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Review

Bioinspired Polymers: Bridging Nature's Ingenuity with Synthetic Innovation

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Abstract: This review delves into the cutting-edge field of bioinspired polymer composites, tackling the complex task of emulating nature's efficiency in synthetic materials. The research is dedicated to creating materials that not only mirror the strength and resilience found in natural structures, such as spider silk and bone, but also prioritize environmental sustainability. The study explores several critical aspects, including the design of lightweight composites, the development of reversible adhesion methods that draw inspiration from nature, and the creation of high-performance sensing and actuation devices. Moreover, it addresses the push toward more eco-friendly material practices, such as ice mitigation techniques and sustainable surface engineering. The exploration of effective energy storage solutions and the progress in biomaterials for biomedical use points to a multidisciplinary approach to surpass the existing barriers in material science. This paper highlights the promise held by bioinspired polymer composites to fulfill the sophisticated needs of contemporary applications, highlighting the urgent call for innovative and sustainable advancements.

Keywords: bioinspired composites; sustainability; advanced manufacturing; multifunctional materials; environmental engineering

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1. Introduction

This paper explores the field of bioinspired polymer composites, emphasizing the multidisciplinary challenges researchers encounter. The primary aim is to mimic the efficiency and functionality found in natural materials within engineered counterparts. A key hurdle is distinguishing mechanical properties from their structural makeup, enabling the customization of materials for specific uses. The study focuses on bioinspired metal-coordination dynamics [1] and polymer–inorganic hybrid materials [2], striving to create materials that can withstand severe conditions, taking inspiration from the durability of spider silk [3] and the strength of bone [4]. The objective is to produce materials that are not only robust and long-lasting [5–7] but also environmentally sustainable, pointing out the existing gaps in material engineering that need addressing to fulfill the intricate requirements of modern applications.

Sustainability stands out as a critical issue, propelling the creation of materials that preserve their mechanical integrity and corrosion resistance while reducing environmental harm. The fabrication of lightweight yet sturdy composites [8,9], coupled with the adoption of sophisticated manufacturing techniques [10,11], underlines a dedication to sustainable practices.

In the domain of adhesion and surface engineering, ongoing research is directed toward developing adaptable, reversible, and eco-friendly adhesive methods. Innovations include beetle-inspired reversible interlocking mechanisms [12] and bio-based polymeric materials [13], with an additional focus on enhancing surface protection and functionality under challenging conditions [14], where bioinspired solutions show significant potential.

The quest for high-performance, responsive devices for sensing and actuation represents another challenge. Investigations include luminescence-based sensors and actuators [15–17] and soft actuators [18–20], aiming for selective detection and flexible actuation. This effort is bolstered by advancements in biomaterials for biomedical uses [21,22], concentrating on dependable substances for drug delivery [23] and tissue regeneration [24].

Environmental concerns have also led to the development of materials aimed at preventing ice formation [25] and promoting eco-friendly surface treatments [26,27], emphasizing the necessity for materials that tackle ecological issues without compromising on performance.

In energy storage and conversion, the pursuit of materials capable of effective CO_2 capture [28] and enhanced energy storage solutions [29–33] underlines the significance of confronting energy and environmental challenges through bioinspired methods. Innovations in conductive adhesives [34], 4D transformations in polymers [35], and solid polymer electrolytes [36] seek to overcome the traditional limitations faced by electrical and electronic materials.

Moreover, progress in bioprocessing and biomolecular engineering, such as the enhancement of specific enrichment for disease markers [37] and the improvement of enzymes acting on lignocellulose [38], underlines the necessity for technologies that boost efficiency and accuracy. These endeavors, together with advances in enhancing the performance of organic light-emitting diodes (OLED) [39] and advancing photoelectrochemical and enzymatic sensing [40], highlight the interdisciplinary approach needed to augment material functionality through bioinspired designs.

This review provides a detailed examination of the challenges and opportunities in bioinspired polymer research. By utilizing state-of-the-art technologies and drawing inspiration from nature, scientists aim to forge materials that not only cater to present needs but also anticipate future requirements, offering promising answers to some of the most pressing issues in materials science and engineering.

2. Biomimicry and Biomimetic Synthetic Polymers

The search for new materials increasingly draws scientists and engineers toward nature for inspiration, leading to the burgeoning field of bioinspired materials science. This area of study marries the complexities of biological phenomena with their synthetic counterparts in polymer science, demonstrating how the natural world drives material innovation. By emulating the molecular makeup of ice-binding proteins or the complex structure of nacre, researchers bridge the gap between biological insights and synthetic advancements.

In the field of biomedical engineering, significant advancements have been made through the development of various polymeric materials designed for specialized applications. Among these, threonine-based polymers, such as pThr and pHPMA, have been identified for their ability to inhibit ice recrystallization, a property crucial for cryopreservation technologies [25]. The engineering of antifouling polymers marks a significant step forward in creating surfaces resistant to biological contamination, which is vital for a range of biomedical devices and implants [41]. Innovations in drug delivery systems have led to the development of bioinspired polymeric nanoparticles encapsulating dopamine, offering new avenues for intranasal dopamine replacement therapies in the treatment of Parkinson's disease [23]. The use of 2-methacrylooyloxyethyl phosphorylcholine (MPC) polymers in the fabrication of artificial organs and biomedical devices highlights the material's high performance and compatibility with biological systems [42]. Glycopolypeptides have emerged as biofunctional materials with potential applications across various biomedical fields [43], while saccharide-responsive smart copolymers have shown promise in enriching sialylated glycopeptides for disease diagnosis [37].

In the area of material science, polymers have been engineered to enhance their mechanical properties, such as strength, toughness, and adhesion. MXene-based polymer composites have been developed to increase the Young's modulus and strength, utilizing a brick-and-mortar structure for improved durability [5]. Continuous fiber-reinforced polymer composites offer enhanced toughness, critical for structural applications [6]. The integration of graphene into polymer nanocomposites has been a key focus, optimizing both strength and toughness for advanced materials [7]. High-aspect-ratio polymer fibers draw inspiration from natural locking devices found in beetles' wings, resulting in reversible interlockers with unique mechanical properties [12]. Nucleobase-containing polymers, produced through thiol-ene polymerization, have yielded tough bioplastics and ultra-strong adhesives [13]. Additionally, polymer gels reinforced with dendritic crystals have been developed to provide reversible and adaptable adhesion capabilities [44].

The field of energy storage and conductivity has also benefited from advancements in polymer technology. Poly(aryl ether sulfone) nanocomposites have been engineered for high-temperature energy storage, boasting enhanced mechanical and electrical performance [3]. Copolymers bearing catechol and Li(+) ion-conducting anionic pendants have been explored as organic cathodes for lithium storage, offering new possibilities for energy storage technologies [31]. Catechol-rich polymers, deposited via atmospheric plasma, serve as redox-active thin films for lithium-ion batteries, contributing to the development of more efficient energy storage solutions [45].

Surface modification and protective coatings have seen innovative developments with the application of polymers. Poly(dodecyl methacrylate) (P12MA) has been used to create low-friction surfaces in high-viscosity solvents, improving the performance and lifespan of various mechanical systems [46]. The engineering of 4-arm poly(ethylene glycol) hydrogels with metal–ligand coordinate complexes allows for the control of material mechanics, providing materials with customizable viscoelastic properties [1]. Protective coatings based on alkyl-silanized polymers with nano-silica have been developed to protect magnesium alloys against corrosion, extending their usability and durability [47].

In the domain of smart materials and sensing, significant progresses have been made. Liquid crystal nanoparticle actuators enabled by polymer surfactant-assisted assembly offer smart interfaces with adjustable light and color, opening new possibilities for display technologies [16]. Graphene–polymer heterogeneous sensing junctions have been developed for high-performance humidity sensors, suitable for integration into wearable devices [17]. Conjugated polymers and liquid crystal elastomers have been used to create near-infrared light-induced, ultrafast soft actuators, capable of tunable deformation and motion, indicating a leap forward in the development of responsive materials [19].

Table 1 outlines the diversity of bioinspired materials, pairing various biological inspirations with their biomimetic synthetic polymers. This categorization covers a broad spectrum of sources, from general bioinspiration to specific biological structures, such as bone and leaves, marine organisms, such as mussels and barnacles, and principles, such as biomineralization. It presents a comprehensive view of biomimetic polymers' applications, extending from antifouling polymers to composite materials designed to replicate natural structures.

