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Recent Advances in the Field of Bioinspired Materials

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التطورات الحديثة في مجال المواد المستوحاة من الطبيعة

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الملخص:

تقدم العديد من المواد المستوحاة من الطبيعة وظائف محددة تسمح لنا بالعيش والازدهار، بما في ذلك المواد الحاملة للأحمال ذات الكثافات المنخفضة وقدرات امتصاص الطاقة المحسّنة، التي تعتبر ضرورية لانقباض العضلات، والمتانة، والحماية من الشمس، مما يسهل المرونة وسهولة حركة الأطراف. تمكّن "الرسبيروستات" من مقاومة الجفاف والزيادة في تركيز ثاني أكسيد الكربون، بينما تُعدّ "الفايكوسيانينات" ذات الأشكال الأسطوانية مفيدة في تخفيف الموجات، وما إلى ذلك. تتطلب هذه المواد الذكية والتصاميم الوظيفية تحكمًا دقيقًا في الوقت والبيئة ونمو المكونات المختلفة حسب حجمها وتعبئتها. لقد شملت التعديلات اللاحقة على هذه التجمعات الطبيعية فوق الجزيئية دقة واستخدام المحفزات من أجل تحسين أداء النماذج النهائية. وعلى الرغم من أن هذه الاستراتيجيات ملحوظة، نظرًا لاهتمامنا المتزايد بالإنتاج على نطاق واسع والتصاميم غير التقليدية للمواد المستوحاة من الطبيعة، والتي تكون جاهزة أيضًا للتعديل الهرمي الفوري، فإنه من المناسب أن نتساءل عن التجمعات النانوية الطبيعية الأخرى التي يمكن أن تحقق وظائفها المدعومة بالشكل دون الحاجة للدعم الخلوي في ظل الظروف القاسية للطبيعة.

إذا استلهمنا من تصميم الطبيعة في بناء مثل هذه المواد المستوحاة من الطبيعة، فإن لدينا القدرة على إنتاج نماذج ذات أداء أفضل أثناء إجراء الأبحاث في مجال راسخ يتخصص حاليًا في هذه الأنظمة. يتناول هذا النص بعضًا من أحدث التطورات في بناء واستخدام جزيئات الفيروسات النباتية، ويهدف إلى تحديد ما يجعلها مفيدة للتعديل اللاحق قبل الإنتاج المحتمل للمواد المستوحاة من الطبيعة، المصممة لتطبيقاتها المختلفة والتي تعتمد الآن على خصائصها المستهدفة للخلايا وانتقالها. تهدف هذه المراجعة إلى تسليط الضوء على التطورات الحديثة في مجال المواد المستوحاة من الطبيعة.

الكلمات المفتاحية: *المواد المستوحاة من الطبيعة، هندسة الأنسجة، تطبيقات الطاقة، خلايا الطاقة الشمسية، تنقية المياه.*

Abstract:

Many of the bioinspired materials provide us with specific functions that allow us to live and thrive, including load-bearing materials with low densities and enhanced energy-dissipation abilities that are essential to our muscle contraction, toughness, and sun protection, facilitating pliability and ease of limb movement. Respirocytes enable drought resistance and hypercapnia, and phycocyanins, which have rod-like shapes for wave damping, etc. These smart materials and functional designs have required very precise time, environment, and growth control of various components over their size and packing. Post-modification of these natural supramolecular assemblies has involved precision and catalysts in order to produce some improvements in the performance of the final models. While these strategies are notable, because we are increasingly more interested in larger-scale production and non-traditional designs for bioinspired materials

that are also ready for immediate hierarchical post-modification, it's timely to ask what other natural nano-assemblies might similarly accomplish their form-aided functions without cellular support under the stressing conditions of nature.
If inspired by nature's design in the construction of such softer bioinspired materials, we have the potential for the production of better-performing models while conducting research in a well-established area that is currently specializing in these kinds of systems. This text gives examples of some of the most recent advances in the construction and application of plant virus nanoparticles and aims at determining what makes them useful for post-modification prior to the potential production of bioinspired materials that are designed for their various applications and which are now based on their intrinsic cellular targeting and translocation properties. This review aims to highlight the recent advances in the field of bioinspired materials.
Keywords: *Bioinspired materials, Tissue engineering, Energy application, Solar cells, Water filtration.*

