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# Bioinspired Materials, Designs, and Manufacturing Strategies for Advanced Impact-Resistant Helmets

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**The development of next-generation helmet systems is increasingly guided by bioinspired design strategies that replicate nature's hierarchical and multifunctional structures to achieve superior energy absorption and impact mitigation. This review synthesizes recent progress in materials, structural designs, and manufacturing techniques inspired by biological models such as nacre, woodpecker skull, porcupine quills, beetle exoskeletons, and diatom frustules. Emerging fabrication approaches, including additive freeze casting, manufacturing, and hybrid fabrication techniques, enable the creation of complex, tailored architectures with programmable mechanical responses. Innovations in lightweight nanocomposites, auxetic lattices, and functionally graded foams are highlighted for their ability to improve resistance to both linear and rotational impacts. The integration of smart materials (e.g., self-healing polymers, shape memory materials), sustainable alternatives, and multifunctional reinforcements further advance helmet performance. Key challenges, including design complexity, scalability, long-term durability, computational modeling, and cost-effectiveness, are also examined. Finally, future research directions are outlined, proposing a roadmap for designing safer, smarter, and more sustainable helmets by uniting bioinspired structural principles with cutting-edge materials science and digital manufacturing.**

## 1. Introduction

Helmets have evolved over millennia to meet the demands of diverse environments and applications, ranging from ancient battlefields to contemporary sports, military, industrial, and medical settings. For instance, they have proven highly effective in preventing moderate to severe head injuries in high-impact sports such as American football and cycling.[1,2] In military contexts, combat helmets provide essential protection against ballistic threats, blunt force trauma, and blast-induced traumatic brain injuries (TBIs).[3] Combat helmet development has traditionally prioritized resistance to ballistic impacts and blunt forces. Modern iterations emphasize lightweight materials, expanded coverage, and seamless integration with electronic systems. Materials like aramid and ultra-high molecular weight polyethylene (UHMWPE) offer superior ballistic resistance while ensuring user comfort.[3–5] In sports, rugby helmets have undergone significant evolution, with recent models featuring larger and heavier designs, as well as advanced padding that reduces the head injury criterion (HIC), peak head acceleration, and rotational acceleration in impact tests.[6,7] In cycling, computational biomechanics has shown that while helmets reduce peak linear accelerations and skull fracture risk, they may inadvertently elevate rotational acceleration—a major factor in concussions. To address this, hybridized natural-fiber composites, such as kenaf-reinforced structures, are being explored to address this while offering sustainability benefits.[8]

Industrial helmets are crucial for safety in construction and heavy-duty environments. Recent advances in these helmets focus on thermal regulation, shock resistance, and ergonomic comfort.[9] Materials such as *p*-aramid and carbon fiber composites have outperformed conventional plastics like acrylonitrile butadiene styrene (ABS) and polyethylene (PE) in both strength and heat resistance.[10] Helmets incorporating phase change materials offer thermal comfort by absorbing excess heat, improving usability in hot climates.[11] However, even with improvements, traditional hard hats show limitations in

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protecting against extreme impacts, as evidenced by continuing fatal injuries in industrial settings.[12]

Despite these efforts, conventional helmet materials face key limitations in managing rotational impacts, managing thermal buildup, and maintaining structural integrity under prolonged use.[11] For example, expanded polystyrene (EPS) foam, commonly used in bicycle helmets, performs well under linear loading but inadequately mitigates rotational forces, a primary contributor to severe brain trauma.[10] Thermal discomfort from heat accumulation can discourage long-term wear, compromising safety.[11] Structural defects such as weak interfacial bonding, delamination, shrinkage, and porosity also degrade helmet performance by undermining hardness, wear resistance, and mechanical integrity.[13] These challenges highlight the urgent need for advanced materials and optimized structural solutions.

Recent research in helmet technology has focused on optimizing energy transmission and absorption to mitigate brain deformation and reduce the incidence of mild TBIs.[14] Emerging innovations, such as bioinspired reusable composites, mechanical metamaterials, and fluid-based shock absorber systems, are being explored to enhance energy absorption while maintaining low weight and high structural efficiency.[14,15] These efforts reinforce the pivotal role of helmet systems in minimizing head injuries across a broad range of use cases.

Nature offers powerful inspiration for designing energy-absorbing and structurally efficient materials.[16,17] Biological composites—such as the hierarchical microstructure of arthropod cuticles—achieve exceptional stiffness and toughness that often outperform synthetic counterparts.[18] Bioinspired geometries, including starfruit-shaped lattice structures and fractal morphologies based on bamboo, serpentine, and honeycombs, have demonstrated remarkable improvements in energy dissipation and structural resilience.[19–21] Other promising designs include Bouligand-type architectures in nanocomposites,[22] bone-like nanomechanical gradients,[23] and high-strength spider/silkworm silk analogs.[24] The advent of additive manufacturing (AM) has made it possible to precisely fabricate these complex structures with tailored properties and functionality.[25,26]

This review presents a comprehensive overview of the convergence between bioinspired structural design, advanced manufacturing technologies, and helmet performance optimization. Natural models—such as nacre, woodpecker skulls, bone, and diatom frustules—offer templates for creating hierarchical, lightweight, and damage-tolerant architectures with superior mechanical and thermal performance.[27–30] The integration of AM with computational tools enables replication and enhancement of these structures for engineering applications. Furthermore, data-driven material selection and topology optimization are facilitating the development of composites with enhanced strength, impact resistance, and weight efficiency.[27,31] By leveraging bioinspired principles alongside cutting-edge digital design and fabrication technologies, next-generation helmets are poised to achieve unprecedented levels of protection, comfort, and sustainability across various applications, including sports, defense, industry, and healthcare.

The remainder of this manuscript is organized as follows: Section 2 reviews biological structures that inspire impact-resistant helmet designs. Section 3 examines the translation of these biological insights into engineering design strategies. Section 4 focuses on manufacturing methods capable of realizing such complex architectures. Section 5 addresses material selection strategies, including matrix, reinforcement, and functional elements. Section 6 discusses challenges and opportunities for future research. Finally, Section 7 concludes the review with a summary and outlook.

## 2. Bioinspired Impact Protection Mechanisms for Helmet Design

Effective helmet design requires a deep understanding of the biomechanics of head injuries. Research has demonstrated that different types of brain trauma—such as skull fractures, cerebral contusions, and concussions—arise from distinct mechanical causes, necessitating tailored protection strategies.[32] Rotational acceleration is highly correlated with severe TBIs, including acute subdural hematomas.[33] To address this, helmet designs incorporating rotation-damping mechanisms have been shown to significantly reduce rotational head acceleration and the associated risk of TBIs.[34,35] For instance, snow sport helmets equipped with such systems have demonstrated a dramatic reduction in concussion probability—from 89% to as low as 7%.[35] While helmets are known to reduce the incidence of skull fractures by 69%, cerebral contusions by 71%, and intracranial hemorrhages by 53%, their effectiveness in preventing uncomplicated concussions remains uncertain.[32] This highlights the complex, multifaceted nature of brain injuries and underscores the need for innovative, multifunctional helmet designs.

In this context, nature provides a rich source of inspiration for engineering advanced protective systems. Many biological structures exhibit remarkable energy absorption, fracture resistance, and mechanical resilience, making them ideal templates for helmet design. This section highlights several biological models, including nacre, porcupine quills, beetle exoskeletons, and the woodpecker's cranial system, that inform the design of next-generation impact-resistant helmet systems.

### 2.1. Nacre

Nacre found in mollusk shells is composed of hard aragonite platelets embedded within a soft organic matrix arranged in a brick-and-mortar configuration (**Figure 1**a).[36] Its microstructure exhibits both columnar and sheet layering (Figure 1b), which contributes to its resistance to crack propagation and structural failure under impact.[37] Nacre-inspired composites have demonstrated exceptional energy absorption capacity—up to 60 $J g^{-1}$ in some cases.[38] The dominated platelet sliding mechanisms under tensile loading are key to the high toughness and ductility of nacre[39] (Figure 1c). Sun et al. showed that nacre-mimetic structures have robust resistance to crack initiation and propagation under low-velocity impact testing.[40] Building on this, Gu et al. developed 3D biomimetic conch-shell composites with superior impact performance due to the hierarchical layering.[41] Their study found that incorporating a second level of cross-lamellar hierarchy in 3D-printed composites increased impact performance by 70% compared to single-level hierarchical designs and by 85% relative to nonhierarchical counterparts, as validated through simulations, AM, and drop-tower testing.