Table 1. Bioinspired polymer composites: mimicking nature's design.

Bioinspired Species	Synthetic Polymer	Achievement and Applications	Ref.
General Bioinspiration	4-arm poly(ethylene glycol) hydrogels	Dynamic mechanical loading, viscoelastic properties, metal–ligand crosslinks	[1]
General Bioinspiration	Polymer–inorganic hybrid materials	Crystal growth, structured polymer templates, inorganic hybrid	[2]
Spider Silk	Polymer nanocomposites for high temperatures	Energy density, nanoconfinement effect, high-temperature performance	[3]
Bone	Calcium phosphate oligomers in PVA/Alg networks	Ultra-tough laminate, bending strain and toughness, water content	[4]
Nacre (Mollusk Shell)	MXene-based polymer composites	Finite elements analysis, Young's modulus, strength, damage resistance	[5]
Various Biological Structures	Various FRP composites	Toughening mechanisms, manufacturing processes, damage mitigation	[6]

Table 1. *Cont.*

Bioinspired Species	Synthetic Polymer	Achievement and Applications	Ref.
Graphene	Graphene-based polymer nanocomposites	Strength, toughness, hierarchical structure, mechanical properties	[7]
General Bioinspiration	Ceramic platelet-reinforced piezoelectric polymer	Tensile toughness, thermal annealing, piezoelectric properties	[8]
General Bioinspiration	Cholesteric nanocomposites with cellulose nanocrystals	Hierarchical self-assembly, photonic response, mechanical properties	[9]
Nacre	Alginate–alumina composite films	Strong, stiff, tough, hydrogel-film casting, microstructure	[10]
General Bioinspiration	Clay/polymer aerogels	Mineralization, mechanical properties' improvement, freeze-drying technique	[11]
Beetles (Wing Locking Device)	High-aspect-ratio polymer fibers interlocker	Reversible interlocking, van der Waals force, shear force	[12]
General Bioinspiration	Nucleobase-containing polymers	Tough bioplastics, adhesives, hydrogen-bonding interactions	[13]
Biomineralization Principles	Coating polymers with prismatic films	Crystallization technique, graphene oxide, tribological performance	[14]
General Bioinspiration	Cd-based coordination polymer	Luminescence-based sensing, Schottky diode, hydrothermal synthesis	[15]
General Bioinspiration	Liquid crystal nanoparticle actuator	Adjustable light, color change, photo-humidity response	[16]
General Bioinspiration	Graphene–polymer heterogeneous sensing junction	Humidity sensor, fast response, water metabolism monitoring	[17]
General Bioinspiration	Paper/polymer bilayer actuator	Electrically driven, anisotropic deformation, bioinspired applications	[18]
General Bioinspiration	Conjugated polymers/liquid crystal elastomers	NIR light-induced actuation, soft robotics, tunable deformation	[19]
General Bioinspiration	Graphene oxide–polymer hybrid hydrogels	Smart actuator, strong mechanical properties, thermo-responsive	[20]
Marine Mussels	Metal–polymer hybrid nanostructures in nanofibers	Electrospinning, catechol-grafted polymer, metal nanostructures	[21]
General Bioinspiration	Catecholamine polymers for organ-on-chip	Microfluidic coating, cell culture stability, flow-based technique	[22]
General Bioinspiration	Theranostic coordination polymer nanoparticles	Parkinson's Disease, dopamine replacement, nanoencapsulation, intranasal delivery	[23]
General Bioinspiration	Biomimetic silicified gelatin scaffolds	Angiogenesis, bone regeneration, bioactive hybrid scaffold	[24]
Ice-Binding Proteins (IBPs)	Threonine-based polymers for IRI	Ice recrystallization inhibition, phosphate-buffered saline, low molecular weights	[25]
Hair or Skin	Polymers on chemically structured substrates	Adsorption/desorption, hydrophilic homopolymers, molecular dynamics simulations	[26]
Leaves	Nano-porous polytetrafluoroethene surface	Superhydrophobic properties, hierarchical wrinkling, water repellence	[27]
Carbonic Anhydrase	Porous organic polymer-functionalized membranes	CO_2 capture, mixed matrix membranes, biomimetic material	[28]
Brown Algae	Polysaccharide-based 3D crosslinked network binder	Li-ion battery, Si anodes, volume expansion prevention	[29]
General Bioinspiration	Carboxylate–water coordination polymers	Electrochemical water splitting, hydrogen bond clusters, bimetallic CPs	[30]
General Bioinspiration	Redox-active catechol-bearing polymers	Organic cathodes, lithium storage, catechol polymers	[31]
Sandcastle Worm	Polymer carbon dot membranes	Proton exchange, electrostatic complexation, fuel cells	[32]
General Bioinspiration	Catechol-grafting PEDOT cathode	Aqueous proton battery, high voltage, rate capacity	[33]

Table 1. *Cont.*

Bioinspired Species	Synthetic Polymer	Achievement and Applications	Ref.
General Bioinspiration	Electrically conductive bioinspired adhesive polymer	Metal-free, water-dispersible, high electrical conductivity, adhesive strength	[34]
General Bioinspiration	Chitosan-based resistive-switching memory	Natural solid polymer electrolyte, nonvolatile memory, transparency	[36]
General Bioinspiration	Saccharide-responsive smart copolymer	Enrichment of sialylated glycopeptides, saccharide interaction, glycosylation	[37]
General Bioinspiration	Plant cell wall polymer assemblies	Carbohydrate-binding modules, lignocellulose-acting enzymes, biorefinery	[38]
General Bioinspiration	Uracil-functionalized poly(3-thiophene)	Organic light-emitting diodes, hole-conducting polymers, thermal stability	[39]
General Bioinspiration	Core-shell Au nanorod@TiO_2 with l-DOPA polymer	Photovoltaic, enzymatic sensing, bioinspired heterostructure	[40]
General Bioinspiration	Antifouling polymers	Biointerface control, nonspecific interaction reduction, biomedical applications	[41]
General Bioinspiration	Phospholipid polymer biomaterials	Artificial organs, blood compatibility, polymer biomaterials	[42]
General Bioinspiration	Glycopolypeptides	Biomedical applications, stimuli-responsive behavior, self-assembling structures	[43]
Creeper Suckers	Dendritic-crystal-reinforced polymer gel	Reversible adhesion, phase-transition, finite element analysis	[44]
General Bioinspiration	Catechol-rich polymers	Redox-active, plasma deposition, lithium-ion battery cathode	[45]
Synovial Joints (Lubrication)	Poly(dodecyl methacrylate) brushes	Tribological behavior, solvent confinement, viscoelastic behavior, load shielding	[46]
Lotus Plant	Alkyl-silanized coating for Mg alloy	Hydrophobicity, corrosion resistance, silica surface modification	[47]
Mussel Adhesive Polymers	Copolymers with poly(ethylene oxide) side chains	Wear resistance, adsorption layers, electrostatic and catechol anchoring	[48]
Nacre (Mollusk Shell)	Graphene-reinforced polymer with multilayer structure	Tensile strength, electrical conductivity, graphene content	[49]
Snail and Mussel	Poly(dopamine methacrylate-co-hydroxyethyl methacrylate)	Strong adhesion, thermal conductivity, carbon nanotubes, phonon transport	[50]
Barnacles	Hydrogel–polymer hybrids	Adhesive strength, hydrophobic interface, antifatigue, one-step polymerization	[51]
Bone	Calcium phosphate and organic polymer composites	High-toughness ceramics, carbonated apatite, organic-inorganic interface	[52]
Marine Mussels	Catecholic priming layer for polymers	Enhanced adhesion, crosslinked polymethacrylate, molecular dynamics	[53]
Nacre	Alumina/polymer composites	Lamellar structure, freeze casting, mechanical performance, fracture mechanics	[54]
General Bioinspiration	Calcium carbonate precipitation in polymer vesicles	Microreactors, polymersomes, mineralization, calcium carbonate	[55]
General Bioinspiration	Aluminum–polyethylene terephthalate composite	Enhanced strength and plasticity, friction stir processing	[56]
General Bioinspiration	Borneol fluorinated polymers	Antibacterial, antifouling, fluorine components, natural antifouling agent	[57]
General Bioinspiration	Dopamine-melanin nanoparticles in polymers	UV-Shielding, hollow nanoparticles, dopamine polymerization	[58]
General Bioinspiration	CuS/PVDF nanocomposite films	Platelet-reinforced, enhanced absorption, brick-and-mortar structure	[59]
General Bioinspiration	Shape-memory polymer with light-coded crystallinity	4D transformation, photothermal effect, spatial heterogeneity	[35]

