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Review

Emerging trends in advanced biomimetic composite materials inspired by biological structures and functions in nature

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Abstract: The integration of artificial intelligence (AI) into the design of bioinspired materials offer optimization and generation of new structures and properties of composite materials. The fascinating ability of animals and plants to create complex structures, optimized naturally over millions of years, makes them a subject of interest for scientists, especially in the field of biomimetics. Biomimetics is an interdisciplinary science that draws inspiration from nature to produce new materials and structures, including biocomposites. Bioinspired composites are considered next-generation materials because they can be manufactured using natural ingredients, ensuring sustainable development. The potential of bioinspired materials is used in many sectors, such as biomedical, energy, clothing, aerospace, automotive, and sports. Here, we aim to review the recent progress of works related to biomimetic nature-inspired functional materials. This review is divided into several sections covering achievements in the following fields: Honeycomb-inspired sandwich composite structures, composite materials mimicking the behavior of insect cuticles, self-healing structures, impact-resistant materials, and bioinspired materials with special properties. Emerging trends and current achievements have been broadly reviewed. Our aim of this review is to discuss the latest achievements in the field of biomimetic nature-inspired biomaterials in terms of design and inspirational sources that highlight the current trends. In the discussion, we evaluate future implications of nature-inspired materials and the potential benefits that may arise in their development using generative AI.

Keywords: biomaterials; nature-inspired materials; biomimetics; biocomposites; biological strustures

1. Introduction

Since the beginning of civilization, people have been inspired by the natural world, which contains many optimixed solutions that can become an inspiration for new materials and new technologies. By observing living organisms, humans have created new materials and technologies inspired by the way they move, locate, and self-repair. For instance, the inspiration of birds and the shape of seeds carried by the wind resulted in the development of aerodynamic structures [1,2]. Moreover, nature is capable of building extraordinary materials and molecular objects, such as minerals, bones, or muscle fibers. New materials, such as composites and nanocomposites, are produced to imitate specific properties and functions of nature-inspired materials. A special area of application of bionically inspired materials is surface structures; from liquid-transporting surfaces and through friction-reducing to self-cleaning surfaces [3]. The base material can be natural (e.g., biopolymer such as protein, cellulose) or synthetic (plastics) and contain organic and inorganic components. Research on bioinspired materials for biotechnology enables the large-scale replacement of conventional materials with renewable resources, thus making industrial processes more cost-effective and ecological [4]. Biomaterials obtained from renewable raw materials, the creation of which is inspired by nature, are used in areas as diverse as medicine and biomedicine, aerospace and automotive industry, agriculture, environmental protection, and electronics [5,6].

Biomimetics is a field of science that is a promising method for the synthesis of materials. Reproduction of the mechanisms of production of living materials or at least their structure must enable obtaining materials with similar properties. Nature has the ability to design materials adapted to satisfy different purposes simultaneously. For example, spiders of the species *Nephila clavipes* produce threads with different properties, depending on the composition of proteins, the task of which is to capture prey, scaffold for movement, and protect eggs [7]. Biomimetics consists of reproducing solutions that occur in nature: Structures, processes, behaviors, and shapes. The reproduction of biomaterials in laboratory conditions (development of production technology) requires precise knowledge of their structure, chemical composition, and structure both on macro and micro scales [7].

Currently, the greatest beneficiary of bioinspired materials is biomaterial implantation. An important feature of biomaterials is their biocompatibility with the body, that is, lack of toxicity and impact on the immune system. Biomaterials can be substances of natural origin, such as proteins, peptides, or polysaccharides, or synthetic products: Polymers, ceramic materials, and their composites [8]. They can be used as modern dressing materials or intelligent implants used in tissue engineering (including scaffolds for tissue cultures, artificial tendons, ligaments, bone cement, heart valves, bypasses, or stents). They can be used to make surgical materials (e.g. threads, screws, drains, catheters, endotracheal tubes) [8]. Genome editing enables targeted modification of bacterial cultures, which can then produce special enzymes to combine inorganic materials with organic ones [9]. Lu et al. [10] developed an enzyme for bioinspired recycling of poly(ethylene terephthalate). Other applications of materials and natural phenomena include enzymes that decay textiles from mycelium, synthetic laboratory leather, genetically modified bacteria using collagen as a starting material, and superwood. Superwood, with increased hardness and strength, is a new material created by the removal of hemicellulose and subsequent hot pressing. This process causes the natural cell walls to collapse, and special nanofibers are created from the cellulose [11]. Laboratory leather is produced using genetically modified yeast cells that produce liquid collagen, which is then shaped and finished in a simplified and environmentally friendly tanning process [12]. The interwoven fibers of the mycelium are very similar to plastics made from fossil polymers and externally resemble expanded polystyrene. A future application of mycelium is flexible printed circuit boards that could contribute to sustainable electronics. Furthermore, bacteria can overcome the resistance of plastics to biodegradation [13].

The increasing concerns about the environment and health have led, in the last decade, to more sustainable production methods and reduced energy consumption, which in turn contributes to the use of lighter structures [14,15]. Materials from renewable sources are being sought to replace not only the reinforcement phase but also the matrix of composite materials. The reinforcement phase can be made from plant fibers such as cotton, flax, hemp, and the like, or fibers from recycled wood [16,17]. Bioinspired polymeric and ceramic materials are increasingly used in innovative vehicle designs, showing great potential in increasing their energy efficiency due to lower weight and reduced aerodynamic drag, contributing to the sustainability of the supply chain [18–21].

The matrix can be polymers of natural origin, such as starch and vegetable oils [22]. The current state of biopolymer technology means that synthetic thermoplastics and thermosetting plastics dominate the commercial production of biocomposites; for example, in wood–plastic composites (WPCs), polypropylene, polyvinyl chloride, and polyethylene are used as the matrix [23]. Vegetable oils modified to produce cross-links are used, to a small extent, for the production of biocomposites. Epoxidized vegetable oils used with isocyanates and acrylics are the basis of the emerging thermosetting biopolymer industry. Currently, it is not possible to completely eliminate synthetic substances in the matrix, but research is being carried out to maximize natural substances in biocomposites [24,25]. Natural rubber, cereal proteins, starch, polyhydroxyalkanoates, and polylactic acid are considered potential thermoplastic biopolymers [22,26]. Techniques for manufacturing bioinspired composites are based on traditional composite and plastic processing techniques, such as injection molding, extrusion, hand lay-up, pressing, and filament winding [27].

Designing new materials requires high computing power and efficient algorithms. By integrating artificial intelligence (AI) into the design of biomimetic composite materials, the design processes of new structures can be accelerated. Using machine learning algorithms, AI systems can analyze large amounts of data, generate concepts and prototypes, and optimize design parameters. AI-generated bioinspired materials have emerged as a transformative approach in materials science. AI is the ability of machines to learn and perform tasks on large data sets [28,29]. Basic AI methods include deep learning algorithms, Natural Language Processing (NLP), artificial neural networks, digital twins, genetic algorithms, large language models (LLMs), machine learning, and many others [30–32]. AI enables the generation and analysis of novel structures based on natural structures that have been optimized over thousands of years of evolution. AI can radically accelerate the discovery of materials necessary for the development of next-generation ecological technologies [33–35]. The integration of AI with intelligent materials can lead to the creation of autonomous systems that will independently optimize production processes, as well as predict and adapt to changing conditions [36,37]. Thanks to advanced algorithms, we can predict how a given material will behave in different conditions, which enables better matching to the needs of the project [38,39]. In the context of sustainable development of materials technologies, it is necessary to take into account the sustainable acquisition of raw materials necessary for the production of intelligent materials as well as the impact of the disposal of intelligent materials on the environment [40]. In recent years, the Digital Twins (DTs) approach has been rapidly developing, integrating the Internet of Things (IoT) and AI [41,42]. DT is a virtual model of a real process, material, or product that facilitates testing, optimization, and simulation of the behavior of structures in complex operating conditions.

The literature includes review articles on nature-inspired designs in wind energy (2024) [2], advances in composites for specific applications (2023) [43], mechanical properties of fiber-reinforced composites with bio-inspired helicoidal lay-ups (2024) [44], bio-inspired life-like motile materials (2022) [45], impact-resistant biological and bio-inspired materials (2020) [46], bio-inspired damage-tolerant materials (2024) [47], biomimetic composite materials toward efficient mobility (2021) [20], natural fibers and their composites (2023) [16], and natural fiber reinforced composites (2021) [17]. These articles present, in detail, selected aspects of the structure, fabrication, and applications of selected bio-inspired materials. Our aim of this article is to present a broad view of bio-inspired composite materials with a tabular presentation of the most interesting results based on a review of research papers from 2020–2025.

