polymers, metals, ceramics, or cementitious materials. A self-healing concrete has been also realized using bacteria that are able to precipitate calcium carbonate in concrete sealing micro-cracks [30]. This innovative concept has been successfully applied at small or lab-scale tests. However, some limitations have been identified in large and real-scale applications [31].

3.7 Multifunctionality

Natural materials and structures are multifunctional, i.e., they do not absolve a single role but generally provide diverse important properties that are useful to enhance organismal survival and reproduction. For example, sharkskin with its texturized denticles is able to provide, e.g., fluid drag reduction, anti-fouling, and antimicrobial functionalities. Compared to biological ones, artificial materials appear to be less effective and wasteful [32]. These materials are discrete solutions generated to absolve one or a few rigid and distinct functions. Their diversity is achieved by sizing rather than by substance variation, and is typically mass-produced and not customized [32]. Presently, material scientists are however designing and fabricating multifunctional composites for various applications taking inspiration from hierarchical micro/nanostructures and biological functions (see [33] for a review).

4 Hybrid Design Lab: Experimental Designs Closer to Nature

The Hybrid Design Lab (HDL) is a laboratory of the Department of Architecture and Industrial Design of the University of Campania "Luigi Vanvitelli", founded in 2006 and dedicated to bio-inspired design and the relationship between design and science. The HDL interdisciplinary team aims to transfer theoretical and experimental research, achieved in biosciences, new materials, and technologies, to the design innovative and sustainable products and services. The following examples show how different functional biological features can be applied, often complementing each other, in sustainable bio-inspired designs.

4.1 Designing Bio-based Products on Life Cycle Disposal Time

HDL carried out different projects aimed to develop products with natural materials coherent with their time of use. Orthopedic supports are examples of reduced life cycle products used in a limited therapy time; nevertheless, they are usually produced using conventional polymeric materials with high-temporal disposal processes. *Thumbio* emerged as an example of a promising bio-based orthopedic brace for hand and wrist immobilization in case of inflammatory, degenerative diseases, and small fractures (Fig. 5). This brace was produced using a biodegradable composite made of a bioplastic matrix based on starches and waste liquid from the buffalo mozzarella production and hemp fibers (*heterogeneity*) to modulate stiffness and elasticity according to the degree of immobilization indicated by the orthopaedist. The arrangement of the fibers in the bioplastic depends on the location of the type of lesion or inflammation and, therefore, on the movements that must be prevented and the micro-movements that can be allowed (*anisotropy, adaptability*). The bio-composite is also functionalized with natural anti-oedematous and anti-inflammatory herbal ingredients which slowly release phytotherapeutic principles during the healing process, avoiding the use of creams (*multifunctionality*). At the end of its short life, the product can be composted, releasing no harmful substances for the environment due to its fertilizing properties [34] (Fig. 6).

Fig. 5 Thumbio. Bio-based orthopedic brace for hand and wrist immobilization. Credits: Clarita Caliendo (Design); Carla Langella (Scientific coordination); Carlo Santulli (Material engineering); Antonio Bove (Orthopedics)

4.2 Designing and Valorizing Waste

Other than being reduced, waste can be also valorized by transforming it into a new resource enhancing its unique characteristics in an expressive way. Based on a learning from nature approach, inspired by the ability of natural systems to reuse and regenerate materials and energy, the project "+Design − Waste" carried out by HDL, was aimed to design products developed by reinterpreting different types of waste. Through a multidisciplinary approach, which involves design, material science, and biology, waste was nobilitated raising the final economic value through the project of products such as jewelry, furniture, fashion, and accessories. In the *Diaglass* project, glass waste obtained from broken building glass was upcycled and enriched with gold flakes (*heterogeneity*) through a specific heating process giving life to precious jewels inspired by diatom material and forms (Fig. 7).

By imitating nature, upcycling products should remain in the production environment in which they originated to minimize transport environmental costs. In the Flora project, waste from floriculture production was used to make biodegradable pots sold in the nurseries to contain plants (Fig. 8). The presence of coarse fragments

Fig. 6 Thumbio and different material solutions showed in the international itinerant exhibition "Italy: The Beauty of Knowledge", Farnesina, Rome 2018

Fig. 7 Diaglass. Jewels inspired by diatom material and forms made of upcycled broken building glass enriched with gold flakes. Credits: Serena Miranda (Design); Carla Langella (Scientific coordination)

Fig. 8 Flora. Biodegradable pots made of bioplastics with fragments of floral petals and leaves. Credits: Maria Petrillo, Lorenzo Villani (Design); Carla Langella (Scientific coordination)

of petals and leaves in the bioplastic provides strength, color heterogeneity, clearly communicating the ethical value of upcycling.