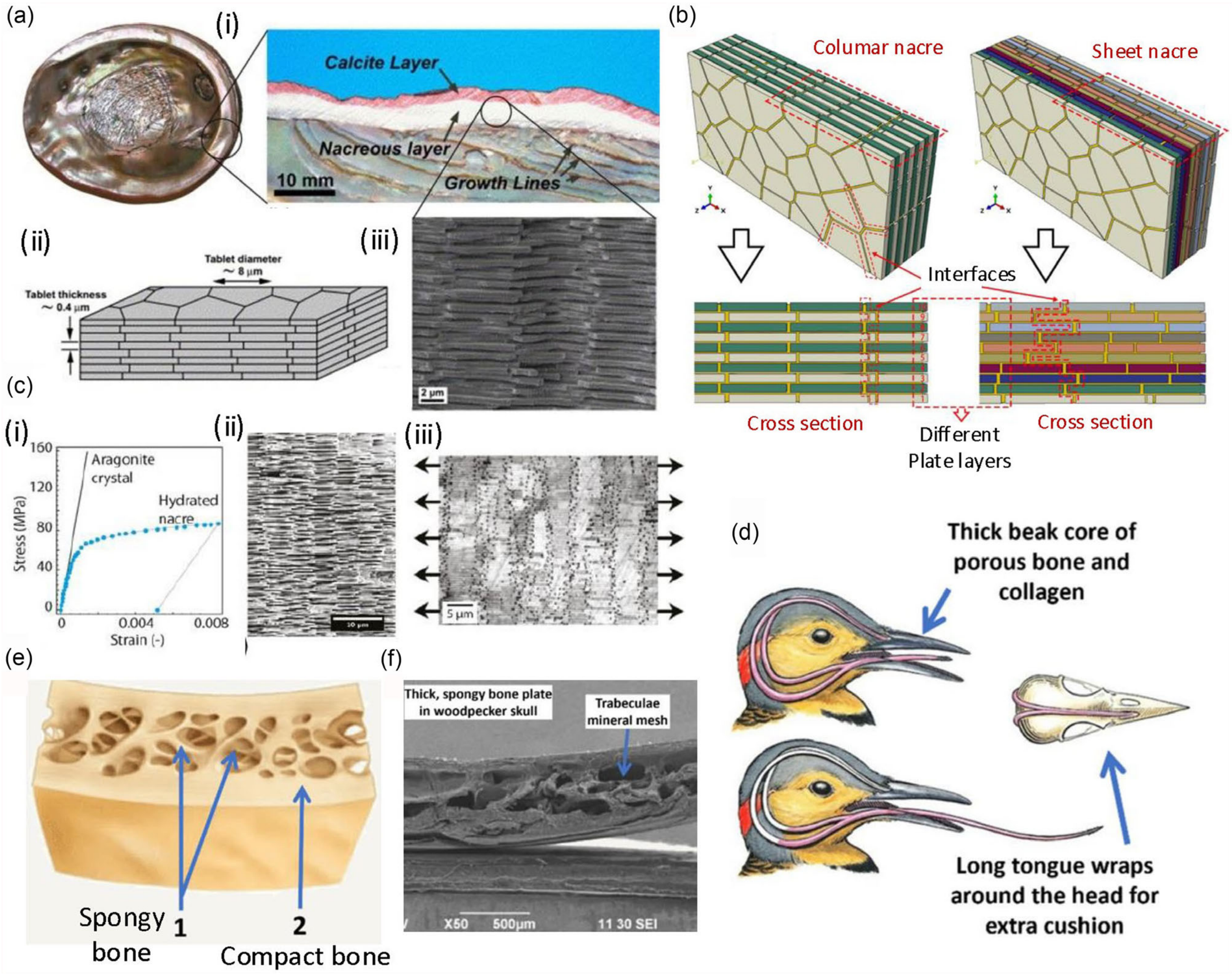


**Figure 1.** Bioinspired impact-resistant structures derived from nacre and woodpecker skull. a) Hierarchical architecture of nacre. i) Macroscale: Red abalone shell showing a layered arrangement; ii) mesoscale schematic illustrating aragonite tablet organization; and iii) SEM image of nacre fracture surface revealing toughening morphology. Reproduced with permission.[36] Copyright 2007, Elsevier. b) Microstructural views of nacre highlighting columnar and sheet configurations that resist crack propagation via layered architecture. Reproduced with permission.[37] Copyright 2024, Springer Nature. c) Mechanical performance of nacre: i) Bending stress–strain comparison between nacre and monolithic aragonite; ii) SEM image of platelet layering; and iii) SEM image showing platelet sliding as a primary toughening mechanism under tensile loading. Reproduced with permission.[38] Copyright 2014, Wiley. d) Woodpecker cranial adaptation with the tongue wrapping around the skull to aid in vibration damping and shock isolation during pecking. Reproduced with permission.[45] Copyright 2011, PLOS. e) Schematic of woodpecker cranial bone structure illustrating the arrangement of spongy and compact bone regions. Reproduced with permission.[17] Copyright 2024, MDPI. f) SEM image of spongy bone between the beak and brain, functioning as a natural impact-absorbing structure. Reproduced with permission.[17] Copyright 2024, MDPI.

The plastic deformation and stress redistribution mechanisms in nacre give rise to visible "white bands," a hallmark of energy dissipation, enabling the material to be up to 40 times tougher than its constituents. Future helmet designs can leverage reinforcement learning algorithms and topology optimization tools to digitally evolve nacre-inspired microstructures, resulting in even greater impact performance and weight efficiency.[42,43]

### 2.2. Woodpecker Skull

Contrary to earlier assumptions that the woodpecker skull acts like a shock-absorbing cushion, recent studies suggest it functions more like a rigid hammer to efficiently transmit impact forces.[44] However, the woodpecker exhibits several anatomical adaptations that mitigate brain injury despite repeated high-g impacts. These include: a long tongue that wraps around the skull, acting as a stabilizing structure; porous, spongy bone positioned between the beak and brain; and a layer of cerebrospinal fluid that helps dissipate mechanical energy (Figure 1d).[45] Wang et al.[45] and Yoon and Park[46] demonstrated that these biological adaptations have inspired microscale shock-absorbers for protective devices and microelectromechanical systems. While the precise function of each component in impact mitigation is still under investigation, the multimaterial, hierarchical structure of the woodpecker's cranial system provides a rich template for designing biomimetic shock-absorbing helmet liners.

 

Structural elements that mimic the transition from spongy to compact bone (Figure 1e,f) may be especially useful for mitigating both linear and rotational impacts in advanced helmet systems.[47]

### 2.3. Porcupine Quills

Porcupine quills exhibit remarkable mechanical strength and energy absorption due to their specialized layered architecture (**Figure 2**a).[48] Structurally, each quill consists of a thin outer cortex surrounding a core of closed-cell foam made of α-keratin, providing both lightweight design and mechanical robustness (Figure 2b).[49] Inspired by this natural composite, Li et al. developed a hexagonal bionic structure composed of a soft black phase and a stiff white phase, which exhibited excellent impact performance across a broad velocity range (1–7 $m\ s^{-1}$).[50] X-ray microcomputed tomography revealed a functionally graded design in the internal foam, contributing to improved load distribution and energy dissipation.[51] In addition to the core-shell structure, porcupine quills possess microscale barbs that enhance adhesion to external surfaces and facilitate progressive energy absorption during deformation.[52] These combined features—layered morphology, gradient density, and integrated barbed geometry—make porcupine quills a compelling model for buckling-resistant columns and helmet liner structures capable of absorbing high-energy impacts (Figure 2c).[50,53,54] Furthermore, quill-inspired structural designs have been successfully prototyped using 3D modeling techniques. As shown in Figure 2d, a bioinspired ribbed honeycomb structure derived from porcupine quill geometry exhibits energy absorption of 30.01 $kJ\ kg^{-1}$ with an impact efficiency of 87.16%, significantly outperforming traditional honeycomb cores.[55] These results highlight the potential of porcupine quill-inspired structures for enhancing helmet liner performance under dynamic loads.

### 2.4. Beetle Exoskeleton

The exoskeleton of the diabolical ironclad beetle (*Phloeodes diabolicus*) is known for its extraordinary mechanical resilience, with a complex hierarchical structure composed of interlocked, hardened elytral segments connected by weakened, compliant interfaces (Figure 2e).[56] These layered, interdigitated geometries help distribute mechanical stress, delay crack propagation, and enhance energy dissipation under extreme compressive loading.[57] Inspired by this natural armor, researchers have developed biomimetic plate structures that surpass the performance of traditional crash-protective designs. For instance, beetle elytra-inspired plates have demonstrated an improvement of up to 115% in energy absorption compared to conventional honeycomb panels under dynamic compression.[58] Additionally, hyperbolic lattice patterns modeled after the beetle's forewing microarchitecture (Figure 2f) have shown superior crashworthiness, offering a promising approach to helmet shell optimization.[59] The beetle elytron plate (BEP)—a synthetic analog incorporating graded stiffness and complex interlocking geometries—has been shown to outperform a conventional honeycomb plate (HP) in both impact toughness and structural stability (Figure 2g).[60] These beetle-inspired structures introduce new opportunities for lightweight, fracture-resistant helmet shells that can maintain integrity under severe impact scenarios.