Table 1. *Cont.*

Bioinspired Species	Synthetic Polymer	Achievement and Applications	Ref.
General Bioinspiration	Graphene oxide/polymer nanocomposite paper	High strength, toughness, dielectric constant, graphene oxide	[60]
Peacock Spider	Micro-structured polymer surfaces	Antireflective, scanning electron microscope, optical properties	[61]
General Bioinspiration	Photonic polymer coatings	Color-changing, humidity-responsive, liquid crystal networks	[62]
General Bioinspiration	Copper–polydopamine composite	Metal matrix composites, electrical conductivity, thermal conductivity	[63]
General Bioinspiration	Methacrylic copolymers with thiazolium and catechol	Antibacterial coatings, thermogravimetric analysis, differential scanning calorimetry	[64]
General Bioinspiration	Peptide–polymer conjugates	Coil-to-helix transition, calcium ion control, bioconjugate	[65]
General Bioinspiration	Graphene/polymer composite strain sensor	Stretchable, adaptable, self-healing, biomineralization-inspired	[66]
General Bioinspiration	Peptoid Polymers	Bioinspired, sequence-specific, biomedicine, nanoscience	[67]
Nacre (Seashells)	Ceramic–polymer composite	Compression fatigue, dental applications, brick-and-mortar structure	[68]
General Bioinspiration	Konjac glucomannan/graphene oxide nanocomposite	Biocompatibility, bioactivity, tissue engineering, food packaging	[69]
Gramicidin-A (Ion Channel)	Solid-state polymer with biological ion channel	Nano-porous membrane, ionic permeability, molecular simulations	[70]
General Bioinspiration	Ferroelectric polymer arrays	Photodetector, neuron signal transduction, photoisomerization	[71]
Ice Plant Seed Capsules	Programmable polymer gel	Responsive materials, 3D origami structures, direct laser writing	[72]
Mussels	Polymer-based energetic composites	Explosive crystals, polydopamine coating, enhanced mechanical properties	[73]
General Bioinspiration	Energetic polymer composites	Mechanical properties, safety, hierarchical interface design	[74]
Mussel	Antifouling and antimicrobial polymer membranes	Polydopamine, poly(N-vinyl pyrrolidone), strong hydrogen bonding	[75]
General Bioinspiration	Bioinspired polymer for Li-ion battery	Flexible nanogenerator, piezoelectricity, energy harvesting	[76]
General Bioinspiration	Robust polymer memristor	Artificial injury response, sense of pain, flexible electronic skin	[77]
Fish Swim Bladder	Hollow microfiber with conducting polymer/graphene	Liquid environment sensor, hollow-structured, triple-phase interface	[78]

3. Research Trends

The forefront of materials science is defined by dynamic and responsive materials, focusing on those that adapt their properties in response to external stimuli. Materials such as 4-arm poly(ethylene glycol) hydrogels, which are crosslinked with dynamic metal–ligand complexes [1], highlight the potential for advances in self-healing, adjusting mechanical properties, and adapting to environmental changes. This research lays the groundwork for developing smart drug delivery systems and adaptive structural elements, pushing the limits of materials' capabilities.

In the domain of hybrid and composite materials, blending organic and inorganic elements leads to materials possessing exceptional mechanical, thermal, and electrical characteristics. Studies on polymer–inorganic hybrid materials [2], polymer nanocomposites [3], and ultra-tough composites [4] showcase their extensive applications, from electronics to structural parts. Introducing biopolymers with inorganic nanoparticles [4] signals a move toward biocompatible and environmentally sustainable materials. Future research aims to refine these composites for specific applications, balancing performance with environmental considerations.

Bioinspired structural design draws from the complex hierarchical structures found in nature, as seen in MXene/polymer nanocomposites [5] and bioinspired ceramic/polymer composites [54]. These efforts seek to emulate the mechanical excellence of materials such as nacre, focusing on scalability, toughness, and durability.

Advanced processing techniques, along with a commitment to sustainability through methods, such as friction stir processing [56], self-assembly [59], and atom transfer radical polymerization [60], enable precise control over material structure and properties. The emphasis on sustainable practices, including the use of green materials [52] and applying PDA films for surface functionalization [63], reflects a dedication to minimizing the environmental footprint. Future studies may explore novel processing techniques and sustainable materials to enhance properties while reducing environmental harm.

The investigation of functional and smart composites, illustrated by polymer vesicles as microreactors [55] and the development of piezoelectric polymer composites [8], uncovers materials that can actively engage in chemical reactions or respond to electrical impulses. This nascent field promises materials that can sense, respond, and adapt to their surroundings, paving the way for smart materials suitable for sensing, actuation, and self-repair applications.

Advancements in materials, such as high-aspect-ratio polymer fibers [12] and polymer-based composites with improved surface characteristics [50], feature the importance of surface engineering in boosting material performance. Enhancing interfacial bonding and surface functionalization can significantly improve composite performance. Future research is poised to discover new coatings and surface treatments that enhance adhesion, durability, and functionality.

Table 2 provides a comprehensive overview of bioinspired polymer composites, detailing cutting-edge materials, their preparation methods, and their broad applications across various sectors.

Table 2. Biomimetic polymer composites and their methods of preparation for various applications.

Polymer/Composition	Preparation	Ref
	Materials Science and Composite Development	
4-arm poly(ethylene glycol) hydrogels crosslinked with dynamic metal–ligand coordinate complexes	Engineered for decoupled spatial structure and mechanical performance, with control over mechanical hierarchy and viscoelastic properties through the concentration of metal–ligand crosslinks.	[1]
Polymer–inorganic hybrid materials	Utilization of structured polymer templates as substrates to support crystal growth, leading to the formation of polymer–inorganic hybrid materials through the translation of the polymer-film pattern into the crystal nucleation face.	[2]
Polymer nanocomposites with poly(aryl ether sulfone) and wide-bandgap artificial nanosheets	Inspired by spider silk, anchoring poly(aryl ether sulfone) to the surface of nanosheets to prepare nanocomposites that exhibit enhanced mechanical and electrical performances at high temperatures.	[3]
Ultra-tough composite with poly(vinyl alcohol) (PVA), sodium alginate (Alg), and ultrasmall calcium phosphate oligomers (CPO)	Integration of CPO within PVA and Alg networks through a simple three-step strategy, inspired by bone structure, to achieve strong multiple molecular interactions and high bending toughness.	[4]
Polymer vesicles as microreactors for calcium carbonate precipitation, using polymersomes loaded with carbonate ions	Encapsulation of salts and selective permeability to calcium ions triggered by calcimycin, demonstrating mineralization of calcium carbonate within polymersomes.	[55]

