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Review

Nature-inspired innovations: unlocking the potential of biomimicry in bionanotechnology and beyond

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Received: 19 July 2023 / Accepted: 16 November 2023

Abstract
Bionanotechnology research has surged to the forefront of scientific innovation, propelling the exploration of cutting-edge technologies and interdisciplinary collaboration. Biomimicry, which harnesses nature's ingenuity, drives the development of novel research-based solutions in diverse fields such as vaccines, medicine, and biomedical devices. Nature's role is becoming increasingly pivotal in addressing complex challenges related to environmental conservation, human health, and pandemic preparedness, including those posed by SARS-CoV-2 and other emerging pathogens. Progress in this domain encompasses understanding nature´s mechanisms to develop advanced materials inspired by biological structures. Biomimetic innovations have the potential to revolutionize industries, reduce environmental impacts, and facilitate a more harmonious relationship between humans and nature while considering bioethics, underlining the necessity of conducting responsible research and implementing biomimetic advancements conscientiously. As biomimicry continues to grow, integrating ethical guidelines and policies will ensure these nature-inspired technologies' sustainable development and application, ultimately contributing to a more resilient and adaptive society. This mini-review article broadly overviews bionanotechnology applications based on natural examples.

Keywords Bioinspiration · Bioethics · Bionanotechnology · Biomimicry applications

1 Introduction

From a chemical perspective, biomimetics is a branch of organic chemistry that imitates natural reactions and various existing enzymatic processes [1]. The study of nature and its applications in human lives has seen remarkable developments in molecular structures, polymers, natural processes and designs, soft materials (body tissues and bones), and biomaterial composites [2]. The importance of biomimetics lies in the innovative design and development of efficient solutions that can be applied to commercial products and industrial processes. The International Standards Organization, in their ISO 18458:2015, has stated a definition for biomimetics as "the application of research and development approaches of interest to practical applications and which use the knowledge gained from the analysis of biological systems to find solutions to problems, create new inventions and innovations, and transfer this knowledge to technical systems." [3].

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Discover Nano (2024) 19:186 | https://doi.org/10.1186/s11671-024-04153-y

Organisms studied in biomimetics span a wide range, from bacteria to more complex organisms such as fungi, plants, and animals. Some plants and animals in arid regions can collect water from mist and condensation; inspired by these unique traits, researchers have developed bio-inspired mist collectors [4]. However, while investigating these applications, it is crucial to consider the scope of the research and approach it with an understanding of how organisms produce and maintain the compounds they release and how we can apply this knowledge to our technology. In addition, biomimetics is not limited to mimicking organisms' physical structures or behaviors. Researchers are increasingly exploring the potential of biomimetics in materials science, for example, by studying how certain organisms can self-repair or self-assemble, which could lead to the development of self-healing or programmable materials with self-assembly properties [5]. As biomimetics continues to expand, the opportunities for innovation are limitless. By learning from nature's vast solutions, scientists and engineers can develop novel technologies and materials to address global energy, sustainability, healthcare, and transportation challenges. A comprehensive list of examples of types of bioinspiration was published recently by Aish and Sun (2020) as part of the Bioinspire-Museum project, and the reader is directed to that paper for specific references binned by bioinspiration type [6]. This minireview focuses on giving a broad overview of bioinspired applications at the nano and microscale.

Bioethics plays an important role in biomimicry research. It is responsible for regulating laws and principles that determine the limits for the proper and conscious use of natural resources [7]. Benyus suggests that biomimetics can be used to judge the ethical correctness of technological innovations because nature, through years of evolution, has learned what works and endures [8]. Nature's principles often contribute to ecological health and ecosystem integrity. As such, technological and biomimetic innovation should adhere to design principles aligning with natural principles and promote an inclusive ethic considering ecological limits [9]. Biomimetic research aims to establish a new approach to ecosystems, characterized not by domination and exploitation but by learning from nature [10]. Applying bioethics in biomimetics encourages principles that connect human behavior with biological and medical management and the environment. These connections are biomimetic hybrids that involve designing and managing a complex system [10]. Aish and Sun (2020) argue that the associated ecological footprints for bioinspired applications should be low or zero, seeking to affect the environment positively and not only serve human needs [6].

2 Biomimetics: development and applications

The advancement of biomimetic studies has broadened the scope of scientific research, enabling the development of enzyme models that can be used alongside synthetic enzymes. New ideas have emerged regarding the potential applications of biomimetics in bionanotechnology, including enzyme trials, vaccines [11], protein-based biological derivatives, polysaccharides, corals, and sponges for scaffolding [12]. Additionally, the development of bio-inspired surfaces should aim for durability [4], with examples that show the potential biological control of structures when they are on the nanoscale, being able to exhibit a variety of desirable properties and polymorphisms [13].

The implications of biomimetics are significant, as they contribute to research and facilitate the observation of natural behaviors for imitation, ultimately providing solutions in medicine and advancements in new technologies. Biomimetics is closely related to green technology, presenting research based on biological inspiration. This allows the development of solutions derived from the evolution of nature and promotes the efficient and sustainable use of natural resources, which helps to foster environmentally friendly practices [4]. Biological scaffolds based on proteins like collagen, elastin, gelatin, silk, or polysaccharides like alginate, cellulose, chitin/chitosan, and hyaluronic acid [12], have been widely used due to their biodegradability, biocompatibility, and applicability in tissue engineering. Developing new biomimetic structures with a wide range of chemical and physical properties promotes the use of bio-based scaffolds resembling the original tissue, which enables new tissues to grow in their environment in a naturally controlled manner, as da Silva et al.[14] showed with collagen/nanotube biocomposites for bone regeneration: their biocomposite is bioresorbable and biodegradable and has the desired mechanical rigidity while maintaining a 3D nanostructured surface resembling the original bone. A natural nanoparticle (NP), human serum albumin (HSA), has been extensively used as a drug vehicle due to its advantages of biocompatibility and non-toxicity before or after degradation [15]. However, it faces challenges such as poor structural stability in circulation due to its characteristics and complex in vivo composition of proteins and enzymes [16]. Gao and coworkers overcame these [16] by developing red blood cell (RBC) membrane-camouflaged HSA NPs (RBC-NPs) based on a cell membrane-coating strategy: coating the RBC membrane on the surface of HSA NPs endows RBC-NPs with both suitable physicochemical properties of HSA NPs (complete biodegradation, sustained release, and compatibility with hydrophobic drugs) and unique biological functions of RBCs (prolonged systematic retention time, less reticuloendothelial system (RES) uptake, and reduced immunorecognition).

3 Bionanotechnology approaches

The adoption of biomimetics in various industries has increased over time, with innovations such as Michael Kelly's barbed wire inspired by the Osage orange bush [17] and micropatterns that mimic shark skin microstructured roughness which disrupt the formation of bacterial biofilms without the use of bactericidal agents [18, 19] (Fig. 1). Line patterns observed on the periostracum of *M. edulis* (blue mussel) have a similar pitch and width as those used in an engineered structure recently published by Cordero-Guerrero (2023) [20] on an aluminum alloy; the former natural surface offers reduced algal spore attachment and germination [21] while the latter synthetic surface was proven to reduce *E. coli* attachment.

Marine organisms have been extensively researched for their biomimetic potential, including the tubeworm Phragmatopoma californica's adhesive composition [22]: this bioadhesive is organized into two sets of polyelectrolytes with opposite charges. Initially, the bioadhesive is fluid, but it quickly becomes insoluble when the two components interact and come into contact with seawater. A dormant catechol oxidase, ready for the swift oxidation of peptidyl-DOPA, triggers the creation of a uniformly cross-linked matrix. Polyphosphate shells, stabilized by divalent cations, surround water-filled pores. The final product is a robust and flexible water-filled adhesive foam. Further exploration of the worm's clever adaptations could provide insights into the design principles for creating self-activating, fluid-filled foam adhesives underwater from water-soluble macro-precursors. Another marine organism, Actinia (anemones), inspired the development of a biomimetic micellar nanocoagulant for effective water pollutant removal based on the invertebrates´ tentacles, which trap food, as recently published by Liu and coworkers [23]: the Actinia-like micellar nanocoagulant, which has a core–shell structure, can easily disperse in water while resisting aggregation. For effective coagulation, the nanocoagulant inverts its structure like Actinia. The shell undergoes hydrolysis into large aggregates that destabilize and entrap colloidal particles. At the same time, the core is exposed to water, akin to the extended tentacles of Actinia, and absorbs dissolved contaminants. With its capability to eliminate a wide range of contaminants and yield high-quality water, this technology holds promise as a cost-efficient alternative to existing water treatment processes.