### 2.5. Skull

The human skull serves as a powerful natural model for impact resistance and energy dissipation, offering valuable design cues for optimizing helmet liner systems. Composed of a combination of dense cortical bone and spongy trabecular bone,[61] the skull's hierarchical structure is inherently designed to absorb and distribute mechanical energy, much like modern helmet liners aim to do. Zhang et al.[54] investigated the use of hierarchical lattice structures inspired by the trabecular architecture of bone, demonstrating that such bioinspired designs significantly reduce the risk of head injury compared to conventional EPS liners. These structures enhance both crush efficiency and structural compliance, mimicking the skull's natural ability to attenuate force through controlled deformation. Building on this concept, Zarei and Kruger[62] developed 3D woven honeycomb structural composites for helmet liners that replicate the force distribution characteristics of cranial bones. Their results showed enhanced energy absorption capacity and reduced back-face deformation, closely aligning with the skull's strategy of spreading impact energy over a larger surface area. Chirwa et al.[63] examined composite shell stiffness and concluded that materials with lower in-plane shear strength could enable additional energy-absorbing mechanisms. This behavior parallels the skull's capacity to accommodate and dissipate force without catastrophic failure. Furthermore, Zhang et al.[64] proposed functionally graded foam (FGF) helmet liners that emulate the spatial variation in density and stiffness found in the human skull. These graded materials offer improved adaptability to different loading conditions, reducing peak acceleration and enhancing wearer comfort. Together, these studies underscore the skull's value as a bioinspired template for designing next-generation helmet liners that optimize impact attenuation through graded, hierarchical, and energy-dissipating structures.

## 3. Design Principles for Helmets with Enhanced Energy Absorption

Building on the biological strategies reviewed in Section 2, this section will explore how these insights have been translated into engineering principles for next-generation helmet design. The design focus has shifted from purely passive protection to active, adaptive, and multifunctional systems capable of mitigating both linear and rotational impacts.

### 3.1. Hierarchical and Anisotropic Structures

Hierarchical lattice structures inspired by nacre and skull are increasingly used in advanced helmet liners. Zhang et al.[54] demonstrated that such architectures outperform traditional EPS liners in dissipating impact energy. Similarly, anisotropic foams—such as directionally aligned polyether sulfone—have demonstrated a 40% reduction in peak rotational acceleration and a 37% decrease in linear acceleration.[33] These anisotropic

 

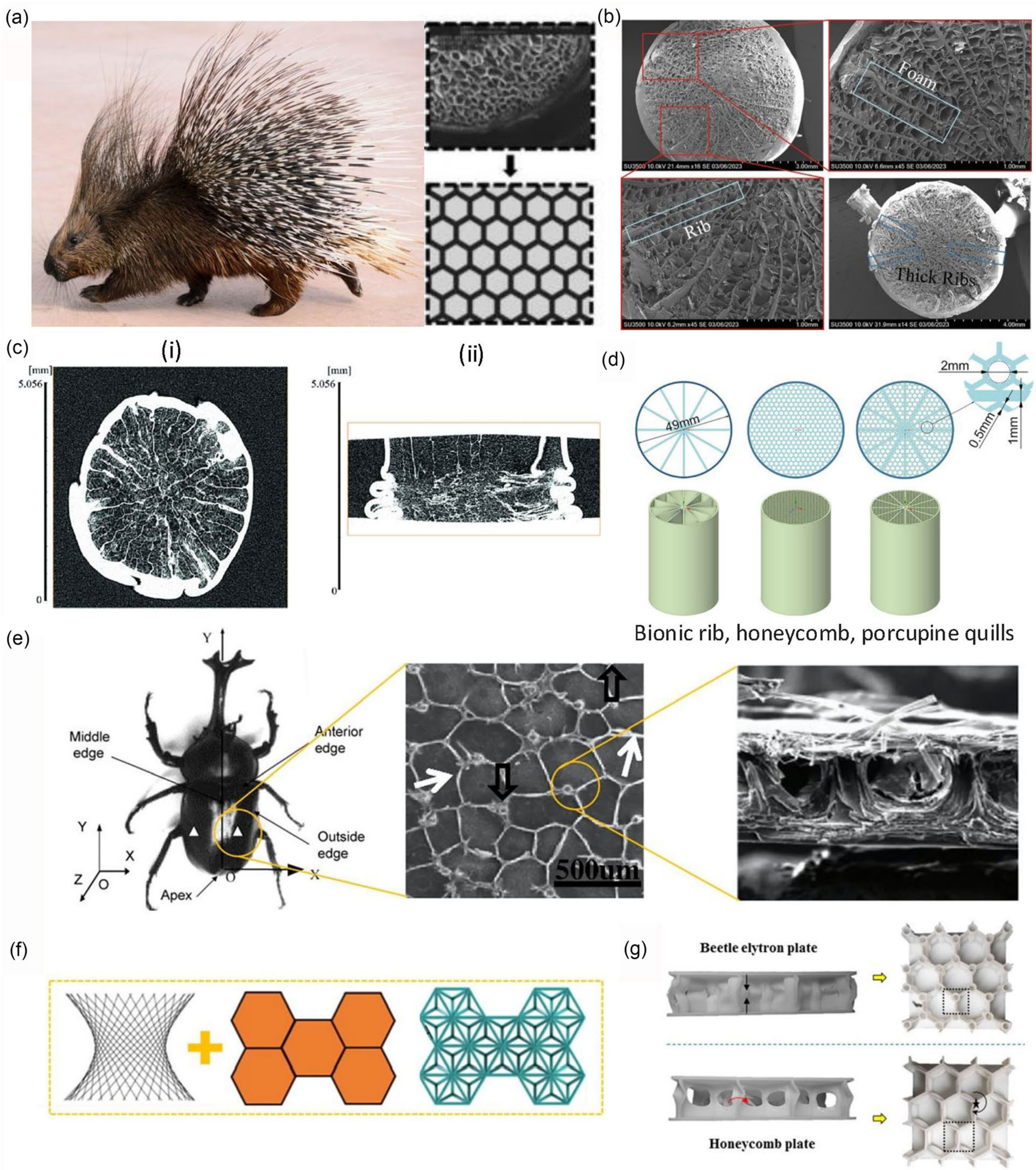


**Figure 2.** Bioinspired impact-resistant structures modeled after porcupine quills and beetle exoskeletons. a) Photographs of a porcupine and its quill, showing a hexagonal outer geometry and hierarchical composite internal architecture. Reproduced with permission.[37] Copyright 2024, Springer Nature; and[48] 2005, Elsevier. b) SEM images of porcupine quills illustrating energy dissipation features and internal microstructures that enhance toughness. Reproduced with permission.[49] Copyright 2023, Springer Nature. c) Mechanical response of the porcupine quill under compression: i) Transverse cross-section and ii) longitudinal cross-section reveal characteristic deformation modes that contribute to energy absorption. Reproduced with permission.[55] Copyright 2021, Springer Singapore. d) 3D model of a bioinspired composite rib structure integrating honeycomb geometry and porcupine quill features for enhanced crashworthiness. Reproduced with permission.[49] Copyright 2023, Springer Nature. e) Cross-sectional view of a beetle elytron displaying a trabecular architecture that contributes to stiffness and lightweight performance. Reproduced with permission.[56] Copyright 2020, Springer Nature. f) Bioinspired lattice design derived from beetle forewing structures, optimized for impact resistance and mechanical robustness. Reproduced with permission.[59] Copyright 2021, Elsevier. g) Comparison of a bioinspired BEP and a traditional HP, highlighting superior stiffness gradients and energy absorption in the former. Reproduced with permission.[60] Copyright 2017, Elsevier.

 

materials guide energy flow along preferred directions, significantly enhancing protection during oblique impacts.[65]

A prominent example is the WaveCel helmet (**Figure 3**a), which employs a collapsible, cellular liner structure that crumples, flexes, and glides to absorb both linear and rotational energy.[66,67] Unlike conventional EPS-based liners, this structure dynamically adapts to impact forces, mimicking deformation patterns found in natural cellular materials.[66,68] Materials like TPU (density $\approx$1200 kg m$^{-3}$) are suitable for fabricating such complex structures.

### 3.2. FGFs

Inspired by the graded stiffness of biological tissues, such as bone, FGFs have emerged as an effective strategy for impact mitigation. Zhang et al.[64] demonstrated that negative-stiffness-gradient FGFs can reduce the HIC value by over 40% compared to uniform-density foams. These materials offer tailored responses by spatially varying stiffness and density, thereby enhancing both protection and comfort.

### 3.3. Rotational Impact Management

Since rotational acceleration is a primary contributor to TBIs, modern helmets are integrating rotation-damping systems such as MIPS (Multidirectional Impact Protection System), Flex liners, and omni-directional suspension. These technologies rely on relative motion between helmet layers, functioning similarly to the natural slip plane between the brain and skull. Bland et al. found MIPS to be the most effective across multiple injury metrics, especially under oblique impacts.[69]

### 3.4. Auxetic and Lattice Designs

Auxetic lattice structures—characterized by negative Poisson's ratio behavior—have shown great promise in both energy absorption and conformability to complex head shapes. Inspired by the quills of hedgehogs and porcupines, these re-entrant structures expand laterally under tension, thereby enhancing structural stability and energy dissipation.[70] For example, lattice liners constructed with PA12 and Nylon 6/10 demonstrate both high stiffness and low density (Figure 3b), enabling lightweight, durable applications.[71] Simulation studies report up to a 72.65% reduction in HIC, validating their effectiveness in mitigating concussions and skull fractures.

### 3.5. Materials and Embedded Sensors

The integration of MEMS accelerometers, piezoresistive sensors, and IoT technologies enables real-time monitoring of linear and rotational impacts. These smart systems provide early injury detection, data logging, and feedback loops for users or medical personnel.[65] Combined with piezoresistive materials, they can actively sense deformation and relay warning signals, opening possibilities for adaptive helmets that respond to trauma in real-time.