Table 2. *Cont.*

Polymer/Composition	Preparation	Ref
Mechanical Performance and Composite Materials' Enhancement		
MXene/polymer nanocomposites with nacre-mimetic brick-and-mortar structure	Modeled and analyzed for deformation behavior, showing enhanced Young's modulus and strength via the interlocking mechanism between MXene fillers in the polymer matrix.	[5]
Bioinspired toughening of fiber-reinforced polymer composites	Review of biomimetic approaches and engineering composite developments for designing and manufacturing high mechanical performance and multifunctional composite structures.	[6]
Graphene-based nanocomposites	Advances in bioinspired approaches to improve mechanical properties, involving the structure and mechanical properties of GO papers, novel graphene–polymer interphases, and synergistic mechanical improvements.	[7]
Piezoelectric polymer composite reinforced with sapphire platelets: poly(vinylidene fluoride-trifluoroethylene) (P(VDF-TrFE))	Layer-by-layer fabrication of sheets reinforced by aligned sub-micron-thick sapphire platelets, with thermal annealing to improve crystallinity and mechanical properties.	[8]
Hierarchically self-assembled, cholesteric nanocomposite with cellulose nanocrystals (CNC) and polymers featuring ureidopyrimidinone (UPy) motifs	Synthesis of hydrophilic, nonionic polymers with UPy motifs via reversible addition-fragmentation transfer polymerization, co-assembled with CNC to form ordered cholesteric phases with controlled helical pitch.	[9]
Polymer composite films with alginate (Alg) matrix and alumina (Alu) micro-platelets, crosslinked by calcium ions (Ca^{2+}) and improved by polyvinylpyrrolidone (PVP) coating on platelets	Hydrogel-film-casting method for layered organic/inorganic microstructure, aiming for simultaneously strong, stiff, and tough composites.	[10]
Mineralized clay/polymer aerogels	A bioinspired approach using a layer-by-layer method to produce alternate layers of polymer and silica on the surface, improving mechanical properties.	[11]
Aluminum composite reinforced with soft polymers (polyethylene terephthalate)	Processed using the friction stir processing technique, showing enhancement in strength and toughness.	[56]
Platelet-reinforced polymer films with CuS hexagonal nanoplatelets and polyvinylidene fluoride (PVDF)	Self-assembly of CuS hexagonal platelets into brick-and-mortar structure CuS/PVDF nanocomposite films for enhanced absorption properties.	[59]
Copolymer comprised of polydimethylsiloxane (PDMS) and poly(glycidyl methacrylate) (PGMA)	Atom transfer radical polymerization method. PDMS provides flexibility, and PGMA offers reactive groups and adhesiveness, used as an adhesive between GO nanosheets for the fabrication of GO/PDMS-PGMA papers, enhancing tensile strength, toughness, and dielectric constant.	[60]
Copper-PDA (Cu-PDA) composite derived from polydopamine coating on copper powder particles	Coating Cu powder with PDA films and sintering to enhance electrical and thermal conductivity, inspired by metal matrix composites with nanocarbon phases.	[63]
Organic–inorganic composite materials of calcium phosphate and organic polymers	Bottom-up coprecipitation of polymer and inorganic crystals to mimic bone formation, using eco-friendly materials, such as cellulose and starch, for high-toughness ceramics.	[52]
High-content graphene-reinforced polymer with bioinspired multilayer structure (HEC, HPMC, and PVA)/graphene	Simple solution evaporation and reduction method to prepare polymers/graphene-layered composites with high-content graphene (45 to 75%), optimizing the mechanical and electrical properties.	[49]

Table 2. *Cont.*

Polymer/Composition	Preparation	Ref
Bioinspired lamellar structured ceramic/polymer composites (Alumina/polydimethylsiloxane (Al_2O_3/PDMS) and alumina/polyurethane (Al_2O_3/PU))	Freeze-casting technique to create lamellar structures that mimic the mechanical performance of nacre, including detailed mechanical performance analysis and modeling.	[54]
	Adhesion and Surface Engineering	
High-aspect-ratio polymer fibers	Development of a reversible interlocker inspired by beetle wing locking, using van der Waals force-assisted binding between high-aspect-ratio polymer fibers for flexible, strong shear locking force and easy lift-off.	[12]
Nucleobase-containing polymers	Efficient thiol-ene polymerization to produce nucleobase-functionalized homopolymers and statistical copolymers, harnessing complementary hydrogen-bonding interactions for toughness and adhesive properties.	[13]
Dendritic-crystal-reinforced polymer gel	Introduction of a room-temperature crystallizable solvent into the polymer network, forming a gel adhesive through hydrogen-bonding interaction between crystal fibers and polymer network for reversible adhesion.	[44]
Crosslinked polymethacrylate resin enhanced by a catecholic priming layer	Bioinspired dynamic bonding via a thin catecholic layer to significantly enhance the adhesion strength and toughness of polymer resins on mineral surfaces.	[53]
Polymer-based composite with poly(dopamine methacrylate-co-hydroxyethyl methacrylate) (P(DMA-HEMA)) and vertically aligned carbon nanotubes (VACNTs)	Inspired by snail and mussel adhesion, synthesizing a copolymer that forms strong bonding with VACNTs through pi–pi interactions, achieving high thermal conductivity and strong adhesion.	[50]
Hydrogel–polymer hybrids with a hydrophobic interface	Inspired by barnacle adhesion, combining hydrogels and polymers through introducing an adhesive layer via one-step polymerization, achieving a tough and antifatigue interface.	[51]
Tribological Performance		
Polymers coated with self-organized prismatic films of calcite nano-coatings	GO-mediated compartmentalization and templating prismatic growth of calcite via control of ionic diffusivity into microcompartments for tribological performance enhancement.	[14]
Poly(dodecyl methacrylate) (P12MA)	Brush structures sliding in oil, evaluated under high-viscosity conditions for low wear rates, mimicking the lubricating mechanism in synovial joints.	[46]
Statistical copolymers with medium-length poly(ethylene oxide) side chains	Anchored to surfaces via electrostatic forces, catechol groups, or both, and evaluated for wear resistance under water.	[48]
	Sensing and Actuation	
Cd-based coordination polymer with N-nicotinoylglycinate: $[Cd\text{-}(C_8N_2O_3H_7)_2(H_2O)_2]n$	Hydrothermal method using N-nicotinoylglycinate for turn-on luminescence-based sensing and Schottky diode behavior in device fabrication.	[15]
Liquid crystal nanoparticle actuator (LCNA) with 2-(3′,3′-dimethylSP)	Supramolecular self-assembly via a surfactant-assisted method from functional liquid crystal molecules for bioinspired smart interfaces with adjustable light and changeable color.	[16]
Graphene–polymer heterogeneous sensing junction for humidity fluctuation sensors	Bioinspired atomic-precise tunable sensing junction by confining sensing material into graphene nanochannels for high-performance wearable devices.	[17]

Table 2. *Cont.*

Polymer/Composition	Preparation	Ref
Anisotropic paper/polymer bilayer actuators	Combining hygro-expansion and thermal expansion, fabricated by a simple printing method to exhibit large and anisotropic deformation with a reversible color-change function.	[18]
Conjugated polymers/liquid crystal elastomers actuators	Synthesis of organic photothermal dopant via palladium-catalyzed Stille cross-coupling polymerization, integrated into liquid crystal elastomers for NIR light-induced, ultrafast soft actuators with tunable deformation.	[19]
Polymer–clay hydrogel hybrid	Series combination of tough polymer–clay hydrogels, successively irradiated by near-infrared (NIR) for comprehensive "extension–grasp–retraction" actuation, leveraging GO's rapid NIR energy absorption for thermo-energy transformation.	[20]
Graphene/polymer composite with dynamic crosslinking for stretchable strain sensing	Biomineralization-inspired creation of a composite from graphene, poly(acrylic acid), and amorphous calcium carbonate, yielding highly adaptable and durable strain sensors.	[66]
Ferroelectric polymer arrays with embedded dye molecules for photodetection transmissible to neuron cells	Utilizing photoisomerization of dye molecules in ferroelectric polymer membrane for electric polarization change under light.	[71]
Hollow-structured microfiber with 2D polypyrrole (2DPPy) and reduced GO skeleton for liquid environment sensing	Inspired by fish swim bladder, creating a microfiber with a hollow structure and 2D conducting polymer/graphene skeleton for ultrasensitive sensing in liquid environments.	[78]
Hybrid nano-porous membrane with Gramicidin-A confined in solid-state polymeric thin film	Confined selective ion channel inside nanopores of a solid-state polymer, enhancing ionic permeability.	[70]
Programmable polymer gel controlled by swellable guest medium	Implanting swellable guest medium inside non-swellable host polymers to enhance swelling inhomogeneity for responsive 3D shape transformation.	[72]
Poly(vinylidene fluoride) (PVDF) film with deoxyribonucleic acid (DNA) for beta-phase nucleation	Using DNA to align molecular dipoles in PVDF, resulting in piezoelectricity without electrical poling for energy harvesting.	[76]
	Biomedical Applications and Drug Delivery	
Metal–polymer hybrid nanostructures within 3D electrospun nanofibers, using catechol-grafted poly(vinyl alcohol)	Electrospinning of redox-active polymer for immobilizing and reducing noble metal ions to solid metal nanostructures at ambient temperature.	[21]
Catecholamine polymer-coated microfluidic chips	Flow-based coating technique using bioinspired polymers PDA and polynorepinephrine (PNE) for shelf-stable coating in microfluidic organ-on-a-chip applications.	[22]
Bioinspired theranostic coordination polymer nanoparticles for dopamine replacement in Parkinson's Disease	Encapsulation of dopamine within nanoparticles through reversible coordination complexation, offering a new therapeutic approach for symptomatic therapy.	[23]
Silicified gelatin scaffolds via bioinspired polymer-induced liquid precursor (PILP) for bone regeneration and angiogenesis	Fabrication of hybrid nanocomposite scaffolds through impregnation of Si-containing PILP into porous gelatin scaffolds, followed by in situ polymerization, mimicking natural bone mineralization.	[24]
Phospholipid polymer biomaterials with 2-methacrylooyloxyethyl phosphorylcholine (MPC) polymers	Synthesis inspired by biomembrane surface structure for high-performance artificial organs with excellent blood compatibility.	[42]
Glycopolypeptides synthesized via N-Carboxyanhydride (NCA) polymerization	Production of smart biofunctional materials for biomedical applications, including targeted drug delivery, and potential structural materials for bioinspired hierarchical structures.	[43]