The degree of similarity between man-made composites and biological structures depends, in particular, on the hierarchy and morphology of the fibrous components, which include nanostructuring as a result of self-assembly. Here, we present biological structures that can serve as an inspiration for the production of bioinspired composites for various purposes, including self-healing structures and impact resistant composites. Current examples of bioinspiration in the production of composite materials inspired by biological structures are presented. In Chapter 2, we present the results of searching selected bibliographic databases and analyzing the results using VosViewer. Achievements in the production of honeycomb-inspired sandwich composite structures are provided in Chapter 3. Characterization of composite materials imitating the behavior of insect and plant cuticles is presented in Chapter 4. The characteristics of auxetic bio-inspired structures are provided in Chapter 5. In Chapters 6 and 7, we present achievements in the production of ceramic composites and composites with special properties, in particular structures with anti-fogging properties, shading systems of building facades, multidimensional biomimetic materials, shape-morphing systems, and nature-inspired methods of surface modification of composites. In Chapter 8, we present a discussion on the use of artificial intelligence in the design of biomimetic materials. The current trends and important factors that should be taken into account in future studies on nature-inspired structures and materials are included in the conclusions section.

2. Methods

A search was conducted in selected bibliographic databases Web of Science (WoS) Core Collection, SCOPUS, and PubMed using the following keywords: ‘nature-inspired composites’, ‘bioinspired composites’, or ‘bio-inspired composites’, and ‘biomimetic composites’. The scope of the review was limited to the last 10 years and the first two months of 2025. In the SCOPUS, the criterion ‘article title, abstract, and keywords’ were selected. Alternatively, the available search option ‘all fields’ was used in the WoS Core Collection database. The variable numbers of articles thematically related to nature-inspired composites are presented in Figure 1.

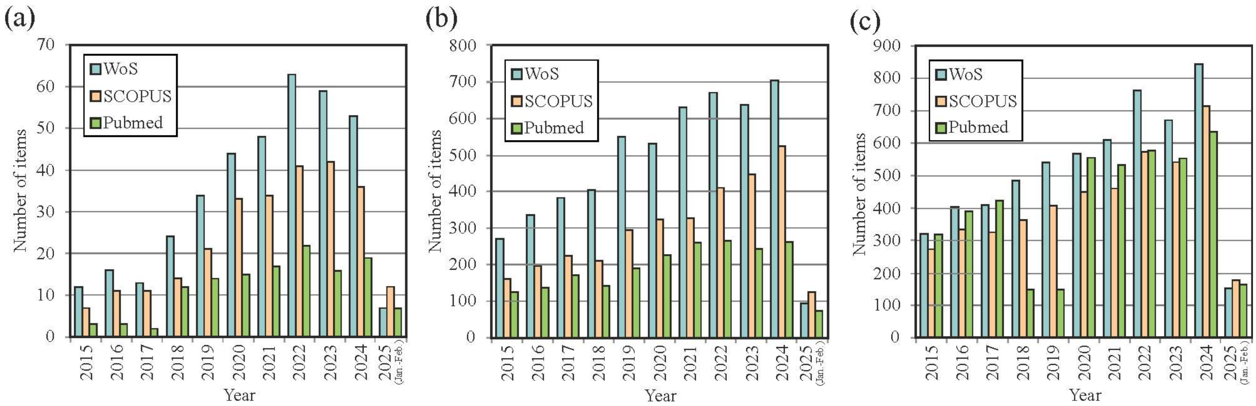

Figure 1. Number of publications in selected bibliographic databases according to the search criteria: (a) nature-inspired composites, (b) bioinspired composites, and (c) biomimetic composites.

In each of the analyzed bibliographic databases, the largest share is held by publications on biomimetic composites. The number of items for this criterion indexed in the WoS Core Collection, SCOPUS, and PubMed databases is 5775, 4638, and 4462, respectively. In the years 2015–2025, an approximately linear increase in the number of items for each search criterion is observed (Figure 1). The number of items meeting the keywords ‘biomimetic composites’ has approximately doubled in the last 10 years. The most dynamic increase in items meeting the criteria ‘bioinspired composites’ or ‘bio-inspired composites’ and ‘biomimetic composites’ is observed in the WoS Core Collection and SCOPUS databases (Figure 1a,b).

Figure 2 shows the network of the publication keywords for the set of publications retrieved based on the keyword ‘bioinspired composites’. Based on Figure 2, it can be concluded that the major research directions include topics that can be defined using the keywords: composites, mechanical properties, bioinspired, and design. Among the research directions, four major clusters can be distinguished, defined by the colors red, blue, green, and brown.

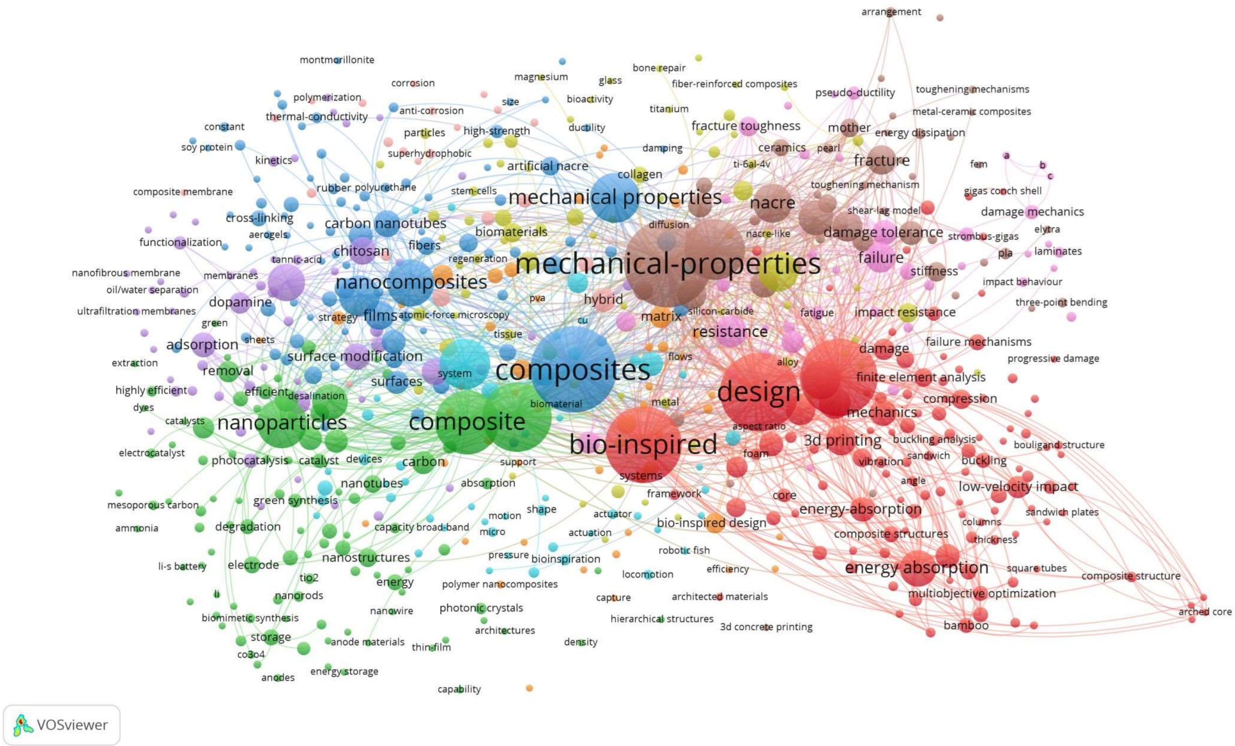

Figure 2. Network of the publication keywords for the set of publications retrieved based on the keywords 'bioinspired composites'.

3. Bioinspired honeycomb cores and matrices for composites

Honeycomb-inspired sandwich composite structures are a new type of material in which two thin metal/composite skin layers are bonded with an epoxy adhesive to a honeycomb core (metal or composite). Honeycomb-based composites, through appropriate arrangement of cell shapes and dimensions, enable a reduction in the mass of the structure while increasing stiffness. The most common geometry is a centrosymmetric hexagonal structure with variable or constant internal cell angles [48]. Despite the excellent strength-to-weight ratio of honeycomb composites, they are susceptible to disbond along the skin-core interface under repeated loading conditions. There are also known approaches departing from the regular cell shape in favor of prismatic cellular cells of different dimensions and variable cell proportions [49].