### 3.6. Topology Optimization and AM

Topology optimization and AM are transforming helmet design by enabling the production of intricate, bioinspired structures such as Voronoi lattices, fractal geometries, and bone-mimetic scaffolds.[30,72] These methods optimize mass distribution and stress dissipation, creating helmets that are lighter, stronger, and more responsive. Mechanical metamaterials derived from these techniques are being fine-tuned to match real-world concussion models, advancing protection standards for future helmet designs.[72,73]

### 3.7. Porosity and Lightweighting Strategies

Biological structures, such as cancellous bone, inspire porosity-tuned cellular architectures for helmet shells and liners.[74] Honeycomb and hybrid hierarchical lattices exhibit progressive buckling, enhancing energy absorption while minimizing mass. Yang et al.[75] report successful deployment of such designs in the automotive and transportation industries, reinforcing their potential in protective headgear.

### 3.8. Multifunctional Capabilities

In addition to impact protection, modern helmets are increasingly designed with multifunctional features to address real-world operational demands. These include acoustic dampening, thermal regulation, antimicrobial resistance, and energy harvesting. For example, wood-cell-inspired porous composites developed by Zhou et al.[76] demonstrated excellent sound absorption, reducing noise-induced cognitive fatigue and hearing damage—an especially critical feature in military and industrial environments. Complementing these efforts, Xu et al. introduced multifunctional mechanical metamaterials capable of simultaneously isolating vibration and harvesting vibrational energy, offering new avenues for self-powered sensor integration and structural health monitoring.[77] The integration of such multifunctional features signals a paradigm shift in helmet design, transitioning from single-purpose protective gear to intelligent and responsive systems tailored for complex operating environments.

In summary, the convergence of bioinspired design principles, advanced materials, and AM is enabling a new generation of helmets that are lightweight, adaptive, multifunctional, and capable of addressing the full spectrum of impact-related injuries. These innovations are applicable across various domains, ranging from contact sports and industrial safety to defense and healthcare, providing a framework for next-level head protection.

## 4. Manufacturing Strategies for Bioinspired Helmet Structures

The advance of next-generation helmet systems is increasingly dependent on innovative manufacturing techniques that enable the realization of hierarchical, multifunctional designs with multiple materials and complex geometries. Methods such as

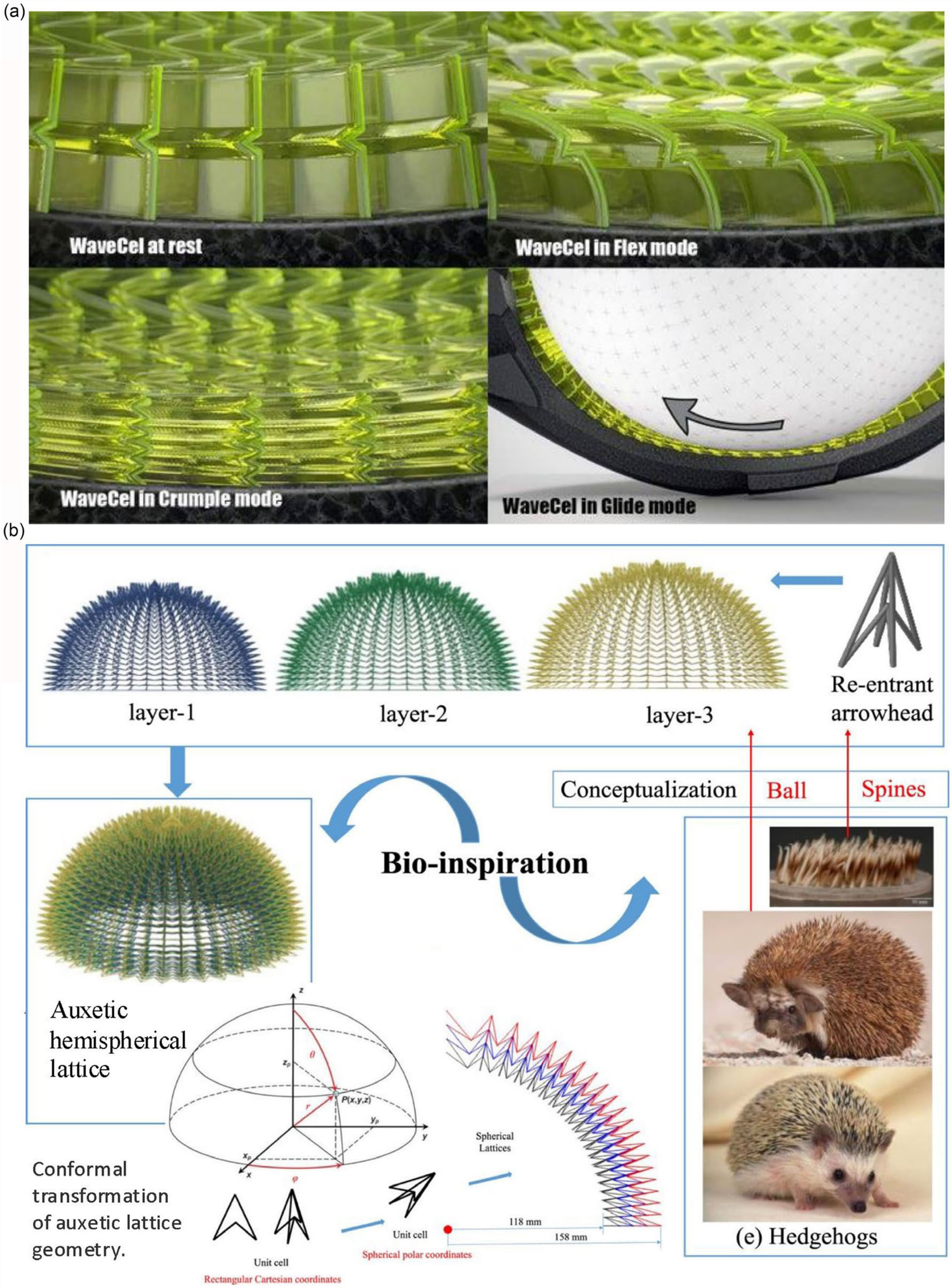


**Figure 3.** Design principles for energy absorption in advanced helmet systems. a) Schematic of a WaveCel helmet liner illustrating its engineered cellular architecture that crumples, flexes, and glides to absorb linear forces and redirect rotational impacts, reducing injury risk. Reproduced with permission.[68] Copyright 2019, Elsevier. b) Configuration and function of bioinspired auxetic lattice liners based on negative Poisson's ratio (NPR) structures, which laterally expand under tension to improve energy dissipation, reduce stress concentrations, and enhance mechanical stability in protective applications. Reproduced with permission.[70] Copyright 2023, IOP Publishing.

lamination, freeze casting, AM, and hybrid fabrication techniques offer the precision, flexibility, and structural control necessary to replicate biological architectures—such as those found in nacre, bone, and pomelo peel—for enhanced energy absorption and impact mitigation.[78,79] Each approach offers unique benefits and presents specific challenges in scalability, structural integrity, and process integration.

### 4.1. Laminated and Functionally Graded Composites (FGCs)

Laminated and FGCs draw direct inspiration from biological systems that exhibit gradual transitions in mechanical properties, enhancing impact resistance and stress distribution. Traditional techniques, such as hot pressing and resin infusion, enable the fabrication of multilayer systems with improved energy dissipation and localized deformation resistance.[80,81] These processes mimic nature's continuous variation in stiffness, enabling improved load transfer and delocalization of stress concentrations.

However, conventional lamination methods are often labor-intensive and susceptible to interfacial delamination under dynamic or repeated impact loading. To overcome these issues, advanced techniques such as Friction Stir AM (FTAM)[80] have been introduced. FTAM promotes strong mechanical interlocking between dissimilar material layers, significantly enhancing flexural strength and interfacial integrity. For instance, PMMA–textile stainless steel composites fabricated via FTAM exhibited superior crush resistance and energy absorption compared to traditional laminates.[80] Nevertheless, the high equipment cost and process complexity of FTAM pose challenges for widespread adoption in helmet manufacturing.

Another promising bioinspired strategy involves foam composites modeled after the cellular structure of pomelo peel. One-step foaming techniques combining fabric layers and tailored polymer matrices have yielded structures with significantly improved compression resistance, bursting strength, and cushioning properties.[81] These systems are particularly effective for low-mass, high-performance energy dissipation. However, maintaining material uniformity and processing reproducibility remains a key hurdle for scaling these foaming processes for industrial production.

### 4.2. Freeze-Casting for Biomimetic Lamellar Architectures

Freeze casting (also known as ice templating) has emerged as a powerful technique for fabricating lamellar, porous structures that emulate biological materials like nacre and bone.[82] This method involves the directional freezing of particle-laden suspensions, followed by sublimation and sintering, to yield anisotropic architectures with tunable mechanical anisotropy, porosity, and microstructural alignment (**Figure 4**a).[83] By varying the solid loading, solvent type, and ice front velocity, it is possible to tailor key features such as lamella spacing, thickness, and interlamellar bonding. For instance, bidirectional freeze casting has produced nacre-inspired $Al_2O_3$–CE composites with flexural strengths approaching 300 MPa and fracture strains of ≈5%, mimicking the damage-tolerant behavior of natural materials.[84] Moreover, complex 3D architectures—such as interlocking alumina scaffolds and graphene-based cork-like monoliths—have demonstrated ultralightweight densities (≈0.5 kg m$^{-3}$) combined with high shock absorption capacity. Further innovations include in situ mineralization, where controlled mineral deposition within a polymeric matrix replicates the brick-and-mortar microstructure of nacre, enhancing toughness and stiffness (Figure 4b).[85]

Despite its versatility and bioinspired fidelity, freeze casting remains constrained by environmental sensitivity (e.g., temperature and humidity fluctuations), long processing times, and the need for precise thermal control during freezing and sublimation.[86–88] These limitations restrict its scalability for mass manufacturing; however, it remains ideal for research prototypes, customized liners, or premium, impact-resistant helmet components.