Table 2. *Cont.*

Polymer/Composition	Preparation	Ref
Methacrylic copolymers bearing thiazolium cationic groups and catechol moieties	Coating various substrates with copolymers for antibacterial activity, with adhesion and performance influenced by polymer composition and substrate.	[64]
Peptide–polymer conjugates sensitive to calcium ions (Ca^{2+}) for reversible coil-to-helix transition	Utilizing calcium ions to regulate the secondary structure transition in peptide–polymer conjugates, with reversible control achieved via competitive Ca^{2+}-ion binders.	[65]
Peptoid polymers with tunable structures for biomedicine and nanoscience	Synthesizing N-substituted glycine backbone polymers offering designable structures bridging proteins and traditional polymers.	[67]
Konjac glucomannan/GO nanocomposite films for biocompatible and bioactive surfaces	Solution-casting method to fabricate ultra-strong, biocompatible nanocomposite films with enhanced mechanical properties.	[69]
Antifouling and antimicrobial polymer membranes with PDA and poly(N-vinyl pyrrolidone)	Coating polypropylene membranes with PDA and further modification by PVP via hydrogen-bonding interactions for enhanced antifouling and antimicrobial activities.	[75]
Nacre-like ceramic–polymer composite for compression fatigue properties	Mimicking brick-and-mortar structure for high fatigue resistance, showing potential in dental applications.	[68]
	Biomedical and Environmental Applications	
Poly(2-hydroxypropyl methacrylamide) (pHPMA)	Synthesized using pThr as a model and tested for IRI activity in neutral PBS. Exhibited potent IRI activity at both low (2.3 kDa) and high molecular weights (32.8 kDa).	[25]
Hydrophilic flexible homopolymers on chemically patterned substrates	Coarse-grained molecular dynamics simulations to study polymer adsorption and desorption on bioinspired, chemically structured substrates for ecofriendly product development.	[26]
Hierarchically wrinkled nano-porous polytetrafluoroethylene (PTFE) surfaces on thermoretractable polystyrene (PS) sheet	PTFE dispersion coated on PS sheet, followed by thermal treatment to induce surface wrinkling through dynamic thermal contraction, resulting in superhydrophobic properties.	[27]
Antifouling polymers	Development of surfaces resistant to fouling by proteins, cells, and bacteria, leveraging specific interactions between designed surfaces, biomolecules, and cells for biomedical applications.	[41]
Hydrophobic alkyl-silanized protective polymer coating for magnesium alloy, modified by trimethylsilylation with hexamethyldisilazane	Reinforcement with nano-silica powder and chemical modification to enhance hydrophobicity and corrosion resistance, inspired by lotus plant leaf structures.	[47]
	Electrical and Electronic Materials	
Electrically conductive bioinspired adhesive polymers: poly(N-methacryloyl-3,4-dihydroxyl-L-phenylalanine-co-3-sulfopropyl methacrylate):poly(3,4-ethylenedioxythiophene) (PMS:PEDOT)	Synthesis involving radical polymerization and oxidative polymerization to create a water-dispersible, lightweight, highly flexible, biocompatible adhesive with high electrical conductivity.	[34]
Chitosan (a natural solid polymer electrolyte)	Solution-processed to form a resistive-switching memory device with a Pt/Ag-doped chitosan/Ag structure, demonstrating reproducible and reliable bipolar resistive switching characteristics.	[36]
Polylactide (a re-processable thermoplastic shape-memory polymer)	Utilizes a digital photothermal effect for spatio-selective programming of crystallinity by physical phase transformation (crystallization), enabling repeated erasing and reprogramming for 4D shape transformation.	[35]

Table 2. *Cont.*

Polymer/Composition	Preparation	Ref
Environmental and Antifouling Solutions		
Borneol fluorinated polymers: poly(methyl methacrylate-co-ethyl acrylate-co-hexafluorobutyl methacrylate-co-isobornyl methacrylate) copolymer	Free radical polymerization method incorporating fluorine components and borneol for antibacterial and antifouling activities.	[57]
UV-shielding and transparent polymer film with bioinspired dopamine–melanin hollow nanoparticles	Synthesis of dopamine–melanin nanoparticles integrated into poly(vinyl alcohol) to enhance UV-shielding performance.	[58]
Humidity-driven color-changing photonic polymer coatings based on hydrogen-bonded, three-dimensional blue-phase liquid crystal networks	Fabrication of coatings exhibiting vivid structural colors and reversible color changes upon humidity variation, for applications such as information encryption and bioinspired camouflage.	[62]
Polyacrylate resin	Super-resolution 3D printing using two-photon polymerization to fabricate antireflective microarrays inspired by the peacock spider's super black structures. The micro-lens arrays exhibit excellent antireflective properties, achieved through tightly packed arrays of slightly pyramidal lenses.	[61]
Energy Storage and Conversion		
Three-dimensional crosslinked polysaccharide network binder for silicon (Si) anodes in lithium-ion batteries, crosslinked with citric acid (CA)	Formation of a 3D crosslinked network around Si particles using sodium alginate (SA) and CA, improving volume expansion handling and electrode robustness.	[29]
Carboxylate–water coordination polymers with hydrogen-bond clusters	Assembly of coordination polymers with transition-metal sites for electrochemical water splitting, inspired by photosystem II's hydrogen bond cluster.	[30]
Redox-active catechol-bearing polymers as organic cathodes for lithium storage	Design of copolymers bearing catechol- and Li-ion-conducting anionic pendants for use in lithium-ion batteries.	[31]
Ultra-robust, highly proton-conductive polymer carbon dot membranes	Fabrication via electrostatic complexation between acidic-group-functionalized polymer carbon dots and sulfonated polyether ether ketone for fuel cell applications.	[32]
Poly(3,4-ethylenedioxythiophene) (PEDOT) with bioinspired catechol pendants for an aqueous proton battery cathode	Grafting PEDOT with catechol pendants to design a high-voltage and high-rate-capacity cathode for aqueous proton batteries.	[33]
Catechol-rich polymers deposited via atmospheric plasma for redox-active thin films	One-step plasma-based synthesis and deposition of catechol-rich polymers, demonstrating potential as organic cathode materials.	[45]
Environmental and Materials Science		
Porous organic polymer-functionalized membranes for CO_2 capture	Incorporating biomimetic material Co-BBP on POPs surface in Pebax matrix, enhancing CO_2 separation performance.	[28]
Energetic polymer composites with hierarchical interface design	Bioinspired "grafting from" polymerization of hyperbranched polyurethane on PDA surface to improve mechanical and safety properties.	[74]
Polymer-based energetic composites with solid explosive crystals reinforced by PDA coating	Coating 1,3,5-triamino-2,4,6-trinitrobenzene (TATB) crystals with PDA to enhance interfacial interactions in polymer-bonded explosives.	[73]
Bioprocessing and Biomolecular Engineering		
Saccharide-responsive smart copolymer (SRSC) with allose units for specific enrichment of sialylated glycopeptides	Integration of allose units into a polyacrylamide chain, enhancing selectivity and binding tunability toward sialic acids through pH and solution polarity.	[37]