1. Introduction to Bioinspired Materials

Bioinspired materials are a category of specifically engineered materials that have been developed as our understanding of natural systems and their construction has expanded (Lazarus et al., 2020). At an abstract level, the goal of bioinspired material fabrication is to marry the mechanical reliability of inorganic materials with the multifunctionality and adaptability of biology (Wei et al., 2023). On a technical level, this can take the form of, for example, replication, direct harvesting, or indirect exploitation. The construction of a material is partially encoded in the underlying mechanical and chemical properties of that system, but recent work has shown that geometry is a critical component of functionality for many complex materials. (Li et al., 2020). Indeed, the structure is often the strongest signature of the observed phenomena (Fernandes et al., 2022).
The classical corollary of bioinspired materials was metals and ceramics shaped to resemble the swords of the ancient Greeks or the glass sculptures of the Renaissance (Barhoum et al., 2022). However, The natural world's functionality has spurred a rise in bioinspired designs, leading to broad potential across different industries in recent years (Broeckhoven & du Plessis, 2022). Materials science is the missing link to cohesively connect research advances across these industry sectors. Discovery in bioinspired materials is interdisciplinary, leveraging the language of biology to create new paradigms in materials science (Zhai et al., 2020). This review aims to highlight the recent advances in the field of bioinspired materials.

1.1. Definition and Significance

Bioinspired materials represent a bridge between the natural and man-made worlds. These materials often replicate structures that are found in nature in order to achieve, in some cases, better performance than non-biological materials (Wang et al., 2020). In most cases, the aim of replicating these structures is to confer new functionalities that were not possible to acquire using conventional synthetic methods (Gan et al., 2021). These materials have applications in various fields, which include medicine, nanotechnology, energy, physics, and environmental science among others (Khan et al., 2022).
In terms of technological advantages, materials found in nature can offer desirable functions that might be difficult to design and fabricate using traditional engineering

(Collins et al., 2021). For example, in the case of self-cleaning surfaces, the use of water reduces the surface energy, so that dirt slides off (Manoj et al., 2020). This has led to the development of superhydrophobic surfaces on many materials from glass to textiles. Lotus leaves have greatly inspired this work. (Ghasemlou et al., 2021) Additionally, self-assembly processes can be used in the technology using nature's design principles, which, in many cases, lead to a reduction in the raw materials used, manipulation with the atoms, and therefore a reduction in energy costs (Ganewatta et al., 2021)Externally, bioinspired materials are often designed with a particular function in mind; therefore, more direct applications are available in the industrial or medical sectors (Du et al., 2022). Internally, biological form and function on the macroscopic and microscopic scales can inspire more biomimetic designs for a wide range of engineered products. (Carotenuto et al., 2022). Whether for implants, sporting equipment, environmental cleanup, or construction, nature provides continuous inspiration and will yield increasing influence on technological strategies as research continues (Li et al., 2021)

1.2. Historical Background

The invention of bioinspired materials links historic leaps of human knowledge with observations of natural phenomena and human needs. Many natural instances of the desired characteristics of smart materials have been investigated (Lazarus et al., 2020) For instance, the first photomicrographs of plant surfaces of Arabidopsis thaliana were produced. In ancient China, approximately 300 BCE, a surface that mimics the water-repelling characteristic of the lotus leaf was produced on ceramics. The first patent for industrial velvet obtained from a silkworm was filed in 1867 (Li et al., 2020).

Combining biological and technological research has since played an important part in several technological sectors. In several studies of natural shapes and synchronicity in biology, sources of inspiration resulted in romantic and poetic as well as in philosophic and scientific responses (Ahmed et al., 2021). With a better understanding of past practices of exploiting nature and biology for their materials and structures, there is now a growing interest in bioinspired materials. (Proppe et al., 2020) The examples indicate the recent direction and tendencies where the actual examination of native and natural organisms becomes an advanced and powerful source in the creation of original materials, proceeding from physical form toward material nature, and often integrating entirely new molecular forms of inspiring nature in the process of technology (Banat et al., 2021).