Polymeric membrane separation technologies have contributed to purifying contaminated or underground water through low-energy consumption filtration. Yang and coworkers (2019) [24] recently demonstrated that an eco-friendly biomimetic coating inspired by the amazing adhesive chemistry found in mussels (via polydopamine) can increase hydrophilicity in typically hydrophobic poly(vinylidene fluoride) (PVDF) membranes, thereby resulting in enhanced infiltration capacity (Fig. 2). This demonstrates the potential for bionanotechnology to merge with industrial biomimetics, creating innovative solutions for various applications across diverse industries.

Another innovation related to energy-saving is the development of aerogels. The *Thalia dealbata* plant has a porous stem featuring an anisotropic architecture of interlocking sheet bridges, which provides lightness and robustness. Wang et al. utilized this structure as inspiration to create a biomimetic aerogel made of cellulosic nanofibers with interconnected sheet bridges [25]. This resulted in ultra-low thermal conductivity and high mechanical stiffness. Using spatial confinement, the researchers synthesized ZrP/RGO (graphene-confined zirconium phosphate) nanospheres. Using a unidirectional freezing technique, they incorporated cellulose nanofibers to prepare a ZrP/RGO/CNF ((graphene-confined zirconium phosphate with cellulose nanofiber) biomimetic aerogel. The aerogel exhibited a biomimetic architecture of interconnected sheets with low density and high porosity, providing differentiated thermal insulation, mechanical rigidity, and flame resistance [25].

Geckos have been extensively studied for their unique adhesive capabilities. Their legs can stick to surfaces without losing adhesion, even after repeated use [26]. This remarkable feature is primarily attributed to the complex structure of the animal's fingertips, [27] whose fibrillar structure has large adhesion controlled friction in one direction and no adhesion in the reverse direction; gecko-inspired adhesives can be useful, for instance, in soft robotic grippers. The *Nelumbo nucifera* plant, commonly known as "lotus," possesses leaves with superhydrophobic and self-cleaning properties due to the microstructure coupled with the non-polar waxes coating, which results in a Cassie-Baxter (non)wetting regime, where water rests on top of air bubbles trapped within the waxy microtubules [28, 29]. These characteristics have inspired research into cleaning and liquid-repellent applications [17, 30]. For instance, biogenic silica-based microparticles, a by-product of the nanocellulose extraction process from pineapple peels, have great potential as a substitute for manufactured microparticles [31] and have been proven to function as a bacterial

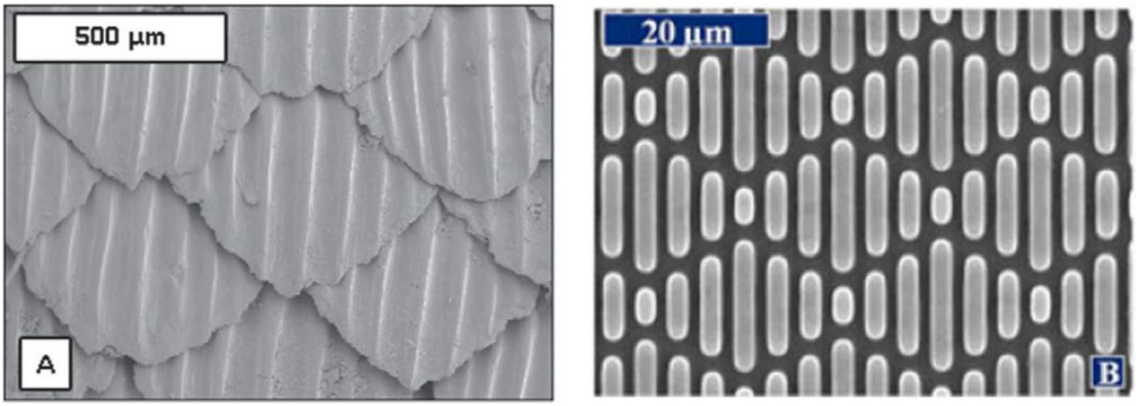

Fig. 1 Scanning electron micrographs of surfaces: **a** Naturally textured spinner shark skin and **b**Sharklet AF™ microstructure on poly(dimethylsiloxane). Reproduced with permission from (A) Magin et al. (copyright Elsevier 2010) and (B) Chung et al. (Creative Commons CC BY, AVS 2007) [18, 19]

anti-adhesive when modified with octadecyltriethoxysilane (OTES) due to Cassie-Baxter wetting regime (Fig. 3)[32]. This application highlights how bio-waste materials could be incorporated into circular economy efforts with minimal ecological footprints, per bioethical requirements for bioinspired applications per Sun and Aish [6]

4 Therapeutic applications

Nanotechnology, in particular, presents a wealth of opportunities for biomimetic exploration, as it involves manipulating materials at molecular and anatomical scales to create novel nanostructures. These advancements can potentially revolutionize various aspects of healthcare, including drug delivery, tissue engineering, and diagnostic tools [33, 34].

One key area of interest is the development of innovative solutions for chemotherapy and regenerative medicine treatments. Researchers can stimulate and control the body's repair mechanisms by designing biomimetic materials that interact with the biomolecules in their environment, enabling more effective therapies. As potential nanoscale vectors, these materials can target specific areas of the body, reducing side effects and improving patient outcomes [35].

The biomimetic approach in nanomedicine for drug delivery applications has been explored since 1995, dealing with synthesizing and characterizing a supramolecular biovector [36]. The nanocarrier showed an enhanced therapeutic

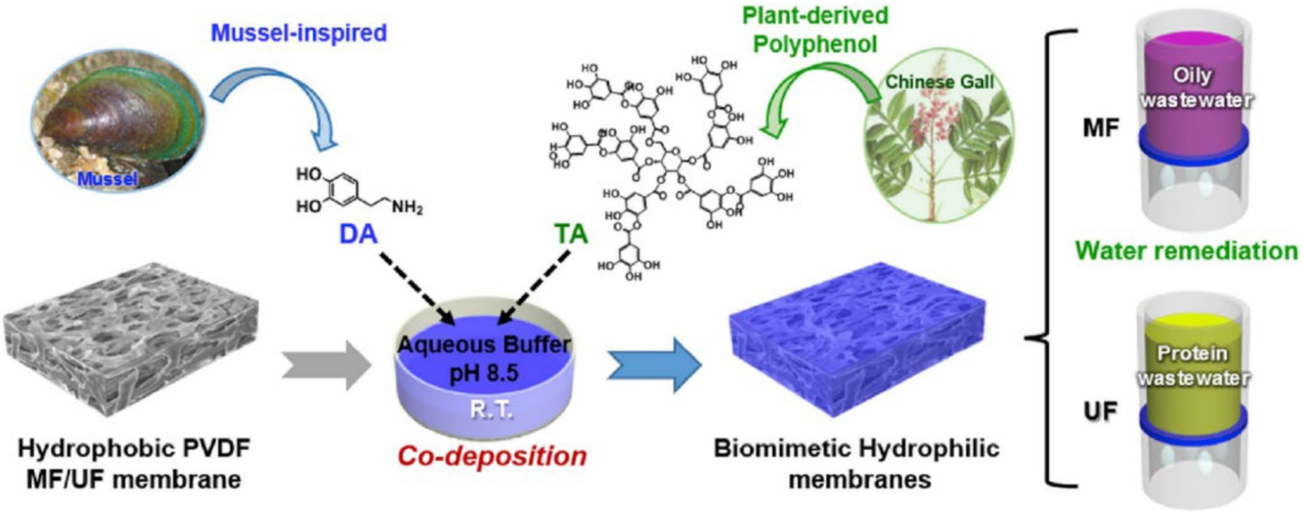

Fig. 2 Co-deposition of dopamine (DA) and tannic acid (TA) on hydrophobic polyvinylidene fluoride (PVDF) membranes for oily emulsion and protein wastewater remediation. MF and UF refer to microfiltration and ultrafiltration, respectively. Reproduced with permission from Yang et al. (2019), Copyright Elsevier [24]

potential due to the biomimetic property of low-density lipoproteins. Aside from the well-known stealth nanocarriers to avoid fast elimination by the mononuclear phagocyte system (MPS), these novel nanoparticles can evade immune detection through surface engineering and preservation of cell membrane antigens (Fig. 4). The synergy between both strategies allows them to acquire ligand recognition, targeted delivery, prolonged blood circulation, and immune escape [37]. Furthermore, the loaded active compounds can benefit from this surface modification, being released at a controlled rate and at the required biological site to exert their therapeutic effect [38, 39].