Table 2. *Cont.*

Polymer/Composition	Preparation	Ref
Lignocellulose-acting enzymes with carbohydrate-binding modules (CBMs) for bioinspired model assemblies	Designing bioinspired assemblies to study CBM mobility and binding affinity, revealing oligomerization and ferulic acid motifs' role in affinity.	[38]
Uracil-functionalized poly(3-thiophene) for hole-conducting in organic light-emitting diodes	Forms physical cross-linkages for high thermal stability and enhanced hole injection/transport capabilities.	[39]
Core-shell Au nanorod@TiO_2 heterostructure coupled with l-DOPA polymer	Designing a composite to enhance photovoltaic and enzymatic sensing performance, where l-DOPA polymer enhances light harvesting and electron transfer.	[40]
Copolymer of chlorotrifluoroethylene and vinylidene fluoride (FK-800) for a flexible and robust diffusive memristor	Fabricating a memristor to mimic human-like self-protection modalities with a sense of pain, sign of injury, and healing.	[77]

4. Outcomes and Achievements

The exploration of bioinspired polymers and their incorporation into the field of materials science and composite development has facilitated notable advances. A crucial breakthrough in this area is the decoupling of a material's mechanical behavior from its structural components, allowing for the fine-tuning of its mechanical hierarchy and viscoelastic properties through adjustments in metal–ligand crosslinks [1]. This breakthrough has led to the creation of polymer–inorganic hybrid materials using structured polymer templates to control crystal growth [2], representing a significant stride forward. The development of materials that maintain high energy density and efficiency at elevated temperatures, through bioinspired nanoconfinement techniques, marks substantial progress in polymer-based dielectrics [3]. The integration of inorganic ionic oligomers within polymer matrices has yielded materials with unparalleled bending strain and toughness, surpassing natural nacre and many synthetic counterparts [4]. Moreover, the successful mineralization of calcium carbonate within polymer vesicles highlights the potential for biomimetic mineralization in confined spaces [55].

In enhancing mechanical performance and developing composite materials, research has led to remarkable enhancements. Emulating a bioinspired brick-and-mortar structure has increased Young's modulus by 25.1% and strength by 42.3%, improving load transfer and damage resistance [5]. Merging natural designs with engineering principles has produced composite structures with high mechanical performance [6]. Graphene-based nanocomposites have benefited from bioinspired hierarchical structures and toughening mechanisms, enhancing their mechanical properties [7]. The creation of high-toughness ceramics that mimic the structure of bone, featuring significant organic–inorganic interfaces, has improved energy dissipation and mechanical resilience [52]. Additionally, polymer composite films inspired by the layered microstructure of nacre have achieved extraordinary levels of stiffness, strength, and toughness [10].

Polymer/graphene composites with a nacre-like layered structure have enhanced mechanical and electrical properties, pioneering a new method for high-content graphene reinforcement [49]. Ceramic/polymer composites with a lamellar structure have shown improved mechanical performance [54]. Innovations include a doubling of strength and a five-fold increase in plasticity in aluminum composites reinforced with soft polymers, processed using a friction stir technique [56]. Engineering hierarchical structures in nanocomposites has led to superior mechanical properties and multiscale deformation mechanisms [9], while bioinspired mineralization techniques have significantly bolstered composite mechanical properties for better reinforcement [11]. Research has yielded high strength and toughness in GO/polymer nanocomposite paper, suitable for electronic and engineering applications [60], and enhanced the electrical and thermal conductivity in copper matrix composites through a straightforward fabrication process [63].

In the sphere of adhesion and surface engineering, recent innovations have tackled complex challenges with significant ingenuity. The development of a reversible interlocker, leveraging the van der Waals forces between high-aspect-ratio polymer fibers, has provided a robust shear locking force while facilitating easy separation [12]. Advances in durable bioplastics and ultra-strong adhesives have emerged from nucleobase-containing polymers that form complementary hydrogen-bonding interactions [13]. Ultra-strong and reversible adhesives, taking cues from the adhesion strategies of creeper plants, enable controlled adhesion and detachment through reversible phase transitions induced by light and heat [44]. Materials combining effective adhesion with anisotropic thermal conductivity, drawing inspiration from the natural adhesion mechanisms of snails and mussels, offer both high surface adhesion and enhanced phonon transport [50]. A simple polymerization process, emulating the adhesion strategy of barnacles, has resulted in interfaces with high adhesive strength, durability, toughness, and fatigue resistance [51]. Furthermore, a bioinspired dynamic bonding technique has significantly improved the adhesion strength of polymer resins, increasing their toughness by 50% [53].

In the field of tribology, significant strides have been made toward improving the wear resistance of materials. Silica surfaces, in particular, have demonstrated high wear resistance, with the performance depending on the anchoring method. The use of catechol groups combined with electrostatic forces has led to enhanced outcomes [48]. By emulating the lubrication mechanisms observed in synovial joints, researchers have achieved impressively low friction coefficients and wear rates under extreme conditions [46]. Additionally, the development of self-organized prismatic films on polymeric surfaces, taking inspiration from biomineralization processes, offers a new avenue for boosting tribological performance [14].

In sensing and actuation, a broad spectrum of bioinspired innovations has emerged. These advancements range from sensors with turn-on luminescence for selective sensing influenced by Ph [15], to materials designed for adaptive light control, self-shading, and color tuning in response to environmental shifts, suitable for smart textiles and bionic skins [16]. Noteworthy achievements include materials that exhibit exceptional humidity sensing over a wide range, with quick response and recovery [17], materials that allow for large and directional deformation, leading to reversible color changes [18], ultrafast soft actuators capable of precise deformation control for applications in micromachines and soft robotics [19], and hybrid hydrogel actuators that simulate an "extension–grasp–retraction" motion, pushing the boundaries of soft actuation [20]. Innovations also include materials with enhanced flexibility, self-healing abilities, and underwater functionality for complex motion sensing [66], advancements in ionic permeability and specific ion channel isolation for new sensing and filtration technologies [70], high-sensitivity photodetection for bioelectronic interfaces [71], programmable polymer gel films for dynamic 3D origami/kirigami structures in bioelectronics and micro-robotics [72], a self-powered flexible nanogenerator with excellent piezoelectric energy conversion efficiency for energy harvesting [76], and ultrasensitive sensors for liquid environments inspired by fish swim bladders, demonstrating unmatched performance across solid/liquid/gas interfaces [78]. These developments signify the profound impact of bioinspired approaches across various scientific and engineering disciplines.

In the biomedical and drug delivery arena, remarkable innovations include integrating noble metal nanostructures into three-dimensional porous scaffolds for sensing, catalysis, and tissue engineering applications [21]. Surface treatments that boost cell viability and functionality in organ-on-a-chip systems represent a significant leap forward in pathophysiological research and drug screening [22]. Novel antibacterial coatings that offer tunable adhesion and antimicrobial properties open new paths for medical applications [64]. Enhanced methods for dopamine delivery for Parkinson's disease treatment, featuring high encapsulation efficiency and lower toxicity, are promising [23]. Progress in materials that are compatible with blood and tissue for artificial organs highlights the potential for revolutionary biomedical devices [42]. Further advancements include targeted drug delivery systems [43], the reversible control of peptide–polymer structure transitions using calcium ions [65], and bioactive scaffolds that support both bone formation and blood vessel growth for vascularized bone regeneration [24]. Developments that bridge proteins and bulk polymers offer adjustable properties for uses in biomedical and nanoscience fields [67], extending to dental materials with superior fatigue resistance [68] and the creation of strong, biocompatible, and bioactive nanocomposite films for tissue engineering and food packaging [69]. Additionally, the development of antifouling and antimicrobial polymer membranes featuring improved hydrophilicity, wettability, and durability [75] marks significant progress.

In both biomedical and environmental contexts, initiatives to control ice crystal growth have shown inhibition activity akin to that of ice-binding proteins at various molecular weights [25]. Efforts to enhance adsorption and desorption on chemically structured substrates are leading to environmentally friendly products with superior performance [26]. The creation of durable superhydrophobic surfaces with hierarchical structures provides exceptional water repellence, ideal for self-cleaning and antifouling applications [27]. Progress in developing surfaces resistant to fouling by proteins, cells, and bacteria is vital for maintaining the functionality and safety of biomedical devices [41]. Advances in the hydrophobicity and corrosion resistance of magnesium alloys, inspired by the lotus leaf, suggest potential applications in industrial anticorrosion strategies. Eduok et al.'s evaluation of the coatings' barrier efficacy and corrosion resistance through electrochemical and surface analyses demonstrates their applicability in metal surface treatments and anticorrosion paints [47] (Figure 1).