2. Natural Structures as Inspiration

Nature's diverse set of structures has long served as an important inspiration in the field of materials science and engineering. Understanding structural characteristics developed by living organisms may provide keys to copying, mimicking, or manipulating the creation of new materials possessing similar functionalities in an engineered, controlled fashion (Wang et al., 2020). Given the tremendous diversity, not to mention age, of natural structures, this is also a very rich vein of ideas to be mined (Vuong, 2022).

Many exciting examples, from micro-scale and nano-scale prototypes to commercial products, turn to biological systems for imaginative, innovative ideas. Some well-known examples are spider silk, the self-cleaning lotus effect, superhydrophobic surfaces showing synthetic water-repelling properties, and shark skin (Wang et al., 2021). The fractal geometries of shark skin's denticles are the foundation of various industrial prototypes, including an anti-algae foil (Liu et al., 2024).

While in some cases attempts to replicate – or to follow the same principles used by nature to achieve – properties of biological structures in engineered structures fail to produce a real impact in the marketplace, some other examples receive considerable attention (Tula et al., 2023). Drag-reducing shark skin underscores the multidisciplinary character of the advancements in using natural structures as inspiration, requiring a blend of physics, biology, and surface engineering. (Perricone et al., 2021). It also underscores the level of collaboration among interdisciplinary camps at the scientific and engineering nexus (Igbinenikaro et al., 2024). Mimicking natural structures in engineered materials and devices typically involves a bottom-up approach, focusing on material science to build nano- and micro-engineered materials and structures (Filippi et al., 2022). Mimicking on a molecular level the composition of elements found in mollusk shells has led to great improvements in impact and penetration resistance in bulletproof vests, and strength in automotive materials (Ghazlan et al., 2021). Mimicking structural characteristics of natural materials has also been applied to tribological, antibacterial, and electrical fields, as well as to various types of coatings protecting surfaces against corrosion (Ganewatta et al., 2021). Mimicking natural structures is increasingly prevalent in the marketplace, particularly positively affecting product quality of hard materials, from cutting tools to automotive parts (Rouf et al., 2022).

2.1. Biological Examples

Bioinspired materials are a unique class of materials inspired and designed to harness nature's deep insight into optimal design for specific functions (Ganewatta et al., 2021). Biological designs involve generations of evolutionary honing of assembly processes to fabricate complex structures with superior functionalities (Zhang et al., 2022). Understanding and mimicking biological systems has thus emerged as an alternative approach for synergizing research across disparate fields like materials science, chemistry, biotechnology, and biomechanics, aiming to combine dissimilar materials and engineering units for engineering and construction, nanomaterials and nanotechnologies, nanobiotechnology, and so on (Wu et al., 2022) Collective group behavior and emergent properties have also been discussed in the so-called engineered systems, consisting of the assembly of identical materials with components, including self-assembled quantum dots and nanocrystals, substrates for electronic and optical devices, and composite low electrical conductivity materials for low noise lithography masks (van et al. 2022).

3. Design Principles in Bioinspired Materials

Taking inspiration from nature to design materials that are capable of performing specific functions has fascinated generations of people and has provided a fertile ground for fruitful collaboration between different fields (Hart et al., 2021). Technological progress in recent years has allowed the development of advanced imaging and computational techniques, contributing to accelerating progress in the field (Choudhary et al., 2022). An important field is to determine what to mimic, that is, designing the "ideas that connect things," the principles. The other is to understand the strategies involved that influence the ways and means of generating materials with sometimes dramatically improved properties. Natural materials are typically composed of a peculiar hierarchy of structures, spanning different characteristic dimensions that in some sense parallel the hierarchy of the human scale of surveillance, through microscopes and various instruments, down to the atomic scale (Ajdary et al., 2021). From a design point of view, the structural hierarchy admits the possibility to include architecture-dependent "knobs" to manipulate the full spectrum of properties from the atomic to the structure-dependent scales. At the level of matter, a process of interplay between form and function is relevant – some of them have inspired potential for materials applications (Musil et al., 2021). Function may induce structure, while form may optimize function; this interplay leads to a multi-faceted link between the system of consideration and other physical, chemical, or biological characteristics of the problem (Collins et al., 2021). In this context, recent studies in the field of bioinspired materials have contributed to identifying principles that underpin the design of materials which generate exceptional strength, toughness, specific properties, or a combination of these, and as highlighted in a work on fracture resistance, crack deflection (Zhang et al., 2020). Nature has devised several strategies to design materials that are strong and tough at the same time over a remarkable range of length scales; the hope is that bioinspired materials of each class would be developed by manipulating the connections among inherent material properties with hierarchical design (Chen et al., 2021). A library of these principles in practice includes bioinspired materials from steady bioevolution as well as from high-throughput material design, ranging from biologically based to biologically inspired systems, and concludes on the potential and the challenges associated with the development of advanced bioinspired materials, inspiring the continuation of theoretical and experimental research on how the biomimetic design principles covered could progress technology (Wang et al., 2020).