### 4.3. AM for Hierarchical Helmet Structures

AM technologies offer unprecedented control over geometry, material composition, and architectural hierarchy, enabling the fabrication of bioinspired helmet structures with enhanced energy absorption and mechanical performance.[89] Unlike traditional subtractive processes, AM allows for the layer-by-layer construction of complex geometries that mimic biological systems such as nacre, bone, and insect exoskeletons (**Figure 5**a).[90] For instance, nacre-inspired structures fabricated via AM—featuring alternating layers of stiff and compliant materials—have demonstrated 25–120% improvements in energy absorption compared to monolithic counterparts (Figure 5b–d).[91–93]

Multiple AM technologies are currently employed for helmet-related applications, each offering unique advantages: 1) direct ink writing (DIW) (Figure 5e) enables extrusion-based printing of viscoelastic inks, allowing embedded reinforcement and multiscale architecture control;[94] 2) stereolithography (SLA) (Figure 5f) and digital light processing offer sub−100 μm resolution, ideal for ceramic-based or photocurable polymer structures;[95] and 3) fused deposition modeling (FDM) remains one of the most accessible and scalable methods, though often limited in mechanical anisotropy and interlayer bonding strength.

These AM techniques have the potential to tailor mechanical performance through structural design, rather than solely relying on material properties. However, challenges remain for AM-fabricated helmets: 1) The mechanical limitations of printable polymers, particularly their low toughness and poor fatigue resistance, can compromise helmet performance under repeated impacts. 2) Interlayer adhesion—especially in FDM—often results in delamination and structural weakening. 3) Multimaterial integration, while conceptually advantageous, is often hampered by thermal mismatch and poor bonding between hard and soft phases, leading to stress concentrations and premature failure. Moreover, the mechanical performance of additively manufactured composites is highly susceptible to variations in printing parameters. Layer thickness, print speed, and nozzle diameter affect interlayer bonding and microstructure, directly influencing strength and energy absorption. Additionally, in large-scale production, precision degradation—commonly observed as structural inconsistencies or alignment drift—poses a significant challenge that can affect the reproducibility and uniformity of helmet liners.

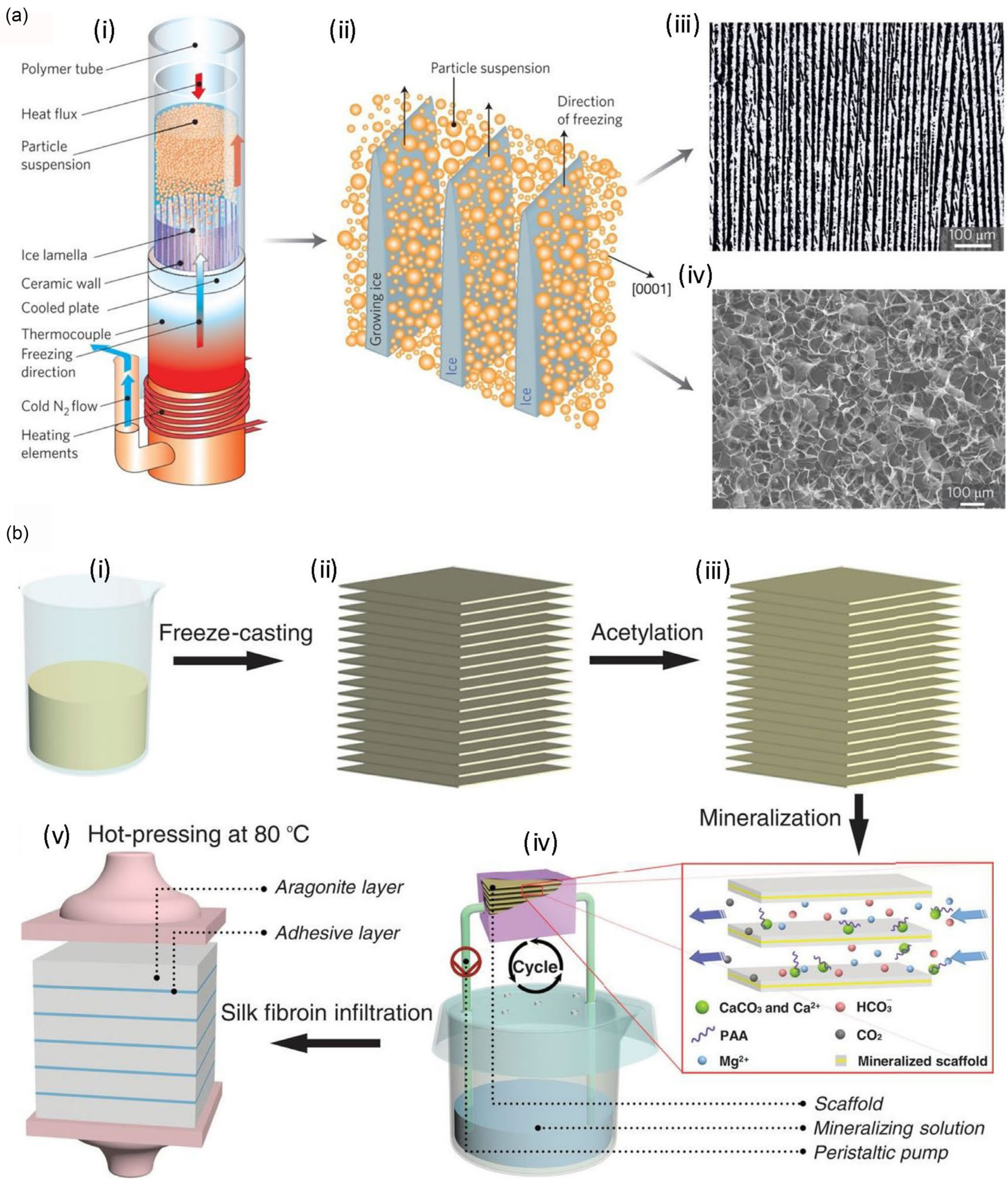


**Figure 4.** Nacre-inspired structures fabricated using freeze casting and in situ mineralization techniques a) Schematic of the freeze-casting process used to create porous, lamellar architectures mimicking natural nacre. Reproduced with permission.[83] Copyright 2015, Nature Portfolio. i) Controlled directional solidification of a suspension forms ice templates, followed by freeze drying and sintering; ii,iii) micrographs of freeze-cast lamellar alumina and iv) porous chitosan reveal nacre-like layered structures. b) Fabrication scheme of synthetic nacre via in situ mineralization, in which mineral phases are deposited within a polymer matrix to reproduce nacre's hierarchical structure and mechanical toughening mechanisms. Reproduced with permission.[85] Copyright 2016, AAAS.