Santulli's research [50], inspired by celery fiber geometry, resulted in the evaluation of the influence of filled and empty areas in cell materials on the composite strength. Embedding fibers into polymer matrix composites is the basis for designing auxetic structures that can perform a number of physical and mechanical functions. The typical behavior of auxetic structures is the negative Poisson's ratio [51]. Bouakba et al. [52] distinguished three fiber architectures based on pore opening angles and pore area and thickness of two hierarchical levels of biocomposite fibers made of trunks of *Opuntia ficus-Indica* and polyester matrix. The cactus fibers-based composites with polyester matrix showed large energy dissipation per unit volume at low cycles and high loading levels. Onck et al. [53] found that the distribution of cell geometries and cell struts has a significant influence on the failure mode of open cell biocomposites. Sun et al. [54] developed honeycomb core sandwich panels fabricated by the hot-pressing process. Honeycomb cores were made of AW-3003-H18 aluminum alloy foils and the face sheet material was EN AW-5052-O aluminum alloy. Impact tests revealed two different failure modes of the honeycomb-core sandwich panels. Mode A with local damage of both the facings and the core and mode B with global deflection of the face sheets. The energy absorption efficiency was significantly improved with increasing the face layer thickness. On the other hand, reducing the cell size resulted in lower perforation resistance. Kolopp et al. [55] found that the selection of front face sheet material is critical for perforation resistance. AW-5086-H111 aluminum and aramid dry stitched fabrics (between 8 and 18 plies) were identified as potential front skin. On the other hand, Park et al. [56] found that perforation resistance of the sandwich structure, composed of Nomex® honeycomb core and carbon/epoxy and glass/epoxy face sheets, is affected by core height. In addition to the geometry and material of the sandwich structure, the impactor diameter [57], the incident angle of impact [58], impact energy [59], and the target size [55] were considered as other factors affecting the impact response of honeycomb structures.

De Rosa et al. [60] investigated the potential of okra (Lady's finger) fibers obtained from the stem of a Malvaceae plant (*Abelmoschus esculentus*) as potential reinforcement in polymer matrix composites. The tensile and flexural tests confirmed that okra fibers show potential as reinforcements in polymer matrix composites. In another work, De Rosa et al. [61] used untreated New Zealand flax (*Phormium tenax*) to reinforce epoxy composites subjected to tensile and flexural tests. Short fibers or quasi-unidirectional arrangements of fibers were considered. Composites reinforced with quasi-unidirectional fibers showed higher strength compared to pure epoxy resin. Observations in nature proved that honeycomb structures do not have to consist exclusively of hexagonal cells. The pulp of plant cells consists of tetraquaidecahedral surfaces with polygonal walls [62]. Honeycomb sandwich composite structures are widely used in the aerospace industry due to their ability to absorb much energy.

Designing load-adapted, complex, lightweight composite structures with bonds and branches from lightweight profiles is a challenge. Another solution may be the use of foams [63], which can be observed in nature in layered composites consisting of stiff shells filled with lightweight foams: Toucan beak [64], porcupine quills [65], hedgehog quills [66], and feather rachises of birds [67]. Hufenbach et al. [68] performed finite element-based numerical simulations of T-shaped profiles to obtain an optimal design of thin-walled composite branches. The authors reproduced the structure of the *Corryocactus brachypetalus*. Nilklas et al. [69] found that the lignified vascular tissue of cactus is the main support of columnar cacti. The lamellae consisting of vessels and fibers are with the rays in an alternating pericyclic order around the stem axis [70]. They do not resemble typical wood with diffuse porosity, such as deciduous trees [68]. Han et al. [71] developed dactyl-inspired sinusoidal-corrugated sandwich-structural honeycomb structures based on the impact region of mantis shrimp's dactyl club. Basalt unidirectional fibers are used as a reinforcing material. Sinusoidal-corrugated sandwich-structural honeycomb structures showed higher bending absorption energy and bending strength compared to traditional unidirectional and plain-woven skin sandwich structural honeycomb structures.

Sun et al. [72] developed sandwich composites with a porous core and a carbon fiber-reinforced polymer (CFRP) top layer with an architecture similar to grass leaves and tree leaves. The primary structural stiffness was provided by CFRP face sheets. The core is responsible for providing the primary in-plane structural stiffnesses. The CFRP/metal-foam sandwich structure and hornbill mouthbone are also composed of two face sheets and a random porous core. Based on the strength tests of the developed panels, it was found that a biomimetic core similar to the fractal distribution of veins in tree leaves is the optimal structure for sandwich structures with CFRP face sheets.

In addition to the traditional honeycomb, the structure of lightweight energy absorbers is inspired by woodpeckers' beaks [73], pomelo peel-inspired honeycombs [74], and spiderweb honeycombs [75]. Table 1 presents achievements in bioinspired honeycomb structures.

Table 1. Recent achievements in bioinspired honeycomb structures (2020–2025).

Inspiration	Material	Type of work	Results	Potential application	Ref.
Grass stems	7 different honeycomb structures made of AW-6063 aluminum alloy	Numerical	Bioinspired honeycomb structure reduces the crashworthiness deformation of the battery-pack bottom shell by up to 30%	Improvement of the crashworthiness of a battery-pack system	[76]
Spider web, bamboo, pomelo peel, grass stem	Carall honeycomb with the following cells: grass stem honeycomb, re-entrant, hexagon, si, spider web, pomelo peel, bamboo, wavy	Numerical	Wavy honeycomb model achieved the highest specific energy absorption (SEA), showing a 5.62% improvement over the hexagonal model	Aircraft industry (hail impact on Carall composite structures)	[77]
The European honeybee *(Apis mellifera ligustica)*	Selective laser sintering-fabricated honeycomb structure from polyamide nylon 12 (PA2200)	Experimental	The corner radius of a cell has no significant effect on bending, the coping radius strongly influences specific flexural strength	Aircraft industry	[78]
Honeycomb	Weaire, Kelvin, and floret honeycombs (AW-6061-T6 aluminum alloy)	Numerical and theoretical	The specific energy absorption of the bioinspired structure was about 44% higher than the traditional honeycomb	Energy absorbers in automotive engineering	[79]
Honeycomb	Octagonal and hexagonal honeycomb structures (aluminum)	Numerical and theoretical	The crashworthiness criteria of the octagonal honeycomb are slightly lower compared with conventional hexagonal honeycomb.	Honeycomb-like energy absorbing devices	[80]
Honeycomb	Hierarchical honeycomb metastructures	Numerical and theoretical	A new honeycomb structure with several superior mechanical properties is obtained	Honeycomb structure with the spacecraft return capsule shell	[81]
Honeycomb	3D-printed fused deposition modeling honeycomb reinforced starfish shape structures (polylactic acid)	Experimental	As the wall thickness increases, the crushing force efficiency value will decrease	Structures with the ability to absorb energy impacts	[82]

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Inspiration	Material	Type of work	Results	Potential application	Ref.
The forewing of a beetle	Bi-tubular thin-walled structure with a core grid (multi-pointed stars and polygons) made of AL-6XN stainless steel	Numerical and Experimental	The triangular grid gives better results than the honeycomb structure	Sandwich structures to absorb the energy of the blast loads	[83]
Honeycomb	Double arrow honeycomb structures (aluminum) introduced into the re-entrant honeycomb with negative Poisson's ratio	Numerical	Two-stage deformation mode under compression provides better mechanical properties of honeycomb structures	Composites exposed to impact	[84]
Vascular bundles of bamboo	Bamboo bundle-reinforced twin-walled structure (aluminum alloy)	Numerical	The proposed thin-walled structure showed improved strength and energy absorption under bending, lateral, and axial loads	High-strength thin-walled structures	[85]
Bamboo cell wall	Functionally graded honeycomb cellular structure (bamboo biomorphic structure) fabricated using fused filament fabrication material	Numerical	Bamboo biomorphic structure showed four times higher impact energy absorption compared to conventional honeycomb structure	Energy-absorbing engineering structures for aircraft and automobiles	[86]
Lotus leaf vein	Honeycomb structure (panel material-AW-5083, honeycomb core material-AW-3003)	Numerical	The addition of walls in the honeycomb sandwich panel reduces the maximum deformation of the rear face sheet by 10.29%	Impact resistant structures	[87]
Honeycomb	Floret, Weaireand Kagome-shaped thin-walled structures (AW-6061-T6 aluminum alloy)	Theoretical and numerical	Developed thin-walled structures are characterized by a specific energy absorption about 44% higher than the traditional honeycomb	Next-generation energy absorbers	[88]

4. Composites inspired by insect and plant cuticles for stiffness improvement

The structure of the insect cuticle consists of a protein and chitin phase and stiffening components, i.e., carbonates and calcium salts (calcite) [48]. The properties of fibrous composite cuticles depend on the orientation of the cuticle and the volume fraction of the major components such as calcium carbonate, type of protein, lipid, chitin nanofibers, water content, and metal ions. The mechanical performance of the cuticle is further enhanced by its shape. The cuticle is corrugated and curved, similar to the stiffened elytra and wings. Twisted cholesteric crystal patterns are found in the iridescent tessellated cuticles of many insects [88]. The cuticle structure may be further stiffened by webs and stringers, and may sometimes take a sandwich-like structure. Insect cuticles are characterized by Young's modulus of resilin of about 1 MPa, soft cuticles up to 50 MPa, and sclerotized cuticles up to 20 GPa at a density of 1–1.3 kg/m^3 [89]. The Young's modulus of chitin nanofibers, which are a component of the cuticle, is more than 150 GPa. Chitin nanofibers are among the stiffest natural fibers. A comparison of the Young's modulus values of natural materials (including cutiles) with synthetic materials is shown in [89]. According to Vincent [90], the cuticle is a multifunctional sensory material whose properties are multidimensional and depend on the level, type, and direction of the load. Zinc and manganese increase the strength of insect bone structures. These elements accumulate in the cutting edges of the mandibles from all orders of chewing insects [91]. The highest concentration of manganese was found in the cutting edges of mandibles.