Gold nanoparticles are being investigated due to their potential for drug vectorization to treat cancer. Current studies focus on targeting macrophages owing to their low toxicity and ability to perform tasks such as drug administration [40, 41]. These cells demonstrate high internalization of the inorganic nanoparticles and have garnered significant interest due to their ability to localize tumors [42]. Magnetic nanoparticles have also been evaluated considering their stimuli-responsive nature upon applying a magnetic field. For instance, Ren et al. immobilized lipases on magnetic iron oxide nanoparticles through a polydopamine film using a biomimetic approach based on an *in-situ* coating bio-inspired by the adhesive proteins secreted by marine mussels. Their positive results highlighted the potential for reusing lipases with high activity and stability at varying temperatures and pH levels [43].

Extracellular matrices have also been addressed, involving the organic–inorganic interface, which aids in the nucleation and growth of hydroxyapatite nanoparticles. Organic matrices contribute to nanoparticle morphology, function, and self-assembled architecture. The use of biomimetic matrices has demonstrated enhanced drug release efficiency and biocompatibility [44]. Other works have explored developing drug delivery systems based on biomimetic red blood cell membrane-coated nanoparticles. Zhang et al. prepared nanoparticles of uniform size and core–shell structure, which showed prolonged in vivo circulation and highly active targeting toward human liver cancer cells through endocytosis mediated by the folic acid receptor. Additionally, the system demonstrated efficient tumor-killing activity by generating singlet oxygen [45].

Furthermore, biomimetic applications have also reached vaccine delivery, as presented in Table 1, gaining interest since 2015. The potential transformative character of nanotechnological techniques stands out as promising strategies for developing nanovaccines (*i.e.*, comprising nanoparticles ranging from 50 to 250 nm to deliver antigens and other

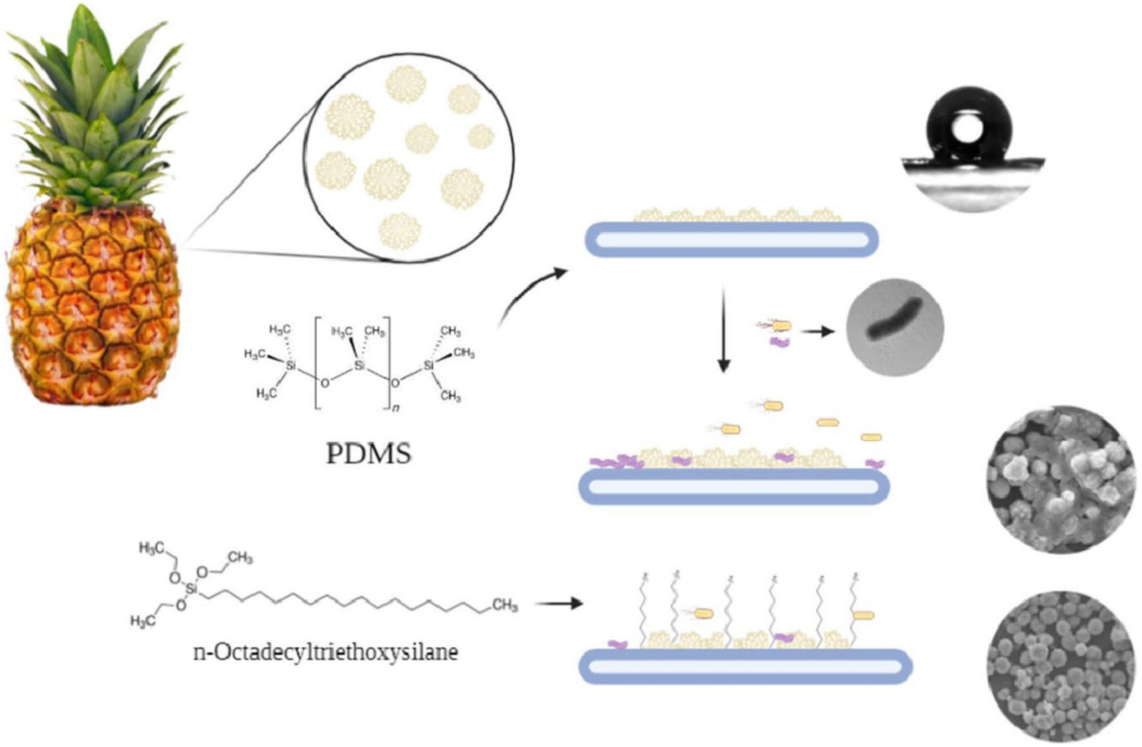

Fig. 3 Spin-coated biogenic silica rosette (BSR) film on polydimethylsiloxane (PDMS) increased the roughness of PDMS film and its water repellency while decreasing the *Escherichia coli* (*E. coli*) bacteria adhesion. Functionalization of the BSR with octadecyltrietoxysilane yields superhydrophobicity, further decreasing bacteria adhesion. Reproduced with permission from Castro-Mora et al. (2022, Copyright Elsevier) [32]

immunomodulatory agents) containing biomimetic nanoparticles as versatile approaches for immunization. These biomimetic nanovaccines possess robust antigenic and immunostimulatory properties, which can contribute to future vaccine designs to create multifunctional nanosystems containing multiple antigens [46]. Noteworthily, their development is being investigated, especially for anticancer [47] and antiviral [48] purposes.

As mentioned, conventional nanoparticles require surface modification to avoid clearance by the MPS, which the decoration and functionalization of biological components can achieve. These bio-engineered nanoparticles are not only able to target the delivery of antigens and adjuvants to antigen-presenting cells, such as dendritic cells (DCs), but also mimic their antigen-presenting function [56] and reduce off-target effect [47]. The activation of DCs and stimulation of T-cells are especially relevant for cancer immunotherapy [57]. Biomimetic nanosystems have demonstrated a suitable safety profile and improvement of the immune response, overcoming conventional subunit formulations' known limitations (*e.g.*, viral vector, attenuated organisms). This application's most relevant emerging platforms are cell membrane-coated nanoparticles, exosome-based nanoparticles, and albumin-binding nanovaccines [58, 59].

Virus-infectious diseases are under the scope of biomimetic nanovaccines, given the high risk represented by the outbreak of a novel pathogen [60]. Virosome-based nanovaccines represent bioinspired nanocarriers as their surface is modified with relevant viral fusion proteins (*i.e.*, antigens) that interact with the targeted cell receptors and promote internalization by endocytosis, leading to a humoral or cellular immune response. This system is currently employed to develop a vaccine against SARS-CoV-2 by the European MI Matrix company [61]. Besides virosomes, other potential vehicles for developing biomimetic nanovaccines against SARS-CoV-2 include lipid nanoparticles, protein nanoparticles, and virus-like particles [62]. A study by Zhang et al. highlights the development of nanosponges derived from human cell membranes to inhibit SARS-CoV-2 infectivity. These nanosponges consist of polymeric nanoparticle cores enveloped by cell membranes from lung epithelial cells and macrophages. The design enables the nanosponges to display surface antigens, acting as decoys for SARS-CoV-2 binding and potentially neutralizing the virus [63].

In addition to drug delivery, biomimetic approaches have been employed in tissue engineering, aiming to mimic the native structure and function of tissues and organs. This involves using biological scaffolds made from proteins, such as collagen and elastin, or polysaccharides, like chitin and alginate, which offer biodegradability and biocompatibility [59]. By incorporating these materials into 3D structures that emulate the natural extracellular matrix, researchers can create environments that promote cellular growth, differentiation, and tissue regeneration, as shown in Fig. 5. [64, 65].