3.1. Hierarchy and Multiscale Structures

Hierarchical organization, by definition, is a system in which the components of an organization are arranged in multiple levels, with each component primarily having a larger number of smaller components in the next lower level (Hilgetag and Goulas, 2020). Multiscale structures and coordination occur at various mass levels in living organisms due to natural, biological, or environmental-related constraints; i.e., hierarchical structures are a coping strategy (Bechtel and Bich, 2021). For example, osteonal bone, as an active, hierarchical composite, is composed of a series of cylindrical osteons, which consist of lamellae. Hierarchical biological materials such as osteonal bone, nacre, and avian feathers have developed specialized hierarchical structures to fulfill multiple functions. Functions could not be achieved when considering lower hierarchical levels alone (Wu et al., 2020)

Indeed, each scale level has been optimized to efficiently fulfill the main required biological function(s) at its specific size. For nacre, it has been demonstrated that arrangement at the nanometer level, layer structure, and bonds provide the majority of the strength (Chen et al., 2020). Likewise, for avian feathers, it is the macroscopic organization that enables the feathers to dry in zero time. An interesting conceptual example is that of feathers in nature, where water droplets are dispelled almost instantaneously using a hierarchical structure (Yang et al., 2023).

The effect is based on not just the real physical properties of water or the barrier properties of the structure on one size scale but results from the combined action of a series of scales, each responsible for an enhancement, the impact of which compounds with the presence of the others, thus converging towards instant response (Schielzeth et al., 2020). Finally, by comparing this polymer-based material with the natural bi-material, topologies, strengths, and stiffnesses of the materials can be tested and compared; in particular, advantages in duplication of the natural web regarding sustainability and the design of new multifunctional and hierarchical bioinspired materials can be underlined. (Long et al., 2021)

4. Bioinspired Materials in Biomedical Applications

Bioinspired materials have already brought revolutionary developments in various fields, and their potential in biomedical applications is enormous. For instance, implants with improved antifouling properties increased tissue integration of medical devices (Harun-Ur-Rashid et al., 2023). Additionally, materials that leverage biological processes in a previously unforeseen manner for new applications can be a powerful platform for novel drug delivery and regenerative medicine applications as well (Trucillo, 2024). Orthopedic and cardiovascular stents can be greatly improved by increasing biocompatibility and reducing the chances of restenosis. Despite their numerous advantages, bioinspired materials have only recently found their foothold in the biomedical field (Zhu et al., 2021).

Important developments in the last few years involve improving the multifunctionality of the materials. This could be as simple as improving surface energy, wettability, or tribology; however, these functionalities can also be tuned to be pH-sensitive or temperature-sensitive (Wang et al., 2021). An important aspect of formulating bioinspired materials is functionalization. This can involve simply the addition of another type of molecule to an already functional coating or material (multifunctional), or it can involve endowing inert surfaces with biological functionality (Aisida et al., 2020).

For multiple applications, there is an interplay between the design principle of the device and the biological requirements of the application (Su & Song, 2021). The development of biointerfacial properties for multifunctional coatings and their relevance with path-breaking insights are being produced with the advancements made in the field of biomimetic coatings (Lee et al., 2023). Nevertheless, there are problems related to the longevity of bioinspired and bioactive materials. The approval of coatings and active agents has been a major roadblock, and researchers have now started to take cost-effective and easy approaches for incorporating bioactivity into materials (Jha & Sit, 2022). Tissue engineering is testing the waters with bioinspiration in the manufacturing of tissue replacements. The need for biomimetic design methodologies in tissue engineering has been highlighted. Based on the literature we studied, it can be said with assurance that the potential of bioinspired materials is constantly being realized within different medical technologies (Yang et al., 2021).