4.3 Designing Bio-inspired Variability

Non-homogeneity, cyclicity, and hierarchization of biological structures can be emulated in sustainable design by using bio-based materials and alternative production processes to generate multiple unusual features, such as discontinuous light effects and transparencies, multisensorial intensity, color variegation, thickness differentiation, and singular textures. In this regard, HDL in collaboration with the CNR- Institute of Polymers, Composites, and Biomaterials (IPCB) developed 60 new bio-inspired material samples with a design-driven approach, starting from raw materials of marine origin including algae, mussel shells, and shrimp, incorporated in biodegradable polymer matrixes (Figs. 9 and 10). The samples were developed within the European project PIER framework led by Città della Scienza. One of its main specificities was that new materials were created by designers and personally produced in a chemical lab with the supervision of chemists. In this experience, the

Fig. 9 Materials from the sea. Bioinspired material samples realized with raw materials of marine origin including algae, mussel shells, and shrimp, incorporated in biodegradable polymer matrixes. Credits: Francesco Amato, Clarita Caliendo (Design); Carla Langella (Scientific Design coordination); Mario Malinconico (Science material coordination)

material design, conducted from the designers' point of view, chose to favor perceptive, experimental, and functional qualities required by the application field (furniture, accessories, packaging), rather than the homogeneity and isotropy that chemists and material engineers generally give priority to. The material design was inspired by biological structures and their properties, favoring discontinuity over continuity, dishomogeneity over homogeneity, color shades and opacity gradients over chromatic and optical uniformity, and the modulation of mechanical performance in relation to expected stress. The samples were conceived by giving particular attention to the aspects of environmental sustainability, the enhancement of natural materials, and the interpretation of biological materials from a design point of view. The relationship of these projects with nature is therefore bivalent since the new materials developed contained raw materials of natural origin as well as were inspired by principles and logics studied in biology. The samples were exhibited in Città della Scienza museum in 2014, and in the itinerant exhibitions "Italy: The Beauty of Science" from 2018 to 2020 and "Italy: The Art of science" in 2021 (Fig. 9).

Heterogeneity and structural hierarchy biological features were also applied in an auxetic 3D printed collar aimed to safeguard the well-being of the neuromuscular system of the cervical spine [35]. The collar had a preventive purpose because it dissuaded the user from keeping his head tilted forward induced by the use of portable devices. It also had a therapeutic function for cervical pathologies with no serious

Fig. 10 Material sample composed of PCL and algae. Design: Francesco Amato e Clarita Caliendo. Design coordination: Carla Langella. Science material coordination: Mario Malinconico

alterations as the chin was slightly supported, partially unloading neck muscles from the mechanical stresses due to head support.

Auxetics are meta-materials observed in nature in the skins of some reptiles such as the salamander, but also in the stems of various plant species. The auxetic structure provides these tissues with greater extensibility and mechanical strength, preventing them from tearing, even when subjected to sudden and intense stress. The auxetic behavior derives from the morphological structure and not from the chemical characteristics of the material. Specifically, a meta-material is defined as auxetic when it has a negative Poisson's modulus. The Poisson's modulus is defined as the ratio of the transverse and parallel deformations with respect to a load applied to the section.

The term auxetic derives from Auxesis, a Greek word meaning to grow, which refers to the increase in cell size when structures are subject to tensile stress.

Generally, when we solicit a material with a positive Poisson's modulus to uniaxial tensile stress, it expands in the stretching direction and thins in the cross-section. Similarly, a material subjected to compression contracts in the direction of force and expands laterally.

A negative Poisson's modulus, on the other hand, means that materials also expand in the orthogonal direction when subjected to a tensile force and contract on all sides when subjected to compression.

The use of the auxetic structure in the collar, compared to conventional materials, results in more resistance, flexibility, breathability, and adaptability to the anatomy of the neck in different postures, like a second skin. The auxetic structure developed by the designer in the final project is a hybridization of two types of auxetic geometries observed in nature: indented cells and rotating cells. In the collar structure, different cell shapes were organized in a strategic position array to differentiate stiffness according to the orthopedical therapeutic indications. This structure resulted in a more effective and sustainable collar compared to the traditional one, allowing the use of less material that can be recycled to produce new 3D printing filaments at the end of its life cycle (Fig. 11).