Diagnostic tools have also benefited from biomimetic advancements. For example, biosensors incorporating biological recognition elements, such as enzymes, antibodies, or nucleic acids, can detect and quantify specific target molecules in complex biological samples. These biomimetic sensors offer improved sensitivity, specificity, and rapid response times

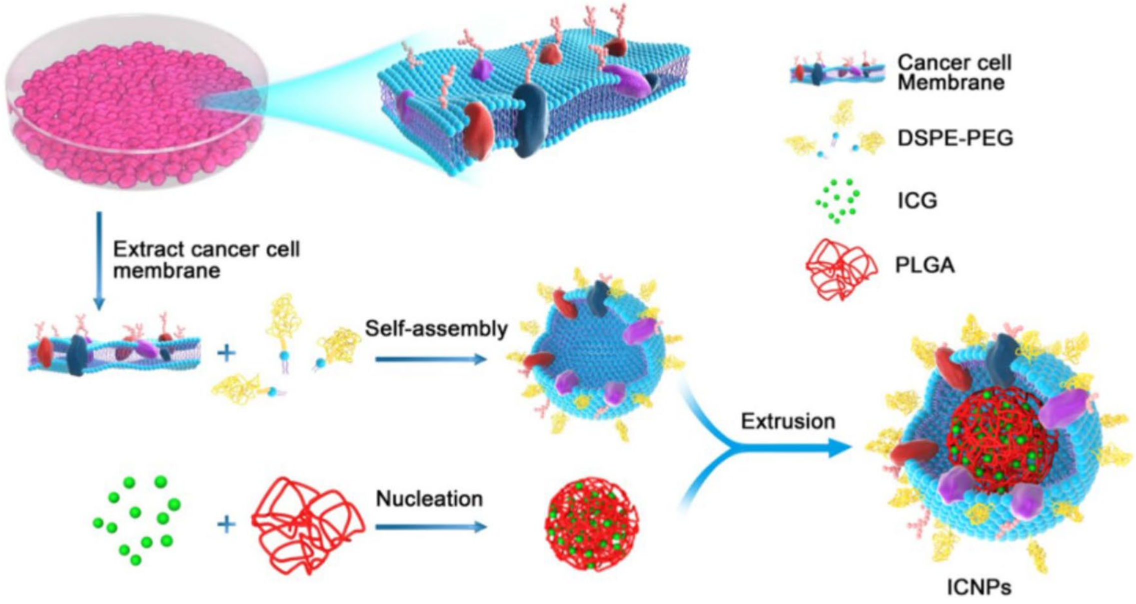

Fig. 4 Preparation of indocyanine green-loaded cancer cell membrane-camouflaged nanoparticles (ICNPs) via extrusion of self-assembled PEGylated phospholipids (DSPE-PEG) with cancer cell membranes and nucleated indocyanine green (ICG) in poly(lactic-co-glycolic acid) (PLGA). Reprinted with permission from Chen et al. (Copyright American Chemical Society 2016) [37]

compared to conventional diagnostic methods [66, 67]. In summary, biomimetic applications as therapeutics are vast and varied, potentially revolutionizing healthcare by offering more effective therapies, innovative tissue engineering solutions, and advanced diagnostic tools. As research in this field progresses, we can expect even more groundbreaking discoveries and developments.

5 Biomimicry from animals

Mosquitoes possess a bundle with an internal radius of less than 15 µm [68], though dimensions may vary among species. By leveraging the unique characteristics of mosquito bites, researchers could develop micro-sized needles that offer improved ease of use and aesthetics. The pain associated with injections typically increases with penetration depths greater than 15 mm and larger needle diameters. In contrast, microneedles have a diameter between 40 and 100 µm and a submicron tip radius, making them less painful [69, 70], which could transform the medical treatment experience. For instance, Terashima and coworkers fabricated a biodegradable microneedle with a diameter of 100 microns and 1 mm in length using polylactic acid sheets via thermal nanoimprint [70]; the resistance force during insertion was similar to that of a 0.18 mm-diameter commercial stainless needle and was proven to penetrate the skin and blood vessel of a mouse, showing its plausibility for medical use. As research continues, we can anticipate further advancements in biomimetic needle technology, enhancing patient comfort and revolutionizing the administration of injectable medications.

In another example, researchers have examined octopus tentacles' unique structure and flexibility to design soft robots with enhanced adaptability, agility, and flexibility. These bioinspired robots hold potential for various applications, including search and rescue operations or medical procedures [71]. Additionally, spider silk's remarkable strength and elasticity have spurred the development of biomimetic materials for numerous applications. Inspired by these natural properties, scientists are creating materials for bulletproof vests, medical sutures, and lightweight structural components [72]. With the advent of skin electronics, flexible and stretchable circuitry is under development, which mimics the epidermis and holds great potential for applications in wound healing and tissue repair, as well as integrated, stretchable electronics (such as microfluidics-based sensing). In one such study, Yuk et al. [73] reported synthetic hydrogel-elastomer hybrids with functional microchannels and micropatterns inspired by blood and lymphatic vessels in mammalian skin, applicable to a wide variety of commonly used elastomers and tough hydrogels (Fig. 6).

6 Cellular level biomimetism

There are a variety of biomimetic applications at the cellular level, such as cell membrane coated-nanoparticles as biomimetic drug carriers (Fig. 7). Gaining a deeper understanding of cellular mechanisms or studying smaller particles that may be part of previously unknown interactions could further advance the field of biomimetics. Such research could provide insights into cellular behavior and facilitate the development of novel technologies and therapies based on the biological principles observed in living systems. For instance, the construction of high-order structures by DNA nanotechnology can recreate cell-like structures for temperature-controlled encapsulation and release of guest molecules, and tubular DNA origami nanoreactors are feasible for designing DNA could allow for the modification of certain cellular components and biological processes [74].

Today, studies on the extracellular matrix are gaining traction to understand cellular mechanisms better. The interest in hyaluronic acid in cosmetology stems from the extracellular matrix comprising collagen, elastin, proteoglycans, and glycosaminoglycans. Researchers have developed gelatin-siloxane microspheres synthesized using a unique emulsion technique, mineralized by immersion in a simulated body fluid solution. The precipitated layer proved the formation of hydroxyapatite and hyaluronic acid pullulan hydrogels, where biomimetic hydroxyapatite was incorporated to achieve durability and manufacture a semi-permanent dermal filler [76]. The presence of pullulan contributed to a uniform distribution of micrometric-size particles and the creation of a homogeneous structure. Subsequently, hydroxyapatite increased the storage modulus, viscosity, and mechanical stability.

Osorio et al. have studied bacterial nanocellulose for organ solid structures [77]. They selected a porcine kidney as an animal model to study kidney failure and used biomimetic development to create 3D micro ducts of bacterial nanocellulose. Additionally, they proposed a method to remove epoxy resin from nanocellulose without affecting its properties, which are essential in biomedicine. Research involving eukaryotic and prokaryotic cells has shown developments in nanodevices with titanium surfaces. Cicciù et al. studied titanium surfaces with 50–100 nm tantalum oxide nano

Table 1 Biomimetic-based nanovaccines for immunization against cancer and viral infectious diseases