4.1. Tissue Engineering

The development of bioinspired materials has propelled the progression of regenerative medicine, an approach aimed at replacing or regenerating tissues to heal injuries or treat diseases (Harun-Ur-Rashid et al., 2023). Tissue engineering is a crucial branch of regenerative medicine, enabling the recapitulation of anisotropic tissues, such as skin, cornea, and cartilage (Chimerad et al., 2023). A key aspect of this approach is the design, fabrication, and optimization of matrices or 3D porous scaffolds that can guide stem cell and progenitor cell behavior to regenerate tissue ex vivo and in vivo. Bioinspired materials can significantly enhance the quality of these 3D scaffolds both structurally and functionally (Wang et al., 2020).

The desired properties of bioinspired materials that facilitate biomaterial-guided tissue regeneration include the following:

(1) Biocompatibility: The scaffold should be non-toxic and able to abate the host

immune response (Abdelaziz et al.2023).
(2) Structural support. The scaffold should structurally facilitate cellular adhesion and cell-to-cell communication, along with preserving space for the infiltration of adult stem cells, progenitor cells, and other cell types (Choi et al.2021)
(3) Mimic the natural tissue environment. The inspiration from nature helps to fabricate porous scaffolds with porosity and pore size similar to native tissues to ensure effective cell seeding and uniform distribution of nutrients and waste products in 3D cultures (O'Shea et al., 2022).
(4) Simulate the native biological signal. Key native components are integrated into the scaffold to generate a biomimetic niche that can behave like natural extracellular matrices. Numerous in vitro and in vivo experimental studies have directly reinforced the potential of bioinspired materials for the fabrication of matrices (Wang et al., 2020).
These are being tested in various clinical trials around the world, with published success in regenerative therapies for both preclinical and clinical studies. Our increasing understanding of various design strategies based on natural systems can further enhance advanced tissue-engineered products for clinical use (Ntege et al., 2020).
Despite encouraging results in experimental preclinical models, the translation of bioinspired scaffolds into practice remains challenging due to their combined integration and function, which can be difficult in a clinical setting (Naghieh et al., 2021).
Significantly, advancements in the field of tissue engineering are multidisciplinary, wherein the integration of engineers, cell biologists, synthetic organic and inorganic chemists, material and polymer scientists, and clinicians becomes crucial. (Ashammakhi et al., 2022). Prevalent pathological conditions such as ischemia, soft-tissue necrosis, peripheral arterial diseases, and oral hard/soft tissue damage require innovative treatment strategies that employ nature's mechanisms of tissue repair by using transplanted cells and bioengineered tissue. Innovative strategies consist of creating structural and functional bioengineered organs through the bioinspired approach. This can involve the encapsulation of various cells into bioengineered organ-like structures that mimic native microenvironments. (Ashammakhi et al., 2022).

5. Bioinspired Materials in Energy Applications

The field of energy constitutes one of the main technological, social, and economic challenges of the current century. However, the importance of this field is not just due to the increasing world energy demand but also to a shift toward energy consumption that is less aggressive to the environment (Ahmed et al., 2022).The continuous miniaturization of electronic devices and the need to make the most of the energy consumed leads to the demand for lighter, more efficient, and more sustainable energy sources. In this context, excellent energy absorption and transformation become crucial engineering goals in several applications, including mainly sensing, communicating, harvesting energy, and delivering power. (Karmakar et al., 2020). At the same time, new frontiers in energy research emerged, such as bioinspired materials and systems. In fact, nature is an exceptional source of inspiration as the energy systems often present high performance in terms of absorption and transformation of the energy contained in the available sources (Katiyar et al., 2021).
The application examples of bioinspired strategies for sunlight absorption include mainly light-trapping surfaces and materials, such as the mimosa super-hydrophobic bioinspired structure for obtaining light management and absorber properties together with minimal