Miessner et al. [92] developed a composite mimicking the behavior of the insect cuticle. Replacing chitin with the cellulose of paper impregnated with the tripeptide DOPA-Gly-Gly enabled the production of a biomaterial that was water-resistant and had high strength in repeated wet–dry cycles. It was found that adding relatively small amounts of the tripeptide, which is then tanned, can significantly increase the hydrophobicity of the paper substrate. In extracellular proteinaceous materials produced by invertebrate animals, high strength insect cuticles, parts of tubes of numerous marine worms, and periostracum of mollusks are obtained by tanning the protein by enzymatic oxidation of catechols of various types.

Wu et al. [93] proposed an insect cuticle-inspired design of high-performance bioplastics exhibiting mechanistic properties similar to those of living muscles under load. They introduced CPAP3-A1, a major structural protein in insect cuticles, to bind to chitosan. The developed CPAP3-A1/chitosan composite outperformed the previously developed chitosan-based composites by about 90 MPa. The proposed design of chitosan-based biocomposites, techniques used to produce the CPAP3-A1 protein, and preparation process of chitosan/CPAP3-A1 composites are graphically presented in [93].

Scarangella et al. [88] developed cholesteric liquid crystal oligomer-based material imitating the striated cuticle of the scarab beetle *C. gloriosa*. As a result of the thermally driven self-assembly process, biomimetic samples with high structural and textural compatibility were obtained. The developed material can be used for the production of optical tags in the field of cryptography. Fernandez and Ingber [94] proposed a biodegradable chitosan-fibroin composite inspired by insect cuticles. The laminate is twice as light as aluminum and exhibits strength and toughness that are sometimes greater than the unstructured component blend. Assessment of microstructure, sclerotization level, and material properties of these materials depends on the measurement method and sample processing. Stamm et al. [95] confirmed that the mechanical properties of insect cuticles depend on the measurement method, sampling site, and sample processing.

The insect cuticle is considered to exhibit the most complex and diverse biomechanical properties of all biological materials. Zeng et al. [96] developed a soybean meal adhesive inspired by insect cuticles and shell pearl layers. A biomimetic structure was constructed based on chitosan-modified 3,4-dihydroxybenzoic acid anchored on molybdenum disulfide nanosheets. Compared to a soybed meal adhesive, the adhesion work of the novel adhesive with a "brick-mortar" structure was 0.867 J, with about a 486% increase. The adhesive showed favorable water resistance and antibacterial properties. Chen et al. [97] developed a gelatin hydrogel reinforced with deacetylated chitin nanofibers and additionally reinforced with quinone cross-linking. The hydrogel showed significantly improved tensile properties compared to a non-cross-linked version. The environmentally friendly properties of gelatin and chitin make hydrogels potentially useful in agriculture and biomedicine. Yuan et al. [98] increased the damping properties of hierarchically structured chitin hydrogels by 100-fold using a binary-solvent-induced strategy to induce the self-assembly of chitin. The properties of the developed hydrogels were observed to be similar to those of insect cuticle structures. Chitin hydrogels also exhibit better damping properties than most synthetic materials and are an alternative to biological materials used in robotics and medicine. Making nature-inspired materials/designing a fully digitalized process is one of the major directions for the development of nature-inspired materials [99].

Key molecular components of insect cuticles with emphasis on their potential applications in the development of biomimetic materials are presented in [100]. Table 2 presents current achievements in composites inspired by insect cuticles for stiffness improvement and water retention.

Table 2. Recent achievements in composites inspired by insect and plant cuticles for stiffness improvement and water retention (2020–2025).

Inspiration	Type of work	Aim	Results	Potential application	Ref.
Tibiae of desert locusts (*S. gregaria*)	Experimental (scanning electron microscopy, confocal laser scanning microscopy and nanoindentation)	Analysis of the effect of microstructure and sclerotization on the elastic modulus of the tibia	While sclerotization determines the difference between the elastic moduli of the tibiae, the anisotropic properties of each tibia are controlled by the specific fiber orientation	Findings deepen the understanding of the effect of sclerotization on the structure-material-function relationship in insect cuticles with strong anisotropy	[101]
Hind tibiae of desert locusts (*Schistocerca gregaria*)	Cyclic bending loads of microdamage of the hind po 1, 24 h, 1 week, and 4 weeks	Repair of microdamage caused by cyclic loading in insect cuticle	In the samples left for 1 week or 4 weeks before retesting, the microdamage had been samorepaired	Composites with the ability to self-heal microdamage	[102]
Insect cutile	Preparation of chitosan/CPAP3-A1 composites, experimental testing of mechanical properties, microstructure characterization	Fabrication of insect cuticle-mimicking biocomposites via introducing CPAP3-A1, structural protein	Bioplastics exhibit mechanical performances outperforming current chitosan-based, biomaterials and many petroleum-based synthetic plastic	3D-printing ink injectable fillers, wound dressing	[93]

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Inspiration	Type of work	Aim	Results	Potential application	Ref.
Arthropod cuticle and pearl layer	Fabrication of SM-MoS_2/CS@DA-Cu adhesive and testing antibacterial effect, the dry/wet shear strength, the toughness, and the water resistance	Preparation of biomimetic soybean meal (SM) adhesive with a “brick-mortar” structure	The wet shear strength of the developed composite was 1.68 MPa, with a 194.7% increase compared to the soybean meal adhesive	The industrial preparation of multi-functional strong composites and plywood	[94]
Olive and ivy leaf cuticles	Preparation of poly(styrene)-block-poly(butadiene)-block-poly(sty-rene/cellulose nanocrystals nanocomposites by solvent casting-evaporation, water permeability measurements, verification of transversal heterogeneity by Raman microscopy and ATR-IR spectroscopy	Experimental investigation of the directionality of the water transport through a graded structure of olive leave cuticles	The transport of water through astomatous olive and ivy leaf cuticles directional and that the permeation is regulated by the hydration level of the cutin-rich outer cuticular layer	Cuticle-inspired compositionally graded membranes	[103]
The exoskeleton of insects	Finite element-based modeling and multi-objective (genetic algorithm) optimization	Simulation of the mechanical response of about 3000 unique gradients of the elastic modulus to normal contacts	Materials with exponential gradients of the elastic modulus could achieve an optimal balance between the load-bearing capacity and resilience	Development of materials with exponential gradients of the elastic modulus	[104]
Plant cuticle	Study of the effect of adding a trifunctional comonomer on the barrier, mechanical and thermal properties of the developed polyesters	Analysis of the properties of cuticle-inspired poly(hydroxyhexadecanoate)-an fatty acid-derived biopolyester	The properties of hydrophobic biopolyesters were found to depend on the crystallinity ratio and the cuticle-inspired polyester composition	The flexible packaging, design rigid, thicker packaging	[105]

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Inspiration	Type of work	Aim	Results	Potential application	Ref.
Asian corn borer (*Ostrinia furnacalis*)	Spatiotemporal expression analysis, fluorescence lifetime imaging, phylogenetic analysis	Research on a newly developed chitin-binding protein with three conserved 18-amino acid motifs and arginine-histidine-rich regions	*Ostrinia furnacalis* cuticular protein hypothetical-1 can form coacervates in the presence of chitosan	Design bioinspired materials with high toughness and strength	[106]

Self-healing composites are materials designed to automatically repair damage and restore their original properties, inspired by biological systems. These materials can autonomously repair cracks, delamination, and other forms of damage without external intervention. The healing process can be triggered by various mechanisms, including pressure, temperature changes, or chemical reactions. Masselter and Speck [107] used this property of plant stems to produce a polyurethane-glass composite consisting of microfibrils and a polyurethane foam matrix. Lim and Huang [108] proposed the use of kapok fibers (*Ceiba Pentandra*) in composites. These fibers are characterized by a large number of cavities providing the ability to absorb and retain oil. The small diameter of the fibers requires a uniform distribution of these fibers in the composite. For this reason, kapok fibers are most often used together with other fibers, including sisal and glass. Thermosetting composites based on hybrid fibers are characterized by high design flexibility and recyclability. Reddy et al. [109] used kapok fabric as reinforcement for hybridization with sisal and glass fabrics in a polyester matrix. Hybridization of fibers improved the Izod impact strength. Norris et al. [110] were inspired by the self-healing functions of bone developed designs of vasculature systems incorporated into a fiber–reinforced polymer by a "lost wax" process. The self-healing process, resulting in recovery (≥96%) of compressive strength after impact, involved the infusion of a healing resin through the vascular bundles. In another article, Norris et al. [111] incorporated bioinspired vessels into a carbon fiber-reinforced epoxy composite laminate. Trask et al. [112] presented the concepts of various self-healing technologies being developed for fiber-reinforced polymer composite materials, most of which are inspired by vascular networks found in biological systems.