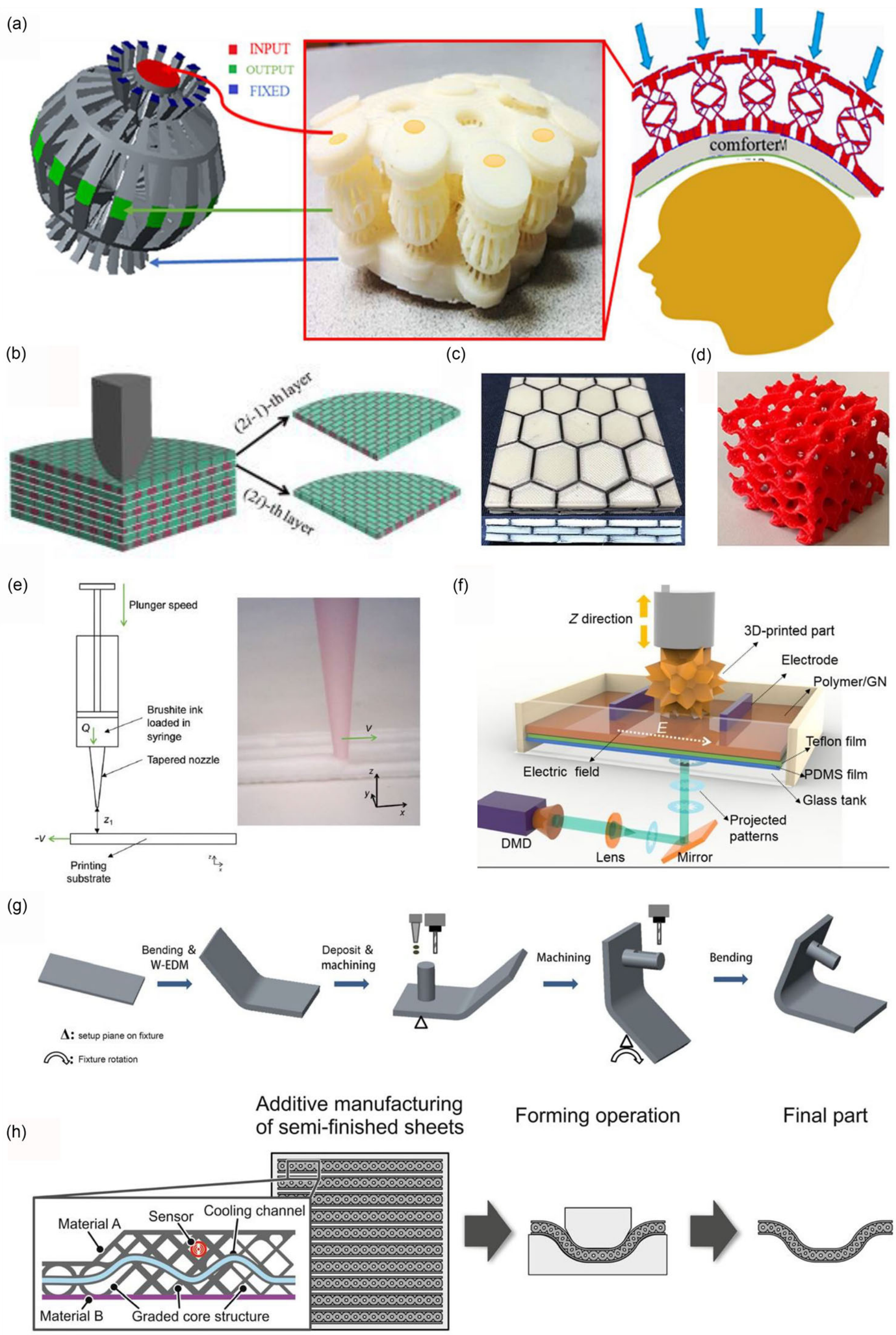


**Figure 5.** 3D printing strategies, structural designs, and mechanical enhancements in nacre-inspired composite materials. a) Additively manufactured helmet liner featuring complex lattice architectures for impact mitigation. Reproduced with permission.[90] Copyright 2023, Springer Nature. b) Schematic of a nacre-like laminated structure with two orthogonally oriented plies repeated through the thickness to replicate the anisotropic energy dissipation of natural nacre. Reproduced with permission.[91] Copyright 2016, Elsevier. c) 3D-printed nacre-inspired specimens using PLA and nylon materials, showing enhanced compressive strength and structural integrity. Reproduced with permission.[92] Copyright 2020, Elsevier. d) Comparison of digitally fabricated porous architectures with real porous structures, demonstrating fidelity in replicating natural forms. Reproduced with permission.[93] Copyright 2020, Elsevier. e) DIW technique for extrusion-based deposition of structured inks to build layered composite architectures. Reproduced with permission.[94] Copyright 2022, ACCScience. f) An electrically assisted projection-based SLA system enabling bottom-up fabrication of nacre-like structures with high spatial control. Reproduced with permission.[95] Copyright 2019, AAAS. g) Hybrid manufacturing route combining AM, multistep bending, and milling to create defect-free composite honeycomb panels with improved formability and structural performance. Reproduced with permission.[100] Copyright 2024, Elsevier. h) Hybrid printing–forming approach in which semi-finished sheets are first 3D printed and subsequently formed into complex final geometries. Reproduced with permission.[101] Copyright 2022, Springer Nature.

 

Despite these hurdles, recent innovations are expanding the capabilities of AM.[96,97] For example, electrically assisted AM enables in situ alignment of graphene nanoplatelets, resulting in tough, lightweight composites with nacre-mimetic architectures and enhanced directional mechanical performance.[95] Hybrid AM–bending processes have been employed to fabricate composite honeycomb structures that maintain mechanical integrity even after being formed into complex helmet contours.[98] Nevertheless, many of these methods involve extensive post-processing steps, low throughput, and limited scalability, which currently restrict their widespread industrial adoption.[97,99] Ongoing research focuses on improving material formulations, interfacial bonding, and process integration, which will be critical for translating AM-enabled helmet technologies from lab-scale prototypes to commercial products.

### 4.4. Hybrid Manufacturing and Smart Integration

Hybrid manufacturing approaches—particularly additive–subtractive hybrid manufacturing (ASHM)—have emerged as powerful platforms for fabricating complex helmet architectures that require both design flexibility and high dimensional accuracy. ASHM integrates the design freedom of AM with the precision and surface quality of subtractive techniques (e.g., CNC milling or laser machining), enabling the creation of multifunctional, high-performance structures (Figure 5g).[100] One compelling example is the use of hybrid AM–forming strategies, where semi-finished printed honeycomb panels are subsequently formed or bent into curved helmet geometries (Figure 5h).[101] This approach allows the production of lightweight, structurally optimized liners that conform closely to human head contours while maintaining energy-absorbing performance. Such geometries are difficult to achieve using AM or subtractive methods alone.

Beyond geometric fabrication, hybrid integration of micro-scale and nanoscale processes—including electrospinning, melt electro-writing, and bioprinting—opens the avenue to smart, mechanosensitive helmet liners.[102] These techniques can replicate the gradient biological tissues found in porcupine quills or cartilage by producing multimaterial fiber networks with tailored anisotropy, porosity, and responsiveness. Such systems are ideal for embedding flexible and stretchable sensors for real-time impact or stress monitoring; antimicrobial or self-healing coatings; and localized reinforcement zones for region-specific protection.

Despite their promise, these hybrid methods also present significant engineering and manufacturing challenges. First, complex toolpath planning is required to transition smoothly between additive and subtractive operations or between micro- and macro-scale fabrication stages. Second, inter-process alignment and registration must be tightly controlled to maintain precision across scales and materials. Third, system integration, involving hardware synchronization and software interoperability, increases both technical complexity and operator expertise requirements.[103] In addition, hybrid systems typically entail higher capital costs, extended production times, and specialized workforce training, which may limit their scalability and economic feasibility for high-volume commercial helmet production. However, their unmatched customizability, multimaterial integration, and fine-scale control make them ideal for premium helmet applications, personalized protective gear, and experimental testbeds for next-generation safety systems. In summary, hybrid manufacturing represents a critical frontier in helmet engineering, enabling the synergistic coupling of design innovation and multifunctionality—a necessity for the evolving demands of sports, military, industrial, and biomedical head protection.

### 4.5. Scalability of Manufacturing Bioinspired Helmets

From freeze casting's tunable lamellar architectures to AM's geometric versatility and ASHM's multiscale integration precision, advanced fabrication techniques offer distinct advantages for realizing bioinspired helmet structures. These strategies translate nature's hierarchical, multifunctional designs into engineered protective systems with enhanced performance. However, scalability remains a key barrier to industrial adoption. Techniques such as DIW and SLA are often limited by long curing times, limited print speeds, and batch-mode processing. Overcoming these constraints requires innovations in parallel printing, automated post-processing, and continuous-feed manufacturing platforms. Process stability is equally critical-parameters like ink viscosity, layer adhesion, and dimensional consistency must be tightly controlled to ensure repeatability across batches. Cost-effectiveness poses another challenge because smart, layered AM-based designs often remain economically uncompetitive due to high material and process costs. Hybrid fabrication approaches, such as integrating 3D-printed inserts into bulk-laminated structures, may offer a practical compromise by preserving performance-critical features while reducing production costs.

Strategic scale-up must also include robust quality assurance, such as in-line optical monitoring, machine learning-based defect detection, and closed-loop feedback control systems. While each method has trade-offs—ranging from material compatibility and process speed to mechanical fidelity—their synergistic integration and continued refinement offer transformative potential for helmet manufacturing. Together, they pave the way for next-generation helmets that are lighter, more impact-resistant, and multifunctional—capable of adapting to dynamic real-world conditions. As these technologies mature, they will bring protective headgear closer to nature's design principles, enabling smart, sustainable, and high-performance wearable protection systems.

## 5. Materials for Helmets

Balancing toughness, weight, and cost remains a central challenge in developing advanced helmet materials that can be manufactured cost-effectively. Traditional trade-offs between these properties are increasingly being addressed through innovative, bioinspired strategies, particularly in polymeric systems. This section explores emerging approaches in matrix selection, reinforcement design, viscoelastic damping, smart additives, and functional coatings for optimized helmet performance.