reflection in solar cells, and the photovoltaic solar cells inspired by coleoptera, a beetle surface with metallic-like properties. (Li et al., 2021)
Although the absorption of a broad range of sunlight wavelengths and the conversion of it into efficient photovoltaic energy remains the major issue in the development of novel solar cells for energy generation, which is the ultimate bioinspired target for converting sunlight into electrical energy (Al-Shahri et al., 2021). Up to now, bioinspiration in solar cells has focused on the improvement of surface light trapping and light absorption in microcavities, crystalline-like and antireflection coatings (Soudi et al., 2020).
In general, the combination of the different energy conversion and absorption mechanisms in a bioinspired design can offer significant performance improvement with respect to the state of the art (Proppe et al., 2020). Furthermore, bidirectional biological energy flow through the surface texture and nanostructure is characteristic of nature, more than a strict integrated optical design, and it deserves further investigation (Lian et al., 2023). Finally, even though the solar cells with bioinspired design may introduce an increase in costs with respect to commercial PVs, they prove to reduce the environmental impact, which is not only an ethical concern but also economically worthwhile. Green energy and energy saving in nature have an increasing value in terms of market potential and have to be developed and deeply analyzed by the scientific community (Yoon et al., 2021).

5.1. Solar Cells

Natural systems provide highly efficient energy conversion, absorption, reflection, and scattering mechanisms to survive and evolve over time. It is therefore an attractive approach to harness these natural systems to develop bioinspired materials for solar energy harvesting (Hao et al., 2022). One popular biomimetic-based solar cell is the 'artificial leaf', which uses the mechanism of natural photosynthesis to produce hydrogen fuel. Biomimetic strategies have mainly focused on mimicking efficient light-harvesting mechanisms coupled with photoinduced electron or hole separation processes (Ortega et al., 2023). Practical applications and features of bioinspired solar cells were discussed. There exist various bioinspired paradigms that have been transformed into real devices to overcome the bottlenecks in current solar cell technologies (Yoon et al., 2021).
However, the above-mentioned fields require a lot of ongoing collaboration among different scientific disciplines. Alongside the promising enhancements of the existing solar cells and functional materials expected in the next decade, bioinspired design concepts that combine photonic and optoelectronic properties to harness light have attracted a lot of research activity (Saxena et al., 2022). However, the main bottlenecks associated with the efficient bioinspired design and rational synthesis of materials are still significant challenges before substantial advances can occur (Barrio et al., 2022). Another major developmental challenge for this field is to demonstrate that the new concept can operate over a wide range of operating conditions with the reliability needed for the technology to be adopted by industry (Mishra et al., 2021). Bioinspired technologies presented compare one efficiency parameter to that of widespread, commercial light-harvesting technologies. This indicates the fundamental link that bioinspired materials can leverage and have the potential to push technology further, once significant research and development challenges can be addressed (Häse et al., 2020).

6. Bioinspired Materials in Environmental Remediation

The increasing importance of bioinspired materials in this field is due to the urgent need for sustainable and efficient methods for solving environmental problems associated with resources and pollution management, mainly due to their ability to absorb, filter, and decompose pollutants (Katiyar et al., 2021). Nature has evolved a series of strategies to tackle the ongoing environmental issues that can be exploited to design next-generation bioinspired materials (Yoon et al., 2021). Inspiration from both materials with transport routes inspired by the natural water cycle and plants is designed in such a way as to concentrate or remediate the pollutants. In contrast, inspiration from microorganisms is distinct in designing bioinspired materials that can biodegrade or transform pollutants into detoxified biomass (Kumar et al., 2020).

Although liquid-based filtration inspired by nature's processes has been gathering attention, the scalable manufacture of filtration products is much more commonplace (Yusoff et al., 2022). Biomimetic wastewater treatment systems are rarely investigated. Pragmatic issues, particularly the removal, installation, and cleaning of the products or the scaling to field scale, are rarely addressed (Sharma et al., 2022). Furthermore, the need to reproduce the fabrication of nanomaterials still attracts a large crowd of scientists around the world, but at the same time, there is comparatively very little research that focuses on taking biomimetic design principles for this home scale (Perricone et al., 2021). Far from the domain of home applications, very few outline the commercialization of new filtering products. Additionally, the implications of each research outcome or the chosen material for long-term purifier ability have been explored at the primary stage (Eray et al., 2021).