Pand and Bond [113,114] developed a self-healing hollow fiber reinforced polymer composite consisting of unidirectional hollow glass fibers in an epoxy matrix with a 'bleeding' ability, in which impact bending damage was reinforced. Infiltration of ultraviolet (UV) fluorescent dye from cracked hollow fibers into the damaged sites in the internal structure of the composite was observed. This feature may be particularly useful in the rapid inspection of large composite panels, primarily in aviation. Kolmakov et al. [115] deposited nanoparticle-filled microcapsules for remediation of composite matrix damaged by deformation. The developed "Repair-and-Go" system enables the capsule's shell to be penetrated to fill the damaged region. Hart et al. [116] incorporated internal vascular networks for delivery of reactive two-part epoxy/amine healing microchannels to internal delamination to self-heal fracture damage in a woven glass/epoxy composite. It was found that the quality of healing is directly dependent on the degree of mixing of the healing agent components in the fracture plane.

Self-healing is gaining increasing interest worldwide as a method for self-resolving damage to materials. Many researchers have explored the incorporation of self-healing capabilities into fiber-reinforced polymers. One bioinspired approach being considered is the use of functional repair components stored within hollow glass fibers (HGFs). Trask et al. [117] incorporated self-healing HGFs into carbon fiber/epoxy laminates and glass fiber/epoxy laminates. A healing resin stored within hollow fibers provided recovery of a significant portion of the flexural strength after damage. Gupta et al. [118], using tri-n-octylphosphine oxide-covered nanoparticles, showed that spherical nanoparticles dispersed in a poly(methyl methacrylate) (PMMA) matrix migrate into the crack formed at the interface between the polymer and the glass layer. The results confirmed the possibility of fabricating multilayer systems that can self-heal.

Harrington et al. [119] studied molecular rearrangements occurring during stretching of the byssal threads of the California mussel (*Mytilus californianus*). Byssal threads are elastomeric fibers composed of multidomain hybrid collagens that lose mechanical properties upon damage. However, the distal portion of the byssal thread can regain its initial properties upon molecular rearrangement.

The project 'Improving the aircraft safety by self-healing structure and protecting nanofillers' [120] developed self-healing composites consisting of an epoxy matrix in which nanofillers were embedded, enabling the researchers to obtain novel self-healing composites reinforced with carbon fiber. Multifunctional carrier systems, including multi-walled carbon nanotubes, nanofibers, graphite, and graphene sheets, were used to produce the panels. The use of self-healing multifunctional composites provides benefits for the aviation industry in the form of reduced number of aircraft failures and reduced costs related to maintenance and downtime. Another project, HIPOCRATES [121], developed microcapsules containing self-healing substances added to a composite polymer blend in which a catalyst was previously dispersed, which initiates the reaction. In the event of a microcrack, the capsule releases a regenerating substance that comes into contact with the catalyst. In this way, the resistance to compressive forces can be increased by about 5–10%. Table 3 presents achievements in self-healing composites.

Table 3. Recent achievements in bioinspired self-healing composites (2020–2025).

Inspiration	Methods	Aim	Resuls	Potential application	Ref.
Mantis shrimp club	Preparation and strength testing of hybrid carbon fiber reinforced laminated composites	Proposal of helicoidal laminate design that diverts fiber damage into matrix split to facilitate recovery	Significantly less fiber damage was observed for helicoidal laminates (HL) as compared to cross-ply laminates. HLs are able to recover up to 91% of their out-of-plane loading strength	Fiber-reinforced laminates are susceptible to damage during use	[122]

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Inspiration	Methods	Aim	Resuls	Potential application	Ref.
Mantis shrimp club	Numerical modeling and experimental testing of helicoidal CFRP laminates, focusing on the Non-Linear Rotation Angle (NLRA)	Proposal of bioinspired CFRP with gradual variations in pitch angle	Gradual helicoidal structures were characterized by increasing the failure load compared to unidirectional CFRP laminate by about 17%	Biomimetic CFRP with increased strength	[123]
Nacre layer	Preparation, mechanical, and anticorrosion testing of a combination of elastomer protective materials by combining waterborne polyurethane and graphite oxide	Development of high-performance elastomer protective material with active self-healing functions	Photothermal properties of graphite oxide enable the biomimetic polymer coating to achieve damage recovery after being irradiated with near-infrared light for 30 s	Creating multi-functional, high-performance smart material	[124]
Chitosan	Preparation of hydrogels, studies of cell viability and adhesive properties of hydrogel extracts, in vitro bursting pressure measurements	Development of adhesive gallic acid-conjugated chitosan/carbon black composite hydrogels	Shear-thinning hydrogels exhibited excellent tissue-adhesive and self-healing properties	Surgical sutures	[125]
Mussel	Synthesis of oxide/polyurethane composites, analysis of microstructure and morphology, thermogravimetric analysis, tensile and compression tests	Design, synthesis, and characteristics of self-healing graphene oxide/polyurethane composites	The composites demonstrated a self-healing efficiency of 87.9%	Electronic skinn protective coatings, water-insensitive devices, soft sensors	[126]
Plant fibers	Fabrication and strength tests of PA6 polyamides containing various healing agents, i.e., cyclic olefinic copolymer and polycaprolactone	Development of a thermoplastic matrix with self-healing properties using polyamide 6 (PA6)	The repair process was able to improve the fatigue life of the self-healing composites by about 77%	Bioinspired composites with the ability to heal micro-damages	[127]
Fiber-reinforced systems	Biofiber manufacturing, survivability of fibers, thermogravimetric analysis	Production of damage-responsive bacterial-based self-healing fibers (BioFiber), which are used to modify concrete	Developed fibers increased crack bridging functionality to control crack growth and crack healing functionality	Reinforcement of cementitious materials	[128]

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Inspiration	Methods	Aim	Resuls	Potential application	Ref.
Connective tissues	Integrating the bottlebrush copolymer functionalized graphene oxide (GO) into a polyurethane matrix via in-situ polymerization	Fabrication of nanocomposites with high stretchability` and rapid self-healing ability	Developed nanocomposite with only 0.5 wt.% of GO loading showed improvement of mechanical properties (toughness increased by 70.8%, ultimate tensile strength increased by 52.1%)	Flexible functional devices, smart materials	[129]
Hydrophobic Materials	Mixing the Polyvinylidene fluoride matrix with nano-sized SiO_2 particles, analyzing coating by electrochemical impedance spectroscopy and potentiodynamic polarization	Development of an Anticorrosion coating with both self-healing properties	The surface exhibits high Liquid repellence and robust self-cleaning behavior	Corrosion-resistant Coatings with self-healing properties and superrepellency	[130]
Tea leaves	Production of self-healing composite materials by integrating tea polyphenols with the polyacrylic acid binder, peel strength measurements, thermogravimetric analysis	Proposal for an anode material for lithium-ion batteries	Tea polyphenols enhanced the adhesiveness and anode's durability without the need for additional organic synthesis	Adhesive strategy for silicon anodes	[131]

5. Auxetic structures

Embedding fibers into polymer matrix composites is the basis for designing auxetic structures capable of performing a number of physical and mechanical functions. The typical behavior of auxetic structures is the negative Poisson's ratio [51], which is defined as the negative ratio of transverse strain to the corresponding axial strain. The Poisson's ratio also depends on other physical parameters, such as strain magnitude, magnetic field, and temperature [132]. Changing these parameters enables us to control the Poisson's ratio and, consequently, the auxetic behavior [133,134]. The basic structures of auxetic materials include chiral structures [135], nodule-fibril structures [136], auxetic helix yarns [137], and 3D re-entrant honeycomb auxetic structures [138]. Chiral auxetic structures consist of a number of struts connecting to nodes. A single chiral auxetic structure consists of central nodes, rectangles or other geometric elements, and linkers. The auxetic effect is achieved by the linkers wrapping and unwinding around the nodes under load. In nodule-fibril structures, the negative Poisson's ratio effect is achieved thanks to the internal structure consisting of nodules connected by fibers. Under load, the nodules rotate around the fibers, leading to the emergence of auxetic properties. Helical auxetic yarns consist of two types of threads. The core thread is thick, yet flexible and, when unstressed, has a simple shape. This thread is wrapped with a thinner thread of increased stiffness. This difference in stiffness causes the structure's effective diameter to change under tensile load. As a result, the entire fabric composed of spiral auxetic yarns stretches in a direction perpendicular to the applied load. The primary limitations of producing auxetic textiles are increased thickness, low structural stability, and difficulty in manufacturing due to complex geometric structures. Examples of auxetic structures exhibiting a negative Poisson's ratio are shown in Figure 3. All these structures have potential applications for composite reinforcement.