Nanosystem	Antigen	Disease (model)	Effect	Ref
Virus-like mesoporous silica nanoparticles with inner mesoporous nanospheres loaded with imiquimod	Ovalbumin	Melanoma (B16-OVA tumor cells)	Dendritic cell maturation and incremented presence of CD8$^+$ T cells	[49]
Core–shell chitosan nanoparticles coated with Teleost erythrocyte membrane	Mannose	Spring viremia of carp	Robust adaptive immune responses	[50]
PLA-PEI cationic nanoparticle	Mannan and ovalbumin	Melanoma (B16-OVA), colorectal carcinoma (MC38), and breast cancer (E0771)	Enhanced accumulation in dendritic cells	[51]
Gold nanoparticles	Lipopolysaccharide-assembly protein (LptD)	*Vibrio parahaemolyticus* infection	Induced specific IgG production	[52]
Mesoporous silica nanoparticles encapsulated with cytosine-phosphate-guanine oligodeoxynucleotide (CpG) and coated with SARS-CoV-2 cell membrane	SARS-CoV-2 Receptor-Binding Domain of the spike protein	COVID-19	Strong antibody levels within two weeks after the first dose	[53]
PLGA nanoparticles loaded with R837 (*i.e.*, agonist against toll-like receptor 7)	Antigens expressed in 4T1 cancer cell membrane	Breast cancer (4T1 murine cell line)	Enhanced bone marrow-derived dendritic cell uptake and secretion of interleukin-12	[54]
CpG-mannose PLGA nanoparticles coated with red blood cell membrane	African swine fever virus (ASFV) antigen (p54)	Viral infectious diseases, in general	Evoked CD4$^+$ and CD8$^+$ T cell activation and B maturation	[55]

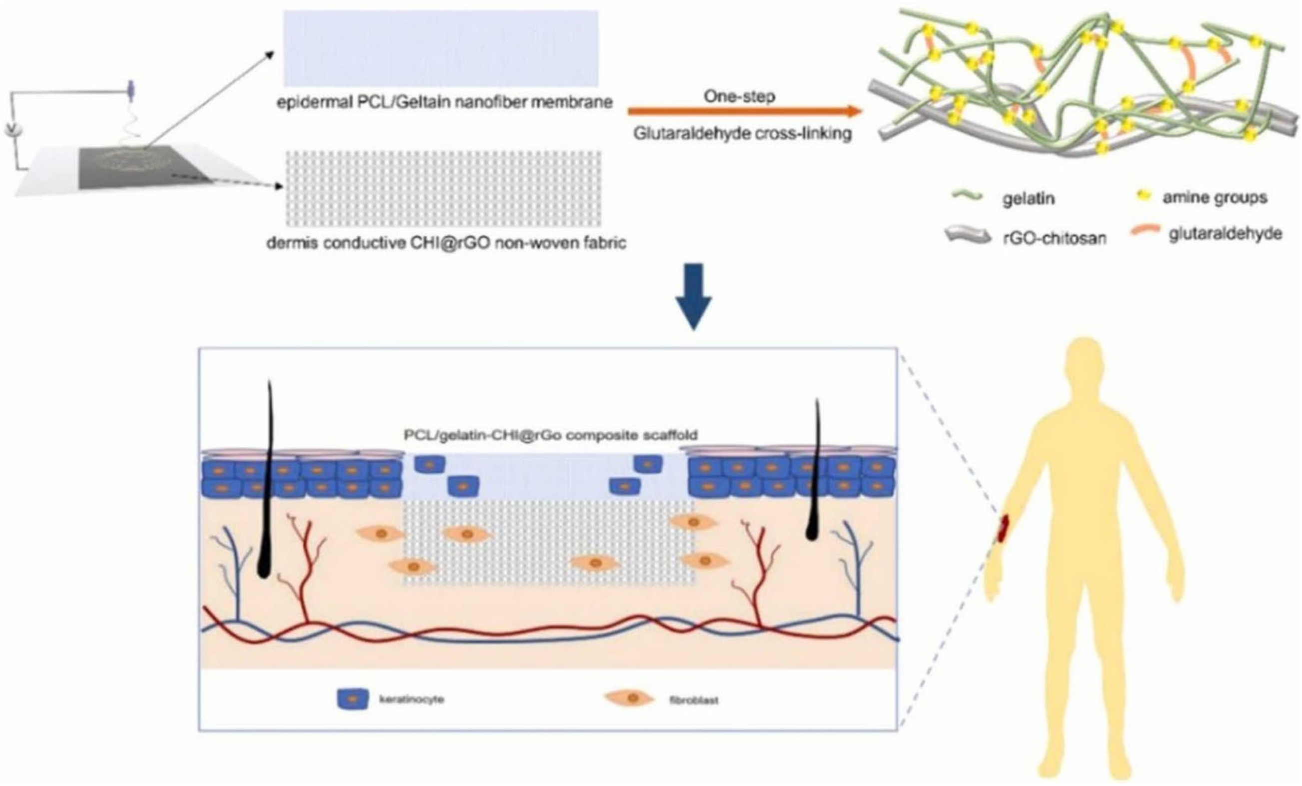

Fig. 5 Diagram of the preparation and grafting of a biomimetic artificial skin scaffold. Reproduced with permission from Song et al. (2023, copyright Elsevier) [65]

points, demonstrating cell viability, which is crucial for regulating transcription factors and genes responsible for bone protein secretion [78]. This nanotopographical characteristic is vital for controlling cell behavior and can be developed for dental implants. Such research encourages further investigation in nanotechnology to promote healing processes and human-body integration.

7 Conclusions

The numerous studies on biomimetic developments in bionanotechnology have extensive implications and potential for large-scale applications. The examples discussed demonstrate the importance of using alternative, bio-inspired approaches to leverage new technologies and drive innovation in various fields. By doing so, we can revolutionize the way we address challenges and develop solutions.

As we continue to explore biomimetic approaches, it is crucial to recognize and address the challenges that may arise in the future. These challenges may include the scalability of biomimetic technologies, ethical considerations, regulatory hurdles, and potential unintended consequences. Addressing these challenges will ensure the safe and effective implementation of biomimetic technologies and foster their widespread adoption and acceptance.

Ultimately, the continued advancement of biomimetics in bionanotechnology has the potential to lead to transformative innovations in areas such as medicine, environmental sustainability, materials science, and engineering, among others. By emphasizing the importance of biomimetics and supporting ongoing research and development, we can unlock the vast potential of these technologies to improve our world.

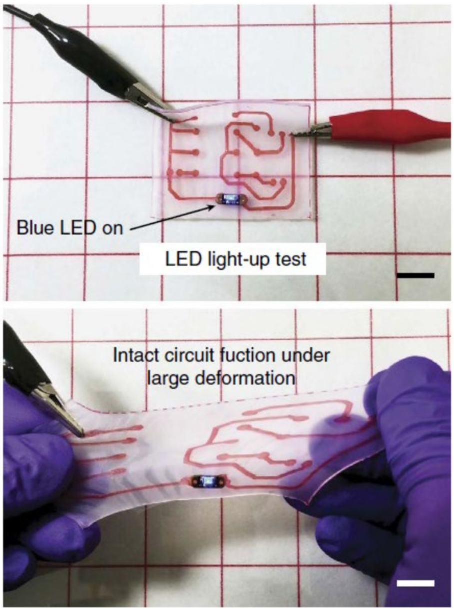

Fig. 6 A stretchable hydrogel circuit board, bioinspired on the flexibility of mammalian skin, patterned on an elastomer connected to an AC power source, can light up an LED and maintain its electrical functionality even under severe deformation. Reproduced from Yuk et al. (2016) under the terms of the CC BY license [73]