In the future, the implementation of eco-friendly materials and devices that harness natural processes represents one of the most promising ways to keep the Earth clean (Almalki et al., 2023).

Dendritic substrates in the water manipulation field have been examined, certifying only pollutant absorption of the materials, ignoring the replication of actual pollutant remediation activities linked to plant roots or the suggestion of implementing this approach with living microorganisms to achieve self-regeneration (Arkas et al., 2022). This vision of biomimetism is uncommon considering the potential field applications and the necessity of eco-friendly materials to improve plant performance to such an extent that, in urban areas, nature-inspired designs can be considered to break down pollutants at the root zone level. The same vision is carried out by synthesizing goethite nanoparticles and depositing them on biochar to promote plants' ability to break down pollutants while eventually proposing the development in situ of such a bioinspired nano-deposit on biochar through biogenic or biomimetic oxidation (Xu et al., 2022).

Embracing an ever-expanding field of research is the symbiosis between humans and plants, and the exploitation of plants' ability to clean the environment. By supporting researchers, designers, and practitioners, we motivate this scientific debate on the integration of the conversion of pollutants in food, perfumes, medicine, papers, and plastic feed from the pharmaceutical supply chain that is establishing itself worldwide into authentic products (Taoufik et al., 2021). A truly sustainable mode of future growth. Some recent bioinspired materials focused on bio-based sponge materials for the sorption of pollutants and the filtration of dyes, bacteria, and total dissolved solids in water have been tested. Furthermore, only the experimental work developed in the lab is shown here. Also, please note that biofilters with flax fibers are among the latest applications of bioinspired materials to plants (Awasthi et al., 2023).

6.1. Water Filtration

Although there are many aspects of water treatment, and even more biological models to look to for inspiration, we will focus on one particular aspect: filtration. The structures obtained from the examples are often applied to enhance filtration properties. The second biological example can be the root system of plants, from which it can be encouraged, resulting in high filtration properties (Wang et al., 2020). Plant roots allow the necessary nutrients to be transported from the soil to the rest of the plant while simultaneously removing toxins (Gavrilescu, 2021). These specialized roots act as a filter; a plant's root system allows the red mangroves to filter out 90-97% of the salt from the water before allowing it into the roots. (Anu et al.2024) Plants like water hyacinth can absorb metals like iron, lead, and arsenic, and some plants like the water lettuce are even able to absorb mercury to a certain extent (Ali et al., 2020).

Inspired by this natural mechanism in a non-waxy rice leaf, textured the leaf with re-entrant pillared micro-texture. This resulted in an efficiency of 55% in blocking the water leaking from textured leaves. Inspired by the structure of fish gills, developed a polymer membrane with a layer of an adhesive hydrogel (Wang et al., 2021). This hydrogel has connected channels made of polyethylene glycol in a random-walk shape. The adhesive-coated gills show no difference in properties from the uncoated gills, still being able to filter the particles effectively and easily. Moreover, the hydrogel can be readily regenerated (Tu et al., 2021). As a practical demonstration, the gills were connected in the air-sea interphase of seawater to obtain solid natural organic matter (Eisaman et al., 2023). Despite a 1 µm pore size of the membrane, the hydrogel layer allowed high flow rates. The fish-gill-inspired membrane could provide a water extraction solution from the ocean (Wu et al., 2024). A further practical adaptation can be achieved by creating separation systems that integrate the membranes into filtration equipment on top of the water column; the ability to regenerate the self-cleaning membranes allows them to be used time and time again (Nguyen et al., 2022). The next step is to assess whether these novel water extraction technologies can be scaled up to create a realistic new way to deliver clean water from the oceans. The current focus of our work is overcoming small-scale demonstration challenges such as material longevity, durability, and cost associated with bulk production (Yusuf et al., 2020).