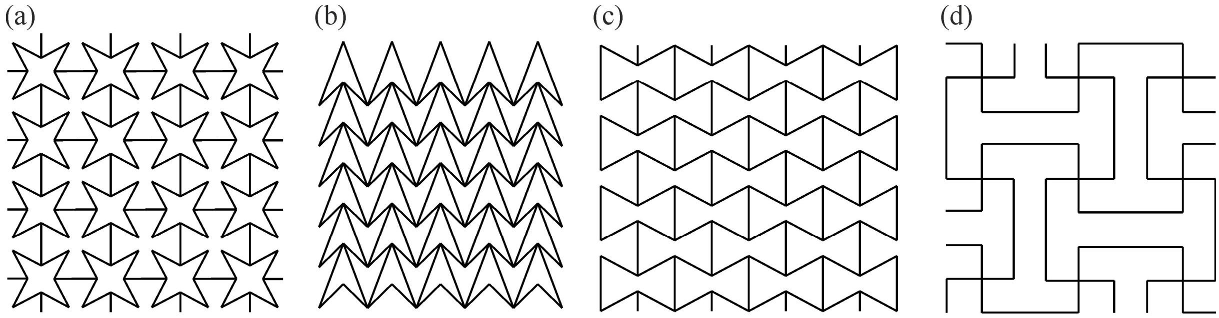

Figure 3. Re-entrant structures: (a) star honeyhomb, (b) double arrowhead, (c) re-entrant honeyhomb and (d) lozenge grids.

Auxetic behavior of materials originates from the deformation mechanism of specific geometries and internal structures in response to uniaxial loads [132]. The unique properties of auxetic structures, such as high fracture toughness, in-plane indentation resistance, synclastic curvature in bending, shear resistance, fracture toughness, and the ability to dampen acoustic vibrations, make these materials desirable for the production of cushioning materials [139], materials used in sports [140], biomedical materials [141], filtration materials [142], and the textile industry [143]. Auxetic materials find applications in the aerospace, maritime, and automotive industries due to their unique mechanical properties [144]. Stiff auxetic materials can be used as medical implant devices, such as bone screws and artificial intervertebral discs [145]. Table 4 presents the current achievements in bioinspired auxetic structures.

Table 4. Recent achievements in bioinspired auxetic structures (2020–2025).

Inspiration	Material	Type of work	Results	Potential application	Ref.
Honeycomb	Re-entrant arc-shaped honeycomb	Numerical and theoretical	An empirical equation is deduced to evaluate the dynamic plateau stress of a re-entrant arc-shaped honeycomb	Auxetic cellular structures	[146]
Honeycomb	Auxetic re-entrant structure	Numerical	Concentric auxetic re-entrant honeycomb crashworthiness is influenced by wall thickness and the number of concentric walls	Absorbing impact structures in mining and automobile	[144]

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Inspiration	Material	Type of work	Results	Potential application	Ref.
Honeycomb	Sandwich armor structure with auxetic core	Numerical	Auxetic structure exhibit a higher energy transformation of The kinetic energy of a projectile compared with the monolithic panel	Human body armor	[147]
Nacre	Uniaxial graded auxetic damper (UGAD) with re-entrant auxetic cores	Numerical and experimental	The superior energy-absorption potential of the UGAD was observed	Shock-absorbing systems	[148]
Rotating unit auxetics	A Penrose quasi-crystal and the long-desired isotropic auxetic	Numerical	The conditions for the emergence of a non-trivial floppy mode responsible for the auxetic behaviour were developed	3D polyhedral materials	[149]
Honeyhomb	3D-printed auxetic tubular structure	Experimental	The tubular structure possess high stability and compressive capacity	Adaptive structures with tunable stiffness	[150]
Cellular structure	3D chiral auxetic structure	Numerical	High crushing behavior of the chiral cellular structure was confirmed	Damping components	[135]
Bone structure	3D-printed chiral structure	Numerical and experimental	Optimal ligaments must have an anisotropic bending stiff-ness	Structures for energy absorption performance	[151]
Bone structure	Gradient triangle auxetic structures	Numerical and experimental	Triangle auxetic structures increased yield strength and Young's modulus by 27.5% and 28%, respectively	Biomedical applications	[152]
The Achilles tendon	3D-printed auxetic structures	Numerical and experimental	The star configuration exhibits remarkable tolerance to tensile fatigue loads	Biomedical applications	[153]
Honeyhomb	Auxetic structure with rotating/chiral architecture	Numerical and experimental	The structural response of the structures subject to off-axis mechanical conditions revealed the correlation to the anti-tetrachiral honeycombs	Auxetic metamaterials	[154]

6. Bioinspired ceramic composites

6.1. High-strength structures

Structural ceramics are well known for their good strength thanks to strong chemical bonds. Unfortunately, due to limited impact strength, the use of technical ceramics in applications requiring both high strength and impact strength is limited. By drawing inspiration from natural structures undergoing evolution over millions of years, hierarchical multifunctional materials can be produced with properties superior to those of structural ceramics. Ceramic composites are highly mineralized natural materials containing at least 60 vol% of inorganic components [155]. Ceramic composites inspired by nature are materials that combine high mechanical strength, high temperature resistance, and corrosion resistance with a unique microstructure modeled on structures found in living organisms. Bioinspired, high-temperature-resistant ceramics are manufactured according to a high-entropy composition-engineering strategy [156].

The ‘Bioinspired structural materials’ project [157] froze ceramic suspensions to create strong ceramic-polymer materials with extraordinary toughness, enabling the production of composites with properties similar to mother-of-pearl and high fracture resistance. The freeze casting technique was used to produce highly porous graphene cellular networks with controlled geometry and cell dimensions, thus influencing the strength and elasticity of the structures. Freeze casting can be used to build ceramic scaffolds with high stiffness and high porosity at the same time.

In the project “Advanced Composites Inspired by Nature” [158], the researchers focused on the combination of spark plasma sintering for suspension freezing and water sublimation to obtain porous structures. The work carried out on the production of scaffold architectures from materials based on carbon nanostructures and ceramic materials led to the development of porous silicon carbide structures with different morphology, degree of structure organization, and high efficiency.

The latest methods for producing bio-inspired ceramic composites rely on high-energy processes, including a field-assisted sintering technique and pressure-assisted or pressureless high-temperature sintering. 3D printing technologies are also expensive and limited in terms of achieving high precision [159]. Literature analysis indicates limitations in the use of bio-inspired ceramic materials related to the high energy cost required for their efficient and scalable production [155].

6.2. Implantation materials

The result of the ‘Bioinspired structural materials’ project [157] is ceramic particles that can organize and disorganize in an emulsion in response to an external stimulus. Potential applications of the developed technology include medicine for the production of ceramic coatings in tissue engineering, ceramic thermal barrier coatings, and bone-like ceramic materials developed for orthopedics. Freeze casting has become a subject of interest, especially in relation to ceramic products and ceramic-polymer hybrid composites. Freeze casting combined with plasma sintering enables increasing the density of ceramic-carbon composites. The potential for self-healing of composites with skin-like properties was investigated. The developed multifunctional systems, which are characterized by high strength, are used in energy production applications, for the production of electronic skin and orthopedic implants.