### 5.1. Matrix Materials and Bioinspired Toughening

Polymers such as polycarbonate and polyurethane remain the cornerstone of helmet construction due to their favorable balance of toughness, weight, and manufacturability. To overcome the trade-offs between performance and cost, recent work has focused on bioinspired strategies that enhance polymer matrices while maintaining processability. For example, waterborne polyurethane (WPU) reinforced with nanocellulose has demonstrated moisture-induced self-healing and shape-retention properties, enabling the fabrication of 3D helmet structures with improved toughness and service life, especially under humid or dynamic loading conditions.[104] A universal toughening framework is the integration of rigid–rubber nanocomposites, such as graphene oxide (GO) embedded in a rubbery poly(caprolactone-*co*-lactide) matrix. This hybrid architecture, applied to poly(L-lactide) (PLLA) systems, synergizes the deformation mechanisms of stiff and soft phases to achieve simultaneous improvements in strength and ductility.[105]

Another promising route is ion-tunable crystallinity in polymer matrices, which has yielded materials with tensile strength up to 58 MPa, toughness approaching 198.8 MJ $m^{-3}$, and elongation over 400%, ideal for integration into wearable impact sensors or smart helmets.[106] These materials combine mechanical adaptability with functional versatility, suitable for both structural and sensing applications. Artificial β-sheet nanostructures, inspired by natural protein folding, have also shown exceptional reinforcement capability. Even at low loadings (2 wt%), these additives raise tensile strength to 152.8 MPa, stiffness to 4.35 GPa, and toughness to 30.3 MJ $m^{-3}$, while also enhancing thermal stability.[107] These results suggest a scalable method for high-performance composite fabrication, though economic and processing barriers must be carefully managed. Lastly, the sustainability profile of matrix systems is becoming increasingly important. Materials such as WPU-nanocellulose composites not only deliver mechanical performance but also support the shift toward eco-friendly and biodegradable helmet components, aligning with broader industrial goals in green manufacturing.[108,109]

### 5.2. Reinforcements: Nano to Multiscale Integration

Reinforcement strategies are essential for improving the mechanical performance of helmet materials without significantly increasing weight. Carbon-based nanomaterials, including graphene and carbon nanotubes (CNTs), provide exceptional strength, modulus, and electrical properties. However, their broader adoption is hindered by dispersion challenges, interfacial inefficiencies, and cost constraints.[110,111] Aramid nanofibers, derived from Kevlar, offer a more scalable and cost-effective alternative. These fibers exhibit high aspect ratios and excellent mechanical properties while avoiding many of the processing challenges of CNTs. For example, Kevlar fiber–graphene oxide (GO) hybrid composites (KFG5) demonstrated a 33% improvement in flexural strength, reaching 219.42 MPa at a density of only 0.993 g $cm^{-3}$. This improvement was attributed to enhanced surface roughness and interfacial bonding, although exceeding the optimal 5 wt% GO content resulted in performance degradation due to nanoparticle agglomeration.

Multiscale hybridization—combining micron-scale fibers (e.g., carbon or glass fibers) with nanoscale additives (e.g., CNTs, rubber nanoparticles)—has emerged as a powerful strategy.[112] In glass fiber–graphene nanoplatelet composites, this approach yielded ≈54% increase in tensile modulus, ≈37% in tensile strength, and ≈75% in impact strength.[113] Scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy analysis (**Figure 6**d,e) confirmed the presence of gradient interphases and improved interfacial load transfer, which enhances both stiffness and toughness across hierarchical structures. Sustainable nanofillers, such as nanocellulose, further offer mechanical reinforcement alongside biodegradability and thermal stability. When paired with inorganic nanoplatelets like Zirconium Phosphate–Reduced Graphene Oxide (ZrP–RGO), nacre-inspired composites exhibit superior flame retardancy, mechanical robustness, and multifunctionality.[114]

### 5.3. Viscoelastic Damping and Gradient Architectures

Viscoelastic materials are indispensable for dissipating mechanical energy and improving helmet comfort, particularly under repeated or oblique impacts. A promising approach involves metal ion-based synergic cross-linking, which creates reversible coordination bonds that absorb and dissipate energy efficiently during deformation. These systems have demonstrated simultaneous improvements in tensile strength, modulus, and hardness, supporting their use in next-generation liners.[115] Double-network composites, such as those comprising cellulose nanofibers and CNTs, offer a balance between high specific strength and electromagnetic shielding, making them attractive candidates for smart helmets with embedded electronics.[116] The concept of gradient interlayers, inspired by natural interfaces like cartilage or wood, allows smooth transitions in stiffness and damping capacity. These architectural gradients minimize interfacial stress concentrations and enhance load transfer while reducing the risk of delamination or failure at dissimilar material boundaries.[117]

### 5.4. Smart Additives and Adaptive Performance

The incorporation of smart materials into helmet systems enables functionalities that transcend passive protection. Shape memory polymers, for instance, can change shape in response to thermal or mechanical stimuli, enabling adaptive fit, impact mitigation, or post-impact reconfiguration. These materials are increasingly compatible with 4D printing, allowing spatial and temporal design of helmet properties. Self-healing polymers, another class of smart materials, autonomously repair microcracks formed during repetitive low-energy impacts. This capability enhances both safety and longevity, reducing the need for frequent equipment replacement and improving sustainability.[118] Agglomerated cork, a natural viscoelastic material, has also attracted attention for its multi-impact capability and ecological benefits. Thanks to its unique cell structure, cork can absorb energy and return to shape repeatedly.[119] Finite element modeling simulations confirmed its ability to outperform conventional synthetic foams in terms of both crashworthiness and user comfort, making it a promising alternative for helmet liners.[120]

### 5.5. Functional Coatings for Protection and Durability

Functional surface coatings serve as the first line of defense in helmet systems, enhancing durability, weather resistance, and

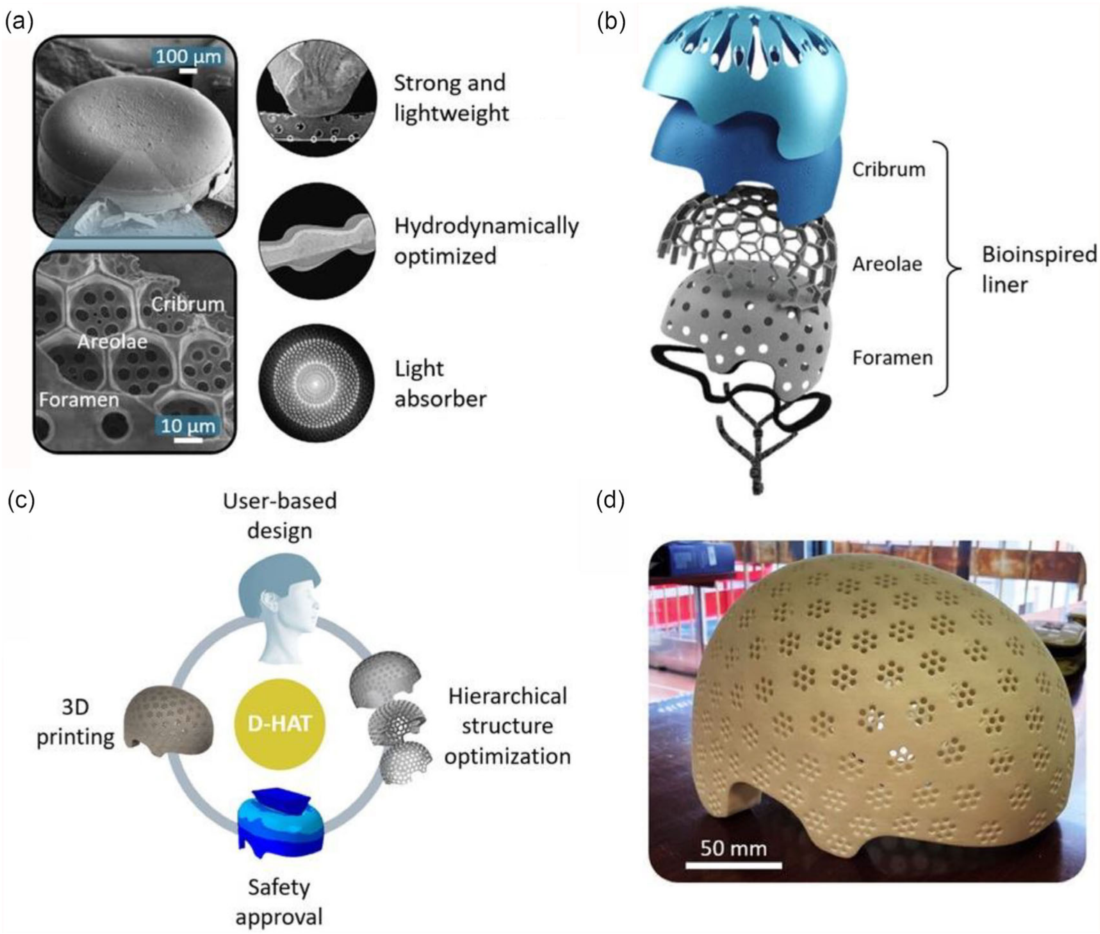


**Figure 6.** Diatom-inspired structural design for next-generation helmet systems.[131] a) SEM images of the *Coscinodiscus* sp. diatom frustule at increasing magnifications, revealing its multilayered silica architecture composed of cribrum, areolae, and foramen, which collectively contribute to mechanical robustness and lightweight structure. b) Conceptual helmet design translates the hierarchical geometry of the diatom frustule into engineered multilayered liners for improved energy absorption, impact resistance, and weight reduction. c) Design roadmap for the D-HAT, encompassing user-centered design, structural optimization of hierarchical layers, finite element simulation for safety validation, and 3D printing of the final prototype. d) 3D-printed prototype of the D-HAT demonstrating the feasibility of integrating biologically inspired architecture into helmet liners through AM. Reproduced with permission.[131] Copyright 2025, Wiley.

overall performance under real-world conditions. Among these, superhydrophobic coatings—such as polyurethane/$TiO_2$ composites—have shown exceptional abrasion resistance, maintaining functionality even after 1000 cm of sandpaper wear.[121] These surfaces effectively repel water and contaminants, minimizing maintenance requirements and ensuring consistent visibility and hygiene in harsh environments. In cold or maritime settings, metallic quasicrystalline coatings provide both ice repellency and corrosion resistance, crucial for applications involving high humidity or sub-zero temperatures.[122] These coatings preserve material integrity and reduce degradation, thereby extending the lifespan of the helmet.