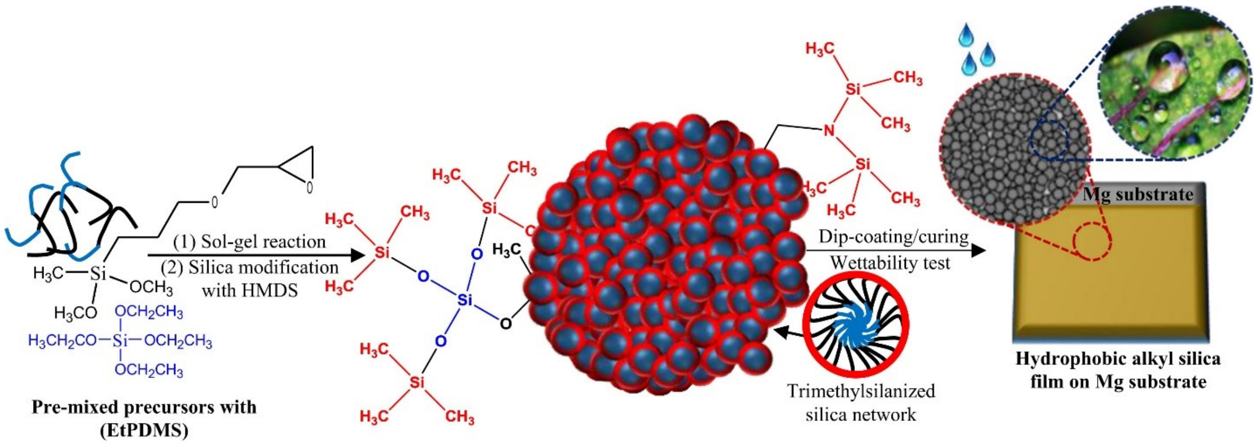

Figure 1. An illustrative preparation protocol of a bioinspired alkyl-silanized coating for Mg corrosion prevention reported in this study [47].

In the area of electrical and electronic materials, notable achievements have been realized, such as the development of a metal-free, high-performance, electrically conductive adhesive. This innovation enables effective electrical connections for a broad range of uses [34]. Another milestone is the capacity to selectively influence the crystallinity in shape-memory polymers, offering a path toward re-processable and environmentally sustainable options for advanced morphing devices [35]. Furthermore, the creation of chitosan-based memory devices, which provide consistent and reliable resistive switching, represents a green alternative for the field of nanoelectronics [36].

Significant progress has been made in environmental and antifouling applications with the development of long-lasting, eco-friendly solutions for combating bacterial and marine biofouling [57]. Advances in polymer films that block UV radiation while remaining transparent to visible light cater perfectly to UV-protection needs [58]. The fabrication of micro-structured polymer surfaces with antireflective qualities, inspired by the ultra-black appearance of the peacock spider, showcases the successful merger of nature-inspired designs with technological progress [61]. Figure 2 features 3D models of various microarrays designed from surface equations and executed in polyacrylate resin via two-photon polymerization. Examined using scanning electron microscopy, these models demonstrate excellent antireflective capabilities with very low reflectance at normal incidence [61].

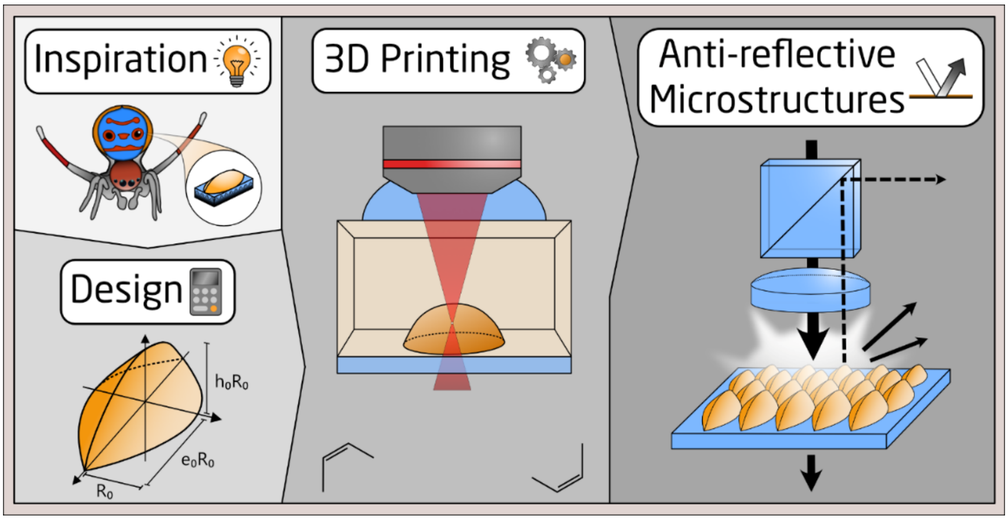

Figure 2. The fabrication and characterization of antireflective microarrays stimulated by the peacock spider's super-black structures encountered in nature. First: different microarray 3D models are produced from a surface equation. Second: the arrays are invented in a polyacrylate resin via super-resolution 3D printing through two-photon polymerization. Third: the bioinspired micro-lens arrays show excellent antireflective properties [61].

Moreover, the development of humidity-sensitive color-changing photonic polymer coatings marks a leap forward in sensing, display technologies, anticounterfeiting, and biomimetic camouflage [62], emphasizing the dynamic and influential nature of research in these areas with wide-ranging potential applications.

In energy storage and conversion, significant advancements have been made. Improvements in the mechanical strength and cycle retention of Si anodes for lithium-ion batteries counter the substantial volume changes during charge and discharge cycles [29]. The production of redox-active thin films via atmospheric plasma deposition marks a significant leap in battery technology, presenting an effective method to enhance lithium-ion batteries [45]. Bimetallic coordination polymers have demonstrated high efficiency in catalyzing water splitting, showcasing outstanding performance [30]. Innovations in lithium storage, featuring ultra-durable electrochemical energy storage solutions that maintain high capacity over numerous cycles [31], and the development of highly proton-conductive membranes for fuel cells that combine resilience with dimensional stability, signify progress in fuel cell technology [32]. The introduction of aqueous proton batteries, characterized by high voltage and superior rate capacity, indicates a notable advancement in energy storage [33].

In environmental and materials science, substantial advances have been achieved in CO_2 separation techniques, attaining performances that exceed the Robeson upper limit for CO_2/N_2 selectivity [28]. The mechanical properties of energetic composites have been enhanced through interface reinforcement, improving tensile strength, compression strength, and resistance to deformation over time [73]. Additionally, energetic polymer composites have experienced significant gains in mechanical and safety performance via hierarchical interface design [74], highlighting the continual innovation and impact of research in these domains.

In the field of bioprocessing and biomolecular engineering, significant progress has been made in improving the selectivity and efficiency of sialylated glycopeptide enrichment. This advancement is pivotal for identifying disease biomarkers [37]. Studies focusing on the affinity properties of carbohydrate-binding modules have offered valuable insights with the potential to enhance bioprocessing, especially in the biorefinery of plant biomass [38]. In the domain of organic light-emitting diodes (OLEDs), the development of new hole-conducting polymers has led to devices that exhibit high thermal stability and superior performance [39]. Innovations in photovoltaic and enzymatic sensing have been facilitated by the incorporation of core-shell heterostructures with bioinspired polymers [40], and the creation of human-like self-protection mechanisms in flexible electronics, which demonstrate remarkable switching endurance, opens up possibilities for enhanced human–robot interactions [77].

These breakthroughs, spanning energy storage and conversion, environmental sustainability, bioprocessing, and more, highlight the dynamic and transformative nature of research in bioinspired materials science. Table 3 details these innovations across a multitude of areas, including structural design, material composition, adhesion techniques, surface engineering, tribological improvements, sensing and actuation, biomedical applications, energy storage and conversion, environmental sustainability, and bioprocessing.

Table 3. Bioinspired material innovations across diverse applications.