Kogut et al. [7] based their work on the tubular structure of trees and developed a ceramic material with a tubular structure using organic precursors, such as acacia, hornbeam, and staghorn sumac, subjected to pyrolysis. After pyrolysis, the material was modified with a ceramic impregnation and subjected to thermal treatment. The obtained ceramic material may have properties that enable potential use in medical implantology [160], catalyst filters, and as a thermal and acoustic insulator.

Hydroxyapatite ceramics based on calcium phosphates are considered one of the best implant materials with high biocompatibility [161,162]. Hydroxyapatite is the main inorganic component of hard tissues, bones, and teeth. A biomimetic hydroxyapatite-related material is aragonite, which is transformed into hydroxyapatite during the hydrothermal process while maintaining its characteristic porous microstructure. Bioceramic hydroxyapatite composites are non-toxic and biologically active materials that demonstrate high corrosion resistance in the environment of tissues and body fluids [7,163].

Mussels (family *Mytilidae*) secrete protein strands that enable adhesion to virtually any substrate. For several years, a bionic approach has been sought to transfer mussel attachment to technical systems. Mussels use oxidative polymerization of dopamine in an aqueous environment at ambient temperature to produce adhesion with oxygen dissolved in water as the oxidizing agent. If a plastic substrate is placed in a bath containing an aqueous solution of dopamine, an adherent polydopamine (PDA) film with a thickness of several nanometers forms on the substrate surface after about six hours. According to Klosterman [164], the mechanism of PDA adhesion can be explained by a decrease in the molecular volume of the monomer unit during polymerization, which is accompanied by the approach of forming PDA molecules into the substrate molecules up to molecular dimensions. With the formation of a PDA film on a polyethylene substrate, the polarity of the surface increases, which is reflected in the improvement of water wettability. PDA films adhere to substrates of very different compositions [165]. Differences in the chemical properties of the plastic surface, whether caused by additives or mineral fillers, have only a minor effect on metallization [166]. The bioinspired concept of plastic metallization is an ecological approach to the electroplating of plastics. Table 5 presents the current achievements in bioinspired ceramic composites.

Table 5. Recent achievements in bioinspired ceramic-reinforced composites (2020–2025).

Inspiration	Methods	Aim	Results	Potential application	Ref.
Bivalve mollusk shells	Centrifugal infiltration and stereolithographic additive manufacturing were proposed for the preparation of ceramic–metal composites (base metal: AW-6061)	Solving the strength–toughness dilemma	The proposed composites benefit from individual phase dimensional control and scalability	Fabricating silica–aluminum composites	[167]
Nacre	Preparation of nacre-like damage-tolerant ceramic/ceramic (alumina) composites with thicknesses up to 1 cm via field-assisted sintering technology (FAST) combined with uniaxial pressure	Improving scalability and reproducibility issues	The composites retain the strength typical of dense alumina (430 ± 30 MPa) with fracture toughness up to 17.6 MPa·m$^{1/2}$ and a crack initiation toughness of 6.6 MPa·m$^{1/2}$.	Damage-resistant structural materials with bioinspired brick-and-mortar design	[168]
The nacreous layer	3D printing mineral-depositing bacteria-embedded ceramic composite materials	Proposal for a novel bacterial stiffening approach in direct ink writing using ceramic-polymer bioinks	A 'printing window' of biomineralization was identified, beyond which bacteria-induced coagulation disrupts extrusion	Strong, tough, and sustainable ceramic materials	[169]

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Inspiration	Methods	Aim	Results	Potential application	Ref.
Nacre	A bottom-up approach combining continuous evaporation-induced self-assembly with resin infiltration, sintering and laminating	Fabrication of nacre-like heterogeneous ceramic-resin composites with locally tunable microstructure	The composites exhibit an attractive combination of impact resistance, low density, surface hardness, and toughness	Advanced heterogeneous materials	[170]
Nacre	The samples were fabricated with 3Y-TZP suspensions and by infiltrating the cast ceramic scaffolds with polymethyl methacrylate	Clinical applications of bioinspired nacre-like ceramic (yttria-stabilized zirconia)-polymer (polymethyl methacrylate) composites	Brick-and-mortar and lamellar composites have good biocompatibility, and the bonding performance of developed composites was better than that of zirconia ceramics	Clinical use as dental restorations	[171]
Nacre	The ceramic/ceramic composites were fabricated via FAST, a suspension that contains the glass-phase precursor Al_2O_3 platelets	Studies on micromechanical properties of bioinspired ceramic-ceramic composite and alumina/glassy phase composite	The main deformation mechanism of bioinspired ceramic/ceramic composites was crack deflection, while the platelet microstructure led to an enhanced fracture toughness.	Bioinspired brick-and-mortar ceramic/ceramic designs	[172]
Nacre	Freeze-cast multilayer alumina composites with different polymer phases (PMMA) were tested to evaluate their fracture toughness and bending behavior	Optimization of freeze-casted bioinspired composites for dental crown applications	Bioinspired ceramic-based composites showed superior toughness and strength compared to current all-ceramic materials	Damage-resistant structural materials	[173]
Nacre	3YSZ ceramic samples with different volume fractions were fabricated by a digital light processing	Fabrication of ceramic composites with exceptional damage tolerance by combining novel biomimetic toughening design and additive manufacturing	The results showed promising possibilities for manufacturing complex ceramic composite components	Damage-tolerant composite dental restorations	[174]

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Inspiration	Methods	Aim	Results	Potential application	Ref.
Nacre	Fabrication and micromechanical fracture toughness testing of bioinspired Al_2O_3-based composites with different polymers (epoxy, PMMA, polyurethane and urethane dimethacrylate/triethylene glycol dimethacrylate)	Investigation into the feasibility of using Bi-directional freeze casting nacre-like Al_2O_3 composites to overcome brittleness	Al_2O_3/PMMA composites showed the highest fracture toughness and high level of strain energy dissipation without crack propagation	Prosthetics and dental in-direct restorations	[175]

7. Bioinspired composites with special properties

Based on the wax-like coating of the lotus leaf, Gupta [176] developed a waterproof structure that captures sunlight and prevents the accumulation of ice crystals. The manufacturing process is carried out on the basis of a mold reproducing the microstructure of a lotus leaf. This mold is used for multiple replications of the structure and is prepared by means of a high-power laser that heats the material to the melting point (approximately 1200 °C). The bioinspired material can be used for anti-icing protection in the automotive industry and defense industries, as well as for protecting satellite dishes and telecommunications towers in winter climates. In the case of civil and military aviation, this can eliminate or significantly reduce chemical defrosting procedures. Additionally, the invented material is characterized by the ability to capture sunlight, which can increase the efficiency of solar cells. In electrical engineering, attempts are being made to reproduce the superhydrophobic structures of lotus leaves on the surface of insulators, enabling us to obtain a surface that enables self-cleaning of insulators by collecting dirt from raindrops rolling down the surface of lampshades [7].

Speck et al. [45] presented a façade shading system based on biological inspiration from the bird-of-paradise (*Strelitzia reginae*). The pollen-bearing inflorescences open automatically after mechanical pressure is exerted by birds carrying pollen to other inflorescences. When the bird flies away, the sheath closes, and the pollen is protected again. The bird-of-paradise petal sheath was shown to consist of rigid ribs that are connected by flexible lamellae [177]. Under the influence of the bird's weight, the lamellae deform, causing the inflorescence to open. Speck and Speck [178] used these features to develop a rib-laminae structure made of glass fiber reinforced polymers (Flectofin®). Flectofin® is a biomimetic, hingeless shading system for architectural façades, capable of continuous and smooth opening and closing cycles [45].

The underwater trap of the aquatic carnivorous waterwheel plant (*Aldrovanda vesiculosa*) also provided inspiration for the shading mechanism of the Flectofold façade [179,180]. The latching of the waterwheel plant involves a complex interaction of different actuation and folding mechanisms, which are self-actuated when the trigger hairs are touched by the prey. The structure and arrangement of the curved folds of the Flectofold system are made of glass-fiber reinforced plastics, which have been further optimized using inspiration from the folding of the wings of the Italian striped worm (*Graphosoma italicum*).

Weather-responsive building facades with autonomous activation are inspired by the hygroscopic movement of pine cone scales (*Pinus spp.*). A characteristic feature of the cone opening movement, from the biomimetic point of view, is the opening mechanism dependent on changes in ambient humidity. Changing weather conditions causes a change in the swelling properties of hygroscopic tissues [181]. The sensitivity of the mechanical response of the artificial structure can be adjusted to changing conditions, including humidity, light, and temperature [182].

The widespread use of 3D printing methods of hygroscopic shape-changing structures ('4D printing') has enabled the construction of actuator systems with complex geometry [183]. Correa et al. [181], inspired by the scales of the Bhutanese pine cone (*Pinus wallichiana*), developed artificial scales consisting of a layer of acrylonitrile-butadiene-styrene and co-polyester with embedded cellulose fibrils. Poppinga et al. [184], inspired by biology, presented the '4D printing' technology for the production of snap-buckling and curved fold origami.