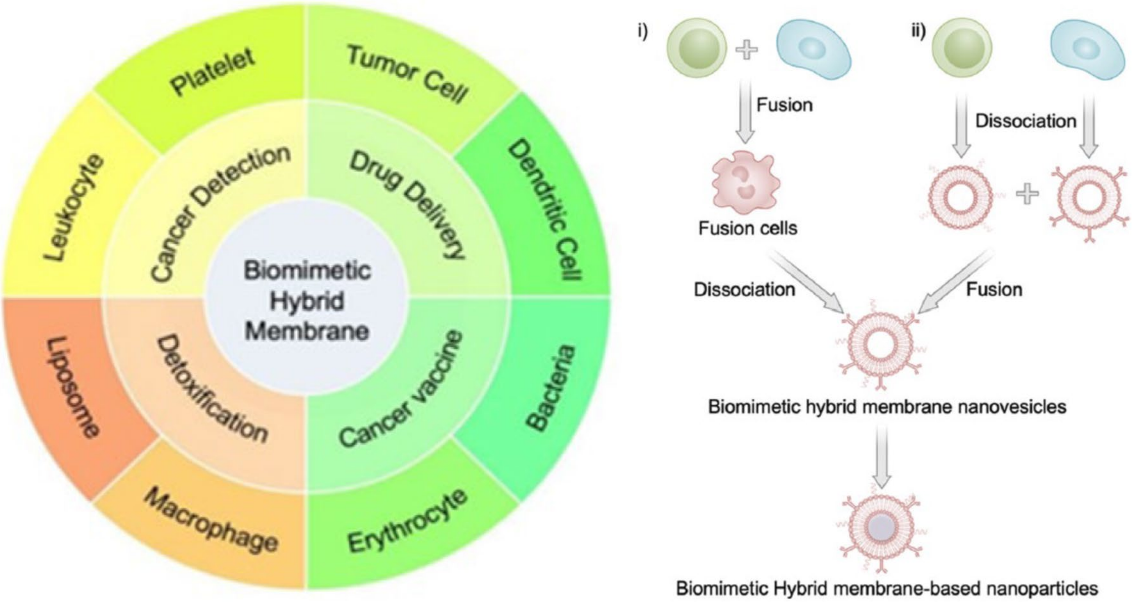

Fig. 7 Left: The origins of biomimetic hybrid membrane-based nanoplatforms (BHMNs) are shown in the outer circle, and the applications are classified by their membrane origins. Right: Synthetic strategies for BHMNs: i) membrane fusion before membrane extraction and ii) membrane extraction before membrane fusion. Reproduced with permission from Liao et al. (Copyright Royal Society of Chemistry, 2020) [75]

Acknowledgements We acknowledge the helpful comments from the peer-review stage.

Author contributions SP and JV were responsible for writing the manuscript, while the corresponding author JV was responsible for conceptualizing the ideas, and DB, MC, and LC all made suggestions. All authors edited and approved the final manuscript.

Funding Not applicable.

Data availability The dataset supporting this review article is included in all the cited articles.

Declarations

Ethics approval and consent to participate Ethics approval is not applicable.

Consent for publication We have included seven figures (Figs. 1 to 7) from previously published literature with required copyright permission from the copyright owners. We have mentioned this in the manuscript with appropriate citations.

Competing interests The authors declare no competing interests.

References

1. Breslow BR. Centenary lecture, biomimetic chemistry. Chem Soc Rev. 1972;1(4):553–80. https://doi.org/10.1039/CS9720100553.
2. Vallet RM, Arcos D. Biomimetic Nanoceramics in Clinical Use: From Materials to applications. In Royal Society of Chemistry, 2016.
3. ISO 18458:2015(en): Biomimetics — Terminology, concepts, and methodology: https://www.iso.org/obp/ui/#iso:std:iso:18458:ed-1:v1:en
4. Bhushan B. Frontiers in nanotribology: magnetic storage, bio/nanotechnology, cosmetics, and bioinspiration. J Colloid Interface Sci. 2020;577:127–62. https://doi.org/10.1016/j.jcis.2020.05.040.
5. Speck O, Speck T. An overview of bioinspired and biomimetic self-repairing materials. Biomimetics. 2019;4(1):26. https://doi.org/10.3390/biomimetics4010026.
6. Aish A, Sun JS. Bioinspire-museum: scoping paper. Paris: Muséum national d'Histoire naturelle; 2020. p. 1–14.
7. Dicks H. Environmental ethics and biomimetic ethics: nature as object of ethics and nature as source of ethics. J Agric Environ Ethics. 2017;30:255–74. https://doi.org/10.1007/s10806-017-9667-6.
8. Benyus JM. Biomimicry: innovation inspired by nature. HarperCollins e-books. 2022; 1–344.
9. Blok V, Gremmen B. Ecological innovation: biomimicry as a new way of thinking and acting ecologically. J Agric Environ Ethics. 2016;29:203–17. https://doi.org/10.1007/s10806-015-9596-1.
10. Holy-Luczaj M, Blok V. Hybrids and the boundaries of moral considerability or revisiting the idea of non-instrumental value. Philosophy and Technology. 2021;34:223–42. https://doi.org/10.1007/s13347-019-00380-9.
11. Zhou S, Huang Y, Chen Y, Liu S, Xu M, Jiang T, Song Q, Jiang G, Gu X, Gao X, Chen J. Engineering ApoE3-incorporated biomimetic nanoparticle for efficient vaccine delivery to dendritic cells via macropinocytosis to enhance cancer immunotherapy. Biomaterials. 2020;235:119795. https://doi.org/10.1016/j.biomaterials.2020.119795.
12. Narayanan KB, Zo SM, Han SS. Novel biomimetic chitin-glucan polysaccharide nano/microfibrous fungal-scaffolds for tissue engineering applications. Int J Biol Macromol. 2020;149:724–31. https://doi.org/10.1016/j.ijbiomac.2020.01.276.
13. Vasconcellos KB, McHugh SM, Dapsis KJ, Petty AR, Gerdon AE. Biomimetic nanoparticles with polynucleotide and PEG mixed-monolayers enhance calcium phosphate mineralization. J Nanoparticle Res. 2013;15:1942. https://doi.org/10.1007/s11051-013-1942-5.
14. da Silva EE, Della HHM, Ferlauto AS, Moreira RL, Resende RR, Oliveira S, Kitten GT, Lacerda RG, Ladeira LO. Nanostructured 3-D collagen/nanotube biocomposites for future bone regeneration scaffolds". Nano Res. 2019;2:462–73. https://doi.org/10.1007/s12274-009-9042-7.
15. Kratz F. A clinical update of using albumin as a drug vehicle - a commentary. J Controll Release: Off J Controll Release Soc. 2014;190:331–6. https://doi.org/10.1016/j.jconrel.2014.03.013.
16. Gao C, Wang Y, Sun J, Han Y, Gong W, Li Y, Feng Y, Wang H, Yang M, Li Z, Yang Y, Gao C. Neuronal mitochondria-targeted delivery of curcumin by biomimetic engineered nanosystems in Alzheimer's disease mice. Acta Biomater. 2020;108:285–99. https://doi.org/10.1016/j.actbio.2020.03.029.
17. Muñíz, R. Biomimética. Herramientas de Diseño Inspiradas en la Naturaleza. Tekhné. 2017; 20(2). https://revistasenlinea.saber.ucab.edu.ve/index.php/tekhne/article/view/3450
18. Magin CM, Cooper SP, Brennan AB. Non-toxic antifouling strategies. Mater Today. 2010;13(4):36–44. https://doi.org/10.1016/S1369-7021(10)70058-4.
19. Chung KK, Schumacher JF, Sampson EM, Burne RA, Antonelli PJ, Brennan AB. Impact of engineered surface microtopography on biofilm formation of Staphylococcus aureus. Biointerphases. 2007;2(2):89–94. https://doi.org/10.1116/1.2751405.
20. Cordero GJ, Jiménez TG, Paniagua SA. Sub-micron patterning of metal oxide surfaces via microcontact printing and microtransfer molding of amphiphilic molecules and antifouling application. J Mater Res. 2023;38:1573–82. https://doi.org/10.1557/s43578-023-00909-x.

21 Kang JY, Bangoura I, Cho JY, et al. Antifouling effects of the periostracum on algal spore settlement in the mussel Mytilus edulis. Fish Aquat Sci. 2016. https://doi.org/10.1186/s41240-016-0007-y.

22. Almeida M, Reis RL, Silva TH. Marine invertebrates are a source of bioadhesives with biomimetic interest. Mater Sci Eng, C. 2020;108:110467. https://doi.org/10.1016/j.msec.2019.110467.