For optical components such as visors and face shields, transparent liquid-repellent coatings provide scratch resistance, antifogging properties, and self-cleaning capabilities.[123,124] These properties are critical for maintaining visibility and safety in dynamic conditions—particularly for military, industrial, and sports helmets. When combined with sustainable core materials like agglomerated cork or nanocellulose-reinforced composites, these coatings form a multifunctional protective envelope. This coating enhances mechanical robustness and surface longevity, aligning with environmental sustainability goals by supporting biodegradable and recyclable helmet components.[125,126]

## 6. Challenges and Future Research

Bioinspired energy-absorbing composites for helmets offer exciting opportunities for next-generation protective systems. However, translating biological principles into scalable, functional, and cost-effective helmet designs presents significant challenges. This section outlines the current limitations and highlights promising avenues for future research and development.

### 6.1. Design Complexity and Manufacturability

Replicating the multiscale, hierarchical architectures found in natural systems—such as bone, nacre, and spider silk[28]—remains a formidable challenge. These biological structures achieve remarkable combinations of strength, toughness, and light weight through intricate material gradients and geometric features. Translating these principles into engineered helmet liners requires advances in materials selection, structural optimization, and manufacturing integration.

AM offers unprecedented control over complex geometries and internal architectures;[127] however, production scalability remains a bottleneck. High-resolution printing sacrifices speed, while large-format AM introduces issues such as nozzle clogging, poor surface quality, and high-energy demands.[128] Emerging technologies like volumetric 3D printing (e.g., xolography)[129] and robotic-arm-based AM for nonplanar fabrication[130] offer potential solutions but are not yet industrially mature.

Achieving an optimal balance among energy absorption, lightweight design, and reusability is still elusive.[120] While anisotropic polymer nanocomposites show promise, their scalable processing remains a key hurdle. For instance, recent work has demonstrated a diatom-inspired helmet prototype (D-HAT) utilizing a multilayered TPU architecture (Figure 6),[131] which achieves up to 70% higher energy absorption than honeycomb liners at comparable densities. This highlights the promise of biomimetic design but also underscores the need for iterative optimization, simulation, and prototyping to meet real-world standards.

### 6.2. Scalability of Manufacturing

The sophisticated geometries and anisotropic material requirements of bioinspired helmet liners pose significant challenges to large-scale production. Conventional AM methods struggle to reproduce these designs reliably across batches. Furthermore, nanocomposite formulations often suffer from poor rheological control and interfacial inconsistencies that impact structural fidelity and reproducibility.[120] Hybrid manufacturing approaches—combining additive and subtractive techniques[132]—offer a promising path forward, but they require process innovations and cost-efficient workflows. Continued research should involve: 1) Developing scalable multiscale reinforcement architectures; 2) optimizing printability of nanocomposite inks; and 3) implementing real-time process feedback systems to ensure consistency and performance at scale.

### 6.3. Material Durability and Environmental Stability

Helmet materials must perform reliably under prolonged exposure to UV radiation, humidity, and mechanical cycling. Many conventional polymers, such as EPS and PP exhibit degradation over time, reducing impact resistance.[133] Although bioinspired composites—such as cuttlebone-like structures and diatom-based multilayer designs—offer enhanced durability,[134] their long-term stability under environmental stresses remains underexplored. Future efforts should aim to quantify long-term mechanical and thermal ageing effects, design materials with intrinsic resistance to UV/moisture, and integrate protective coatings or hydrophobic interfaces without compromising impact performance. Additionally, it is crucial to validate the bioinspired structures under realistic impact conditions to ensure their reliability and protective performance. Such assessments will help establish the suitability of bioinspired composites for real-world applications and support their transition to certified helmet systems.

### 6.4. Sustainability

Sustainability is increasingly central to materials development. Conventional helmet liners predominantly rely on petroleum-based, nonrecyclable polymers (e.g., EPS, PE, PP).[120] A shift toward biodegradable, recyclable, and bio-based alternatives is critical to align with environmental objectives.[135] Materials such as cellulose nanofibers, biodegradable polyesters, and green processing techniques[136,137] show promise. However, challenges remain in ensuring mechanical integrity, thermal stability, and environmental resistance. Opportunities for future work include: 1) Multifunctional sustainable materials combining energy absorption, comfort, and moisture regulation;[138,139] 2) use of 2D nanomaterials and recyclable matrix platforms;[140] and 3) leveraging developments in biodegradable soft robotics for smart helmet integration.[136]

### 6.5. Smart Helmet Integration

Smart helmets capable of real-time impact sensing, health monitoring, and adaptive response represent a frontier in wearable safety systems. However, embedding sensors within bioinspired composite structures introduces challenges such as mechanical–electronic interface durability, signal fidelity and calibration under dynamic loading, and power efficiency in miniaturized devices.[141,142] Improper helmet fit and fastening also significantly contribute to the risk of injury. Studies show that poor fit increases the likelihood of concussions and facial trauma.[143,144] Sensing-enabled helmets, using embedded accelerometers, can now detect improper wear or fastening, providing real-time feedback akin to car seatbelt warnings. Recent advances have demonstrated nacre-inspired composites offering both impact absorption and EMI shielding, a dual-functionality critical for smart systems operating in electromagnetically noisy environments.[145] Continued innovations in flexible electronics, machine-learning-assisted feedback, and sensor fusion will be essential to realize truly intelligent helmets.[136]

### 6.6. Computational Modeling and Design Optimization

Modeling complex bioinspired structures remains computationally intensive. Conventional finite element analysis methods often require high-resolution meshes to accurately simulate hierarchical or architected geometries, leading to long computation times and difficulties in modeling nonlinear damage or plasticity.[140] Emerging computational tools and frameworks include: 1) Artificial neural networks and machine learning-based surrogate models for rapid design-space exploration;[146] 2) XFEM-enhanced fracture modeling to capture crack initiation and propagation in hierarchical structures;[147] and 3) real-time thermal modeling in additive processes such as automated fiber placement for in situ feedback and control.[146] These methods will accelerate design iterations and reduce prototyping costs, ultimately bridging the gap between concept and manufacturable product.

 

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### 6.7. Cost and Accessibility

Despite their superior performance, many bioinspired helmet materials remain cost-prohibitive for widespread adoption. Nanomaterial reinforcements, high-resolution 3D printing, and hybrid fabrication workflows can significantly increase production costs.[3,120] Future research must develop low-cost bio-based materials, explore waste-reducing manufacturing approaches, and standardize performance metrics to facilitate broader industry adoption across sports, military, and industrial sectors.[148,149]

## 7. Conclusion

This review underscores the transformative potential of bioinspired design principles in revolutionizing helmet technology. By emulating optimized strategies for impact mitigation in nature, such as the layered toughness of nacre, energy-dissipating structures in porcupine quills, and interlocking architectures of beetle exoskeletons, researchers have developed composite systems that deliver enhanced mechanical performance, reduced weight, and improved flexibility. These features are particularly valuable in high-risk applications where protection, comfort, and wearability are critical, including sports, military, industrial, and medical settings. Recent advances in additive and hybrid manufacturing have enabled the precise fabrication of complex, hierarchical architectures that were previously unachievable in synthetic materials. Innovations such as auxetic lattices, nanocomposite reinforcements, and FGFs have demonstrated the ability to mitigate both linear and rotational accelerations, directly addressing the limitations of traditional helmet liners in preventing concussive and sub-concussive brain injuries. Moreover, the incorporation of smart materials, such as self-healing polymers, shape memory systems, and sensing-enabled components, is extending helmet functionality beyond passive protection toward adaptive, intelligent systems that respond dynamically to external stimuli and usage conditions. These advances not only improve impact absorption but also enhance fit, durability, and service life.

In the future, research must prioritize the translation of laboratory-scale innovations into scalable, cost-effective production systems. This includes refining material formulations, optimizing process parameters, and establishing robust quality control frameworks to ensure consistency and reliability at industrial scales. Concurrently, the integration of IoT-enabled sensors, machine-learning algorithms, and real-time feedback systems opens a path toward smart helmets with real-time monitoring and predictive safety functionalities. Sustainability will also be a key driver of innovation. The development of biodegradable, recyclable, and bio-based materials, along with green manufacturing strategies, will align helmet production with global environmental goals and circular economy principles. By combining nature's structural intelligence with advances in materials science, computational design, and digital manufacturing, bioinspired helmets offer a pathway to the next generation of head protection. These systems promise enhanced mechanical safety and user comfort, as well as the potential to deliver adaptive performance, environmental responsibility, and a broader societal impact.

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## Conflict of Interest

The authors declare no conflict of interest.

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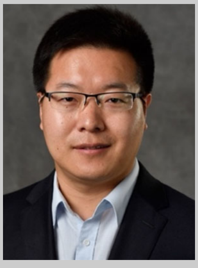

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