Category	Description	Ref. #
Bioinspired Structural Design for Mechanical Enhancement	Bioinspired designs improving mechanical properties (strength, toughness, and Young's modulus) via brick-and-mortar, hierarchical structures.	[4,5,9,59]
Advanced Material Composition for Broad Property Enhancement	Polymer–inorganic hybrids and graphene-based nanocomposites enhancing energy density and electrical/thermal conductivity.	[2,3,7,49,55,60,63]
Innovative Adhesion, Surface Engineering, and Tribological Performance	Molecular/surface interactions leading to ultra-strong adhesives and surfaces with controllable adhesion-detachment, inspired by natural mechanisms.	[12,13,44,50,51,53]
	Improved wear resistance, lower friction coefficients under various conditions, and mimicking natural lubrication systems.	[14,46,48]
Sensing, Actuation, and Biomedical Applications	Responsive materials for smart textiles, soft robotics, bioelectronics through luminescence, color change, and humidity sensing.	[15–20,71,72]
	Advancements in tissue engineering, drug delivery systems, antibacterial coatings for improved health outcomes, and medical devices.	[21,23,24,38,42,43,64]
Energy Storage, Conversion, and Environmental Sustainability	Improved mechanical strength, cycle retention in Si anodes, redox-active thin films, electrocatalytic performance, and proton-conductive membranes.	[29–33,45]
	CO_2 separation performance and mechanical properties of energetic composites for environmental sustainability and safety.	[28,73,74]
Bioprocessing and Biomolecular Engineering	Breakthroughs in sialylated glycopeptide enrichment, optimization of bioprocesses, organic electronics, and enzymatic sensing.	[37–40,77]

5. Testing and Evaluation of Bioinspired Polymer Composites

In the advancement of materials science and engineering, a comprehensive suite of specialized tests and analyses is indispensable for assessing various material properties under different conditions. This section highlights the essential tests across multiple research domains, enabling scientists to precisely evaluate mechanical, physical, electrical, and surface characteristics of materials.

For evaluating mechanical, physical, and tribological performance, it is vital to understand materials' toughness, strength, deformation behavior, viscoelastic properties, and wear resistance. Essential tests in this area include dynamic mechanical analysis [1], the finite element (FE) method for deformation analysis [5], and mechanical testing for bending strains [4]. Tribological tests assess wear resistance [46,48], while specific mechanical tests for ceramics or polymer composites [11,54,59,60], investigation of fatigue behavior under cyclic compression [68], and mechanical assessment under hydrogen-bonding interactions [69] provide a comprehensive evaluation of material resilience.

In material synthesis, structure, and surface engineering, synthesis methods and structure–property relationships are fundamental. This includes using structured polymer templates for crystal growth [2], electro-formation for polymersomes [55], and solution evaporation for reinforced polymers [49]. Surface engineering techniques, such as thiol-ene polymerization [13] and van der Waals force-assisted binding [12], enhance adhesion and develop antifouling membranes [50]. Coarse-grained molecular dynamics simulations for adsorption/desorption studies [26] and the creation of bioinspired polymers [41] are key.

For thermal, electrical, and electronic properties, evaluating material performance under temperature variations and their electrical functionalities is critical. This involves assessments of high-temperature mechanical and electrical performance [3], thermal annealing effects [8], and electrical and thermal conductivity [63]. Characteristics of solution-processed electronic materials [36], digital photothermal effect analysis [35], and light-induced actuation [19,20] are essential for creating responsive and dependable materials.

In sensing, actuation, and biomedical applications, the focus is on materials' responsiveness to external stimuli and biocompatibility for medical applications. This includes luminescence-based sensing [15], supramolecular self-assembly [16], and evaluations of stretchable strain sensors [66]. The efficacy of drug delivery systems is assessed through in vitro and in vivo evaluations [23,24,42], with electrospinning [21] and cell viability tests [22] crucial for biocompatibility assessment.

Advanced manufacturing, environmental, and energy applications emphasize innovative manufacturing techniques and addressing environmental challenges. Tests for reflectance and transmittance characterization [61,62], ice recrystallization inhibition [25], and CO_2 permeability in membranes [28] advance this field. In energy storage and conversion, assessing mechanical properties and cycle retention in batteries [29], along with electrochemical characterizations [30,45], are imperative for improving efficiency and capacity.

Finally, in bioprocessing, biomolecular engineering, and environmental science, the emphasis is on leveraging biological principles for material innovation. This includes tests for specific enrichment capacity [37], fluorescence recovery after photobleaching [38], and photoelectrochemical performance evaluations [40], showcasing the diverse methodologies employed in these groundbreaking research areas.

6. Limitations in Developing Bioinspired Synthetic Polymers

The advancement of bioinspired polymer composites has brought significant breakthroughs to various fields yet faces notable obstacles that hinder their broad implementation and practical use. Grouping these challenges cohesively without overlap offers a clearer perspective on the difficulties encountered and pinpoints specific areas needing dedicated improvement efforts.

One major hurdle is scalability and manufacturing. Moving bioinspired composites from the lab to large-scale production presents considerable challenges due to the intricate fabrication processes required and the necessity for precise control over the properties of materials. Achieving uniformity and the ability to scale up for industrial applications proves challenging, affecting the potential for mass production and commercial success while trying to maintain performance and environmental advantages.

Cost and efficiency present another obstacle. The creation and manufacturing of sophisticated bioinspired materials frequently involve high expenses, particularly when dependent on scarce or costly resources or when elaborate processing methods are needed. These cost considerations restrict the availability and broad adoption of bioinspired materials in diverse sectors.

Durability and stability are also of concern. Even with improvements in mechanical properties, questions about the long-term durability and stability of bioinspired composites under real-world conditions linger. This includes issues related to maintaining enduring stability and consistent performance across various, possibly severe, environments and ensuring the longevity and reliability of materials for use in extreme situations or for extended medical applications.

Furthermore, integration challenges complicate the incorporation of bioinspired materials into current technological and biological systems. The distinctive properties and demands of many bioinspired materials necessitate considerable adjustments and fine-tuning to guarantee that these innovative materials can operate effectively within existing frameworks and technologies.

Identifying these limitations features the critical areas where additional research, creativity, and strategic partnerships are essential to surmount the obstacles to the extensive use of bioinspired polymer composites. Tackling these challenges will not only improve the practical application of these materials across various industries but will also pave the way for new opportunities for sustainable and efficient solutions inspired by the natural world.

7. Future Directions

The advancement of bioinspired polymer composites is at a pivotal juncture, necessitating novel strategies across research, development, and deployment to surmount existing barriers and unlock the full potential of these materials. By consolidating future directions into clear themes, we pinpointed crucial focus areas, as outlined below.

Scalability and manufacturing innovation calls for the creation of scalable and cost-efficient manufacturing methods that maintain the quality and properties of bioinspired composites. Innovating manufacturing techniques to handle the complexity and precision of bioinspired designs is essential for improving commercial viability and enabling mass production.

Sustainability and environmental impact emphasize the importance of a detailed analysis of the environmental impact, recyclability, and lifecycle costs of bioinspired composites. This effort is aimed at promoting sustainable development within the field to ensure that these materials are created and used responsibly, minimizing environmental footprints. It is imperative to focus research on both the scalability and sustainability of these materials, considering their environmental implications.

Advanced material properties and integration highlights the need for incorporating additional functionalities, such as self-healing, adaptability, and sensory capabilities, into bioinspired composites. Expanding the functionalities will broaden their applicability, making them suitable for an extensive range of uses. The development of smart and multifunctional materials that respond to environmental stimuli or perform multiple functions is crucial.

Collaborative and interdisciplinary approaches stress the need for enhanced collaboration across various disciplines due to the complex nature of challenges facing bioinspired composites. Encouraging interdisciplinary research among materials scientists, chemists, biologists, and engineers is vital for sparking innovative breakthroughs and tackling current limitations.

Durability, testing, and performance enhancement focus on improving the durability, stability, and functionality of bioinspired materials in real-world conditions. Conducting thorough in situ testing and longevity studies will provide insights into these materials' performance and degradation mechanisms over time, informing further development.

8. Conclusions

The cumulative achievements in materials science and composite development have marked a path for significant advancements across various sectors. Bioinspired polymer composites have demonstrated their versatility, offering solutions with immense potential across mechanical performance, surface engineering, tribology, sensing and actuation, biomedical applications, electrical and electronic materials, environmental solutions, and bioprocessing. Despite these advancements, challenges related to scalability, cost, durability, and integration pose obstacles to their widespread adoption. Addressing these challenges with creative and focused efforts, including scalable manufacturing, sustainable development, enhancement of material properties, collaborative research, and comprehensive testing, is essential. By prioritizing these future directions, the scientific community can lead the field toward creating sustainable, functional, and technologically compatible materials, opening new avenues for innovation inspired by the intricacies of nature.

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