Biomimetic reinforced additive manufacturing (AM) has opened new possibilities to mimic naturally multi-scale structures in nature. Electric field-assisted 3D printing is developed for manufacturing composites with specific electrical properties [185]. Yang et al. [186] proposed a rotating electrical field for electrically assisted nano-composite 3D printing that can dynamically align multiwall carbon nanotubes of a bionic composite featured with different orientations of reinforcing fibers (known as Bouligand structures). Examples of anisotropic reinforcement Bouliagand architectures in nature can be found in the claws of the lobster *Homarus americanus* and the scales of the fish *Arapaima gigas* [187]. Based on a literature review, Shi et al. [188] presented the advantages of electrospinning in the preparation of nanofibers with ultrafine diameters and high aspect ratios.

8. The use of AI in the design of biomimetic materials

AI is a field of computer science that focuses on creating computer systems that can perform tasks requiring human intelligence [63,189]. This includes learning, reasoning, problem-solving, and data processing. AI can analyze information and draw conclusions to make decisions. It is a rapidly developing field, and its capabilities and applications are constantly expanding thanks to advanced algorithms and the analysis of massive data sets. AI primarily aids in the design phase of new materials, enabling faster human decision-making while minimizing human error [190].

AI algorithms can be divided into several major categories, the most popular of which are supervised learning, unsupervised learning, and reinforcement learning [191]. Within these categories, there are many specific algorithms, such as neural networks (including deep learning), regression models, decision trees, and many others [20]. Artificial neural networks are models inspired by the structure of the human brain, consisting of interconnected neurons. Deep learning is a subset of machine learning that uses deep neural networks to analyze and interpret data [192]. Evolutionary algorithms use processes inspired by biological evolution to optimize solutions. Fuzzy logic algorithms enable working with imprecise data and making decisions based on fuzzy logic. Decision trees represent decisions in the form of a tree, where each node represents a feature test, and the branches represent possible test outcomes. The major learning methods for AI algorithms are divided into supervised learning (SL), unsupervised learning (UL), and reinforcement learning (RL) [32,39]. SL algorithms learn from labeled data, meaning that the expected outcome is known for each input example. The goal of SL algorithms (i.e., k-means, dimensionality reduction) is to find patterns, structures, or groups in the data. RL algorithms (i.e., deep Q-network, Q-learning) learn through interactions with the environment, receiving rewards for desirable actions and penalties for undesirable ones. AI makes it possible to quickly explore large microstructural design spaces in bio-inspired composites. For instance, Gu et al. [192] used hundreds of thousands of finite-element simulations to train a machine learning model to find hierarchical microstructures that make materials stronger and tougher. The best of them were then tested and validated through additive manufacturing, showing that this method is orders of magnitude faster than traditional methods [193]. Abueidda et al. [194] created a convolutional neural network (CNN) with a genetic algorithm to improve two-phase checkerboard composites. They did this by putting softer parts near crack tips to lower stress concentration and make the material tougher. The predictions were very close to the finite element method (FEM) results. A conditional variational autoencoder (CVAE) and a genetic algorithm (GA) worked together to find designs that met the target stiffness and toughness values. The CVAE was about 7,500 times faster than the GA, and explainable AI (SHapley Additive explanations—SHAP) showed that where the material was placed behind the crack tips had a large effect on toughness [194]. Hashemi et al. [195] used supervised machine learning on Sobol-sequence-generated particle microstructures and fast Fourier transform-based homogenization to make surrogate models that reliably forecast characteristics and enable inverse designs for the required thermal conductivity. These AI methods can quickly forecast properties, find design patterns that are not obvious, balance goals that are at odds with each other, and work well even when there is not a lot of labeled data. They are better than brute-force finite element searches for a wide range of composite design issues. Table 6 shows a summary of AI-based techniques used for designing bio-inspired composites.

Table 6. AI-based techniques used for designing bio-inspired composites.

AI-technique	Composite design problem	Outcome
CNN + self-learning + AM validation	Hierarchical microstructures; strength and toughness	Identified tough, strong microstructures validated via 3D printing; accelerated design by orders of magnitude
CNN + GA	2D checkerboard composites with cracks	Optimized placement of soft elements near crack tips to mitigate stress concentration; ML predictions matched FEM results
CVAE + GA + SHAP	Balancing stiffness and toughness	Generated designs satisfying dual objectives; AI revealed that material placement behind crack tip drives toughness
Surrogate ML + inverse design	Particulate composites; thermal conductivity	Trained on Sobol-sequence microstructures and FFT homogenization; enabled accurate inverse design for thermal targets

9. Conclusions

The literature review indicates that there are areas requiring further exploration of the relationships between proteins contained in cuticles and cuticle properties and the mechanisms of interaction of structural molecules. The diversity of insect and plant species, as well as the complex biomolecular assembly pathways, mean that many multi-scale mechanisms of cuticle formation and their interaction are not recognized. Cuticle-inspired materials show promising properties for applications in sustainable environmental protection and biomedicine. Research focusing on performance, plasticity, and fatigue properties can lead to a better understanding of the correlations between functions, properties, and evolutionary biology of insects.

The combination of bionics and topological optimization based on the fractal arrangement of veins in tree leaves is a promising technique for designing materials with enhanced physico-mechanical properties. Although chemical and physical research on natural materials is advanced, the wide development of bioinspired materials is limited by immature processing technologies and difficulties in the economic implementation of products for production.

As a part of future-looking perspectives, the design of bioinspired architectures should focus on improving strength, resistance to damage, and some physical properties, such as electrical and thermal conductivity. Multi-structured construction materials such as honeycomb composites require complex optimization analyses of the shape and dimensions of cells. High expectations are brought by 3D printing technology, which enables the construction of metal and polymer structures that could not be manufactured by other methods, taking into account their technological limitations. Unfortunately, the construction of structures on an ultra- and micro-scale using 3D printing is at the development stage. Bouligand structures have brought many benefits to structures intended for absorbing impact energy. Moreover, fractal and self-similar honeycomb architectures have excellent energy absorption capacity and strength with reduced mass. Network scaffolds require strict control of the distribution of empty spaces, the construction materials used, the scaffold shape, and their dimensions. The development of numerical simulations using the finite element method, the boundary element method, meshless methods, and computer-aided design technologies leads to continuous optimization of designed composite structures in increasingly shorter times. Implementation of the Industry 5.0 concept with AI-assisted parallel processing of big data will bring multi-scale design methods to an even higher level. Digital twins (virtual replicas of objects and systems) are gaining popularity in various industries, enabling visualization, monitoring, and optimization of composite structures.

The development of biomimetics requires collaboration between scientific fields, such as architecture, biology, physics, and engineering. The prospects for the development of biomimetic materials are promising, paving the way for innovative solutions in various fields:

- In the metal industry, materials mimicked on organic structures can be used to produce lightweight and durable structures.
- Biomimetic solutions can contribute to environmental protection, for example, by developing biodegradable materials.
- In construction, biomimetic materials can help increase the energy efficiency of buildings by mimicking natural cooling systems. Moreover, biomimetics demonstrates the potential to develop architectural solutions with balanced strength and weight properties, as well as self-cleaning building facades.
- Biomimetics promotes the use of materials from renewable resources that are highly recyclable and reduce the carbon footprint. This is particularly important in the transportation industry, which is considered one of the largest sources of environmental pollution during vehicle production, operation, and recycling.

• The development of nanotechnology will enable the creation of nanocomposites with controlled structures and properties, enabling precise mimicking of natural structures at the molecular level.

• The 4D printing technique has great potential for future development of biomimetic ceramic structures.

• The development of computer techniques will enable a deeper understanding and inspiration in this field of materials engineering and thus the development and testing of biomimetic structural materials from laboratory scale to industrial implementation.

At the current stage of development of biocomposites with unique properties, their large-scale production is limited by high costs. Furthermore, the complex processes involved in producing biomimetic materials pose a technological challenge.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Author contributions

Tomasz Trzepieciński: concept and design, literature review, data curation, writing–original draft preparation, writing–review & editing; Marek Kowalik: concept and design, literature review, suggestions, writing–original draft preparation; Sherwan Mohammed Najm: literature review, data curation, writing–original draft preparation; Salah Eddine Laouini: concept and design, suggestions, writing–review & editing, supervision; Marwan T. Mezher: literature review, suggestions, writing–original draft preparation, writing–review & editing, supervision.

Conflict of interest

The authors declare no conflict of interest.

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