23. Liu J, Cheng S, Cao N, Geng C, He C, Shi Q, Xu C, Ni J, DuChanois RM, Elimelech M, Zhao H. Actinia-like multifunctional nanocoagulant for single-step removal of water contaminants. Nat Nanotechnol. 2019;1:64–71. https://doi.org/10.1038/s41565-018-0307-8.
24. Yang X, Yan L, Wu Y, Liu Y, Shao L. Biomimetic hydrophilization engineering on membrane surface for highly-efficient water purification. J Memb Sci. 2019;589: 117223. https://doi.org/10.1016/j.memsci.2019.117223.
25. Wang D, Peng H, Yu B, Zhou K, Pan H, Zhang L, Li M, Liu M, Tian A, Fu S. Biomimetic structural cellulose nanofiber aerogels with exceptional mechanical, flame-retardant and thermal-insulating properties. Chem Eng J. 2020;389: 124449. https://doi.org/10.1016/j.cej.2020.124449.
26. Rodríguez LDB. Descripción de las microestructuras superficiales de algunas especies de orquídeas con hidrorepelencia en busca de patrones de estructuras superhidrofóbicas. Lic Dessertation, Universidad de Costa Rica, SJ, Costa Rica, 2016
27. Cerviño P. "Estudio del mecanismo de adhesión de las papilas del gecko. España: Universidad Politécnica de Madrid; 2019.
28. Wang J, Chen H, Sui T, Li A, Chen D. Investigation on the hydrophobicity of lotus leaf: experiment and theory. Plant Sci. 2009;176(5):687–95. https://doi.org/10.1016/j.plantsci.2009.02.013.
29. Koch K, Dommisse A, Barthlott W. Chemistry and crystal growth of plant wax tubules of lotus (Nelumbo nucifera) and nasturtium (Tropaeolum majus) leaves on technical substrates. Cryst Growth Des. 2006;6(11):2571–8. https://doi.org/10.1021/cg060035w.
30 Favret E. Biomimética, tecnología inspirada en la naturaleza. Museo. 2016;28(8):25–32.
31. Corrales-Ureña YR, Bermúdez CV, Pereira R, Camacho M, Estrada E, Argüello MO, Vega-Baudrit JR. Biogenic silica-based microparticles obtained as a sub-product of the nanocellulose extraction process from pineapple peels. Sci Rep. 2018;8(1):10417. https://doi.org/10.1038/s41598-018-28444-4.
32. Castro MM, Vásquez GM, Cordero GJ, Benavides AM, González J, López BMJ, Vega-Baudrit J, Ureña YC. Bacterial anti-adhesive films of PDMS coated with microstructures of biogenic silica rosettes extracted from pineapple peel residues. Surf Interfaces. 2022;30: 101881. https://doi.org/10.1016/j.surfin.2022.101881.
33. Leiro V, Moreno PM, Sarmento B, Durão J, Gales L, Pêgo AP, Barrias CC. 1 - Design and preparation of biomimetic and bioinspired materials, Editor(s): Lígia Rodrigues, Manuel Mota, Bioinspired Materials for Medical Applications, Woodhead Publishing. 2017; 2017: 1-44, ISBN 9780081007419, https://doi.org/10.1016/B978-0-08-100741-9.00001-2.
34. Asha PJ, Chinnu S, Nivitha KP, Renu S, Ameena SVK, Henna TK, Raphey VR, Gangadharappa HV, Sabna K, Pramod K. Bioinspired and biomimetic micro- and nanostructures in biomedicine. J Control Release. 2022;343:724–54. https://doi.org/10.1016/j.jconrel.2022.02.013.
35. Faustino VA, Quirino BCT. Nanomedicina y biomimetismo. Mundo Nano Rev Interdiscip en Nanociencias y Nanotecnología. 2015. https://doi.org/10.22201/ceiich.24485691e.2014.12.49708.
36. Miguel I, Ioualalen K, Bonnefous M, Peyrot M, Nguyen F, Cervilla M, Soulet N, Dirson R, Rieumajou V, Imbertie L. Synthesis and characterization of supramolecular biovector (SMBV) specifically designed for the entrapment of ionic molecules. Biochim Biophys Acta. 1995;1237:49–58. https://doi.org/10.1016/0005-2736(95)00079-i.
37. Chen Z, Zhao P, Luo Z, Zheng M, Tian H, Gong P, Gao G, Pan H, Liu L, Ma A, Cui H, Ma Y, Cai L. Cancer cell membrane-biomimetic nanoparticles for homologous-targeting dual-modal imaging and photothermal therapy. ACS Nano. 2016;10(11):10049–57. https://doi.org/10.1021/acsnano.6b04695.
38. Lee J, Min HS, You DG, Kim K, Kwon IC, Rhim T, Lee KY. Theranostic gas-generating nanoparticles for targeted ultrasound imaging and treatment of neuroblastoma. J Control Release. 2016;223:197–206. https://doi.org/10.1016/j.jconrel.2015.12.051.
39. Castillo HL, Sanabria EP, Murillo CB, Vásquez GM, Menezes DB, Calvo GB, Ramírez AN, Vega-Baudrit J. Topical chitosan-based thermo-responsive scaffold provides dexketoprofen trometamol controlled release for 24 h use. Pharmaceutics. 2021;13:2100. https://doi.org/10.3390/pharmaceutics13122100.
40 Liu XY, Jing QW, Charles RA, Leli Z, Ying FF, Zhe SC. Gold nanoparticles: synthesis, physiochemical properties and therapeutic applications in cáncer. Drug Discov Today. 2021;26:1284–92. https://doi.org/10.1016/j.drudis.2021.01.030.
41. Alshahrani MY, Ibrahim EH. Gold nanoparticles (AuNPs) and Rosmarinus officinalis extract and their potentials to prompt apoptosis and arrest cell cycle in HT-29 colon cancer cells. J King Saud Univ-Sci. 2022;34(8):102304. https://doi.org/10.1016/j.jksus.2022.102304.
42 Kang SH, Lee YK, Park IS, Park IK, Hong SM, Kwon SY, Choi YH, Madsen SJ, Hirschberg H, Hong SJ. Biomimetic Gold Nanoshell-Loaded Macrophage for Photothermal Biomedicine. Biomed Res Int. 2020. https://doi.org/10.1155/2020/5869235.
43. Ren Y, Rivera JG, He L, Kulkarni H, Lee DK, Messersmith PB. Facile, high-efficiency immobilization of lipase enzyme on magnetic iron oxide nanoparticles via a biomimetic coating. BMC Biotechnol. 2011;11:63. https://doi.org/10.1186/1472-6750-11-63.
44. Sheikh L, Tripathy S, Nayar S. Biomimetic matrix mediated room temperature synthesis and characterization of nano-hydroxyapatite towards targeted drug delivery. RSC Adv. 2016;6:62556–71. https://doi.org/10.1039/c6ra06759j.
45. Zhang C, Zhang PQ, Guo S, Chen G, Zhao Z, Wang GX, Zhu B. Application of biomimetic cell-derived nanoparticles with mannose modification as a novel vaccine delivery platform against teleost fish viral disease. ACS Biomater Sci Eng. 2020;6:6770–7. https://doi.org/10.1021/acsbiomaterials.0c01302.
46. Huang L, Rong Y, Pan Q, Yi K, Tang X, Zhang Q, Wang W, Wu J, Wang F. SARS-CoV-2 vaccine research and development: conventional vaccines and biomimetic nanotechnology strategies. Asian J Pharm Sci. 2021;16(2):136–46. https://doi.org/10.1016/j.ajps.2020.08.001.
47. Chen F, Wang Y, Gao J, Saeed M, Li T, Wang W, Yu H. Nanobiomaterial-based vaccination immunotherapy of cancer. Biomaterials. 2021;270: 120709. https://doi.org/10.1016/j.biomaterials.2021.120709.
48. Mittal D, Ali SA. Use of nanomaterials for diagnosis and treatment: the advancement of next-generation antiviral therapy. Microb Drug Resist. 2022;28:670–97. https://doi.org/10.1089/mdr.2021.0281.
49. Gao Y, Zhang Y, Xia H, Ren Y, Zhang H, Huang S, Li M, Wang Y, Li H, Liu H. Biomimetic virus-like mesoporous silica nanoparticles improved cellular internalization for co-delivery of antigen and agonist to enhance tumor immunotherapy. Drug Delivery. 2023;30:2183814. https://doi.org/10.1080/10717544.2023.2183814.
50. Zhang Y, Ma N, Luo C, Zhu J, Bao C. Photosensitizer-loaded cell membrane biomimetic nanoparticles for enhanced tumor synergetic targeted therapy. RSC Adv. 2020;10:9378–86. https://doi.org/10.1039/c9ra08926h.
51. Xu Y, Ma S, Zhao J, Chen H, Si X, Huang Z, Yu Z, Song W, Tang Z, Chen X. Mannan-decorated pathogen-like polymeric nanoparticles as nanovaccine carriers for eliciting superior anticancer immunity. Biomaterials. 2022;284: 121489. https://doi.org/10.1016/j.biomaterials.2022.121489.