5 Conclusions

In this complex framework, the need to design biomimetic materials and constructions based on intelligent and coherent use of resources, scale, and function emerges as a priority, including product duration, type and intensity of use, application context, and disposal choice. These parameters strongly influence the characterization of the life cycle and artifact performances such as the renewability of raw materials or biodegradability at the end of life.

Bio-based materials are encouraging for a sustainable future and their limits should be overcome by enhancing their unique properties creating new ones. New resistant and lightweight configurations, multifunctionality, regeneration properties, circularity, and sustainability can be applied to bio-based materials taking inspiration from organismal designs and working principles. Indeed, organisms also use natural materials often fragile (e.g., biogenic high-magnesium calcite of echinoid skeleton or silica of diatom valves); however, they optimize and adapt their materiality to scale, functionalities, and environmental context using more structural organization (e.g., hierarchy, strategical porosity, textures). Hence, a biomimetic approach that combines the use of bio-based materials with a coherent use of bioinspiration can be configured as a future sustainable and effective line of human design able to integrate and imitate nature through multiple dimensions.

Recent technological advances seem to have opened a new biomimetic era. Technologies such as computational design and fabrication allow the design of complex structures that can perfectly reproduce biological-like functions, whereas material

Fig. 11 Auxetic neckbrace, a detail of the heterogeneous structure. An auxetic 3D printed collar aimed to safeguard the well-being of the neuromuscular system of the cervical spine. Credits: Martina Panico (Design); Carla Langella (Scientific coordination); Carlo Santulli (Material engineering)

scientists lead to the design of new bio-based materials by integrating sustainability and biological materiality into design products. Therefore, the differences between natural and technical entities can now encourage new cutting-edge and sustainable biologically inspired designs increasingly closer to the construction law of organisms.

From a methodological point of view, sustainable biomimicry can be established on the mutual collaboration between disciplines such as biology, material science, engineering, and design [36]. The synergy between disciplines can lead to the awareness of real possibilities of transferring constructional and adaptive characteristics of organisms, scaling them up with respect to the context and dimensions of the final application. Without this synergy, conceptual and sustainable limits can emerge in the design of artifacts, processes, and services since the biological logics and the physical principles are deviated or not fully comprehended. At the same time, biologists and engineers cannot foresee with sufficient reliability the way in which products will be used, maintained, and finally discarded, because these factors are closely linked to the knowledge of market, lifestyles, user attitudes, and, finally, design strategy. An effective collaboration must be mutual [37] and synergic, and not linear and progressive, but interactive, with continuous back-and-forth, trial-and-error paths, as in nature.

This mutuality can be necessarily achieved by facing and overcoming disciplinary specificity, such as differences in objectives, tools, timeframes, and languages [38].

The possibility of developing products and materials inspired by nature and integrated with the environment also emerges from the application of biological complex logics such as cyclicity, adaptability, self-organization, redundancy, hierarchy, and non-homogeneity. These features applied to bio-based materials and artifacts can result in more resistance, durability, originality, and attractiveness, thus suitable for responding to the complex needs of contemporary living. Logics that until a few years ago were impossible to replicate due to their complexity, today can be applied to artifacts increasingly closer to biological ones. Nature can be part of the product and a source of inspiration as well as an active agent, as in the case of materials made by bacterial fermentation or cell culture [39]. In the next sustainable future, biomimetic artifacts will be shaped on the use of renewable and controlled biodegradable materials or waste-based ones. Additionally, they will probably be dis-homogeneous, anisotropic, multi-colored, and biologically produced [40].

In the history of mankind, nature has always been a source of inspiration. The future perspective foresees a new fundamental step forward, leading to the human world in overcoming the negative dichotomy between nature and artifice. In this regard, biomimetics can assume an important role in bringing new knowledge and awareness of the environment, human health, and social equity into the lives of people, offering new and concrete prospects for integrating sustainable strategies, increasing awareness, and improving life quality. Biomimetics must encourage the creation of a human world increasingly closer to nature construction laws that do not impose themselves on nature but are inspired and integrated with it.

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