7. Challenges and Future Directions in Bioinspired Materials

The relatively new field of bioinspired materials has grown over the past years. While there have been many successful applications and solutions in different areas, several main obstacles and issues curbing the wider and more advanced dissemination, as well as deeper exploitation of biological design principles, are still very relevant (Katiyar et al., 2021). Undoubtedly, many of these challenges will be faced in the ongoing and future research work. Consequently, the most intricate and apparently the most challenging issues in biology-in-materials are reciprocal coupling functions of their constituents, business activities, and money limitations (Adjabi et al., 2020). Therefore, wealth and economic constraints are intricately woven through aspects of all challenges below. While most of them emphasize the current challenges, there are some that arise now due to the already developed solutions and findings (Challoumis, 2024). These show their close interaction and complementarity, highlighting that the field is advancing to the second phase of maturity, which is applicable to large convenience, and it is inevitable that the ongoing research becomes innovation-hungry and highly multidisciplinary

(Goodrich & Theodore, 2021). A few key future directions in going from the experimental to the scientific and hence, application dimension domains of bioinspired and biomimetic materials and temporary inorganic structures are suggested.
It is expected that trade-offs must still be identified between cost, sustainability, functionality, aesthetic appeal, top-level technology, performance, and quality with easy scaling up (Parekh, 2024). Finally, regulatory approval, safety in addition to technology transfer, and public uptake will be major factors. It is hoped that the adoption of these research challenges will provide an impetus for this very important and cross-disciplinary field. The scale of production will be an important next step (Barhoum et al., 2022).
Some of the early ideas, such as cost prediction, may no longer apply. More importantly, in light of the large number of materials and processes now becoming available and reported under the heading of biomimetic materials, it will be crucial to choose appropriate criteria in relation to the main biological design concept that a material is addressing (Raees et al., 2023). Going more biologic in our approach, a biomimetic study may be evaluated with reference to how it compares to the current state of technology and the manner in which it is employed, where function is defined by social and aesthetic factors (Cruz et al., 2021). In the most recent spaces, the biological inspiration is often inherent to the functionality required. A truly biomimetic future not only learns from biological systems and functions but also should build on genuine insights and understanding of basic biological processes, biomimetic in that it combines information technology properties with biological sensing processes (Wang et al., 2020)

7.1. Scalability and Manufacturing

The scalability and manufacturability of bioinspired materials is another main challenge when trying to move from a laboratory technological innovation to the market. From a scientific point of view, numerous possibilities exist to produce these kinds of materials; however, from a technological and industrial point of view, many limitations still exist (Lian et al., 2023). In particular, the critical factors to be assessed for the scalability of bioinspired material production are the following: the availability and cost of the resources, the environmental impact of the production process, and the technical feasibility of producing large amounts of these materials (Shashwat et al., 2023). In terms of cost, if the availability of the resources to produce these materials is secure, manufacturing costs will compete with petrochemistry-based polymers on the market (Mukherjee & Koller, 2022). Efficient manufacturing technologies for these designed materials could be tipping points in popularizing and developing bioinspired design. Consequently, some technologies aim to develop and/or improve materials according to various scales or bioinspired designs (Lian et al, .2023)
New strategies as well as new ways of selecting materials include investigating links between raw materials, micro and/or nanostructure as a function of properties, cost levels, and fields of application such as in defense, transportation, multifunctional materials, aerospace, biomedical, pharmaceutical, and automotive (Schrijvers et al., 2020). Furthermore, possible economic, legal, and biological implications of nanotechnology will also be addressed (Sparrow, 2020). For a long time, the scalability of materials has been addressed; however, the lessons from this work can be modified, given that a growing research community in chemistry, physics, and materials science is developing materials and fabrications with applications ranging from drug delivery to microsystems (Al et al., 2021). To succeed in material processing and design for scalability, it is crucial

to investigate the chasm of current scalability or cost-efficiency values in some actual economically important sectors (Allioui & Mourdi, 2023). Moreover, one can get inspiration from evolutionary and ecological concepts in order to step over the gaps between a few years or even decades of laboratory development versus the hundreds or millions of years of evolution with respect to single or multiple constraints in the context of costs. It should be mentioned that the ratio of the maximum and minimum size of the repetition unit is more revealing than a single parameter of cost efficiency.

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