52 Aguilera JA, Hernández AL, Ruíz GMÁ, Monreal EE, Reyes BM, Rosales MS, Pereyra HGS, Angulo C. LptD-antigen system on gold nanoparticles: an innovative strategy in the nanovaccine development. Nanotechnology. 2022;33:295602. https://doi.org/10.1088/1361-6528/ac659b.

53. Chen X, Shi T, Yang C, Chen F, He X, Zhang K, Hu H, Cai L, Leong KW, Shao D. Scalable biomimetic SARS-CoV-2 nanovaccines with robust protective immune responses. Signal Transduct Target Therapy. 2022;7:96. https://doi.org/10.1038/s41392-022-00942-y.

54. Xiao L, Huang Y, Yang Y, Miao Z, Zhu J, Zhong M, Feng C, Tang W, Zhou J, Wang L, et al. Biomimetic Cytomembrane Nanovaccines Prevent Breast Cancer Development in the Long Term. Nanoscale. 2021;13:3594–601. https://doi.org/10.1039/d0nr08978h.

55. Huo J, Zhang A, Wang S, Cheng H, Fan D, Huang R, Wang Y, Wan B, Zhang G, He H. Splenic-targeting biomimetic nanovaccine for elevating protective immunity against virus infection. J Nanobiotechnol. 2022;20:514. https://doi.org/10.1186/s12951-022-01730-0.

56. Hashemi GN, Nemati M, Bakhshandeh A, Arashkia A, Negahdari B. Nanovaccines for cancer immunotherapy: focusing on complex formation between adjuvant and antigen. Int Immunopharmacol. 2023;117: 109887. https://doi.org/10.1016/j.intimp.2023.109887.

57. Meng L, Teng Z, Yang S, Wang N, Guan Y, Chen X, Liu Y. Biomimetic nanoparticles for DC vaccination: a versatile approach to boost cancer immunotherapy. Nanoscale. 2023;15:6432–55. https://doi.org/10.1039/d2nr07071e.

58. Wang Q, Wang Z, Sun X, Jiang Q, Sun B, He Z, Zhang S, Luo C, Sun J. Lymph node-targeting nanovaccines for cancer immunotherapy. J Control Release. 2022;351:102–22. https://doi.org/10.1016/j.jconrel.2022.09.015.

59. Meng Z, Zhang Y, Zhou X, Ji J, Liu Z. Nanovaccines with cell-derived components for cancer immunotherapy. Adv Drug Deliv Rev. 2022;182: 114107. https://doi.org/10.1016/j.addr.2021.114107.

60. Nasrollahzadeh M, Sajjadi M, Soufi GJ, Iravani S, Varma RS. Nanomaterials and nanotechnology-associated innovations against viral infections with a focus on coronaviruses. Nanomaterials (Basel). 2020;10:1072. https://doi.org/10.3390/nano10061072.

61. Asadi K, Gholami A. Virosome-BASED NANOVACCINES; A PROMISING BIOINSPIRATION AND BIOMIMETIC APPROACH FOR PREVENTING VIRAL DISEASES: A REview. Int J Biol Macromol. 2021;182:648–58. https://doi.org/10.1016/j.ijbiomac.2021.04.005.

62. Li S, Liu X, Liu G, Liu C. Biomimetic nanotechnology for SARS-CoV-2 treatment. Viruses. 2023;15:596. https://doi.org/10.3390/v15030596.

63. Zhang Q, Honko A, Zhou J, Gong H, Downs SN, Vasquez JH, Fang RH, Gao W, Griffiths A, Zhang L. Cellular nanosponges inhibit SARS-CoV-2 infectivity. Nano Lett. 2020;20(7):5570–4. https://doi.org/10.1021/acs.nanolett.0c02278.

64. Prerana S, Auhin KM, Savita S, Beena R, Sri S. Biomimetic algal polysaccharide coated 3D nanofibrous scaffolds promote skin extracellular matrix formation. Mater Sci Eng, C. 2021;119:111580. https://doi.org/10.1016/j.msec.2020.111580.

65 Song Z, Jiajun W, Shaojie T, Jing G, Lu W. Conductive biomimetic bilayer fibrous scaffold for skin regeneration. Colloids Surf, A. 2023;656:130211. https://doi.org/10.1016/j.colsurfa.2022.130211.

66. Zhao Y, Danqun H, Jing B, Mei Y, Mei C, Jingzhou H, Huanbao F, Changjun H. Biosensor based on 3D graphene-supported Fe3O4 quantum dots as biomimetic enzyme for in situ detection of H2O2 released from living cells. Sens Actuators, B Chem. 2017;244:1037–44. https://doi.org/10.1016/j.snb.2017.01.029.

67 Yoshimatsu K. Biosensors: biomimetic sensors. Encycl Sens Biosens, Elsevier. 2023;1:393–404. https://doi.org/10.1016/B978-0-12-822548-6.00088-1.

68. Ramasubramanian MK, Barham OM, Swaminathan V. Mechanics of a mosquito bite with applications to microneedle design. Bioinspir Biomim. 2008;3(4): 046001. https://doi.org/10.1088/1748-3182/3/4/046001.

69. Queiroz MB, Shanmugam S, Santos LNS, Campos CA, Santos AM, Batista MS, Araujo AAS, Serafini MR. Microneedles as an alternative technology for transdermal drug delivery systems: a patent review. Expert Opin Ther Pat. 2020;30(6):433–52. https://doi.org/10.1080/13543776.2020.1742324.

70. Terashima S, Tatsukawa C, Suzuki M, Takahashi T, Aoyagi S. Fabrication of microneedle using poly lactic acid sheets by thermal nanoimprint. Precis Eng. 2019;59:110–9. https://doi.org/10.1016/j.precisioneng.2019.05.015.

71 Laschi C, Mazzolai B, Cianchetti M. Soft robotics: technologies and systems pushing the boundaries of robot abilities. Sci Robot. 2016;1(1):eaah3690. https://doi.org/10.1126/scirobotics.aah3690.

72. Vollrath F, Knight DP. The liquid crystalline spinning of spider silk. Nature. 2001;410(6828):541–8. https://doi.org/10.1038/35069000.

73. Yuk H, Zhang T, Parada GA, Liu X, Zhao X. Skin-inspired hydrogel-elastomer hybrids with robust interfaces and functional microstructures. Nat Commun. 2016;7:12028. https://doi.org/10.1038/ncomms12028.

74. Shen H, Wang Y, Wang J, Li Z, Yuan Q. Emerging biomimetic applications of DNA nanotechnology. ACS Appl Mater Interfaces. 2019;11(15):13859–73. https://doi.org/10.1021/acsami.8b06175.

75. Liao Y, Zhang Y, Blum NT, Lin J, Huang P. Biomimetic hybrid membrane-based nanoplatforms: synthesis, properties and biomedical applications. Nanoscale Horizons. 2020;5:1293–302. https://doi.org/10.1039/d0nh00267d.

76. Ghorbani F, Zamanian A, Behnamghader A, Daliri JM. Bioactive and biostable hyaluronic acid-pullulan dermal hydrogels incorporated with biomimetic hydroxyapatite spheres. Mater Sci Eng, C. 2020;112: 110906. https://doi.org/10.1016/j.msec.2020.110906.

77. Osorio M, Martinez E, Kooten TV, Gañán P, Naranjo T, Ortiz I, Castro C. Biomimetics of microducts in three-dimensional bacterial nanocellulose biomaterials for soft tissue regenerative medicine. Cellulose. 2020;27:5923–37. https://doi.org/10.1007/s10570-020-03175-w.

78. Cicciù M, Fiorillo L, Herford AS, Crimi S, Bianchi A, D'Amico C, Laino L, Cervino G. Bioactive titanium surfaces: interactions of eukaryotic and prokaryotic cells of nanodevices applied to dental practice. Biomedicines. 2012;7(1):12. https://doi.org/10.3390/biomedicines7010012.