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REVIEW ARTICLE

Bioinspired Strategies for Excellent Mechanical Properties of Composites

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Abstract

Developing high-performance composite materials is of great significance as a strong support for high-end manufacturing. However, the design and optimization of composite materials lack a theoretical basis and guidance scheme. Compared with traditional composite materials, natural materials are composed of relatively limited components but exhibit better mechanical properties through ingenious and reasonable synthetic strategies. Based on this, learning from nature is considered to be an effective way to break through the bottleneck of composite design and preparation. In this review, the recent progress of natural composites with excellent properties is presented. Multiple factors, including structures, components and interfaces, are first summarized to reveal the strategies of natural materials to achieve outstanding mechanical properties. In addition, the manufacturing technologies and engineering applications of bioinspired composite materials are introduced. Finally, some scientific challenges and outlooks are also proposed to promote next-generation bioinspired composite materials.

Keywords Bioinspired · Composites · Mechanical properties · Manufacturing technologies · Engineering application

1 Introduction

Materials have evolved throughout human history, from the initial use of shells, bones and wood to today's replacement including a variety of metals, polymers and composites. The rapid development of society puts forward higher requirements for the performance of structural materials. However, certain properties of structural materials are mutually exclusive, such as the contradiction between strength and toughness [1]. In addition, it is worth considering how to achieve lightweight structural materials under the premise of ensuring strength. Fortunately, the long-term competition for survival in nature has driven the evolution of natural materials toward high strength, toughness, impact resistance and light weight, providing inspiration for scientists to solve these problems. For instance, bone and nacre achieve excellent strength and toughness simultaneously by utilizing multihierarchy structures and interface characteristics.

Almost all natural materials are composite materials, which are composed of a limited number of components with poor performance but can achieve significantly better properties than each component. In addition, natural materials are not simple mixtures of components. The basic reasons for the excellent performance of natural structural materials include the structure spanning multiple scales, the interface between different components and complex chemical compositions. The hierarchical structure spanning multiple length scales of nano, micro, meso, and macro has a synergistic enhancement effect. Similarly, multiple chemical components work synergistically instead of a single type of component to improve the performance of natural materials. Interfaces can arrest cracks, enhance flexibility and contribute to the viscous response of materials during deformation [2]. In addition, living organisms usually produce specific properties by combining multiple factors rather than a single factor. For instance, mollusk shells use aragonite and proteins to achieve a toughness improvement of several orders of magnitude beyond its component materials through the structure and interface characteristics of

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the brick-and-mortar [3]. Natural materials improve overall properties by positioning optimized components and structures in appropriate areas to adjust local properties. The properties in a single region are defined as local properties, such as strength, stiffness and hardness [4]. In addition, many diverse living organisms have evolved the same core features and design themes in response to natural challenges due to convergent evolution, such as the similar structures. Hence, it is beneficial to develop better structural composite materials by extracting the key features and combining them skillfully [5].

Bionics is a discipline that guides invention and creation by the study of biological structure, function and principle. Bionics provides a variety of strategies, such as modification of natural materials and biomimetic mineralization, for the preparation of new materials. Moreover, the development of biomimetic materials is closely related to the progress of advanced manufacturing technology, especially additive manufacturing, which effectively controls the manufacturing process at multiple scales [6]. In addition, electrospinning can more flexibly control the arrangement of nanofibers so that it has a great advantage in preparing nanofiber composites [7].

In this review, three basic factors that determine the excellent mechanical performance of natural materials, namely, structure, interface and chemical composition, are discussed, and how organisms achieve specific properties, such as impact resistance, fracture resistance, bending resistance and lightweight, are analyzed based on the above three basic factors. Then, the manufacturing strategy of new biomimetic materials and the application of bionic design in engineering materials are introduced in detail. Finally, the existing severe challenges and future development directions are presented.

2 Factors that Determine Natural Material Properties

Commonly, natural materials achieve specific properties by altering multiple factors, mainly including the composition, structure and interface [8] (Fig. 1). The different components and structures bring more flexibility to realize excellent performance to fit the environment [9]. In addition, materials with excellent mechanical properties and specific functions can be achieved by arranging and combining regions with diverse chemical compositions and structures in a regular order. The existence of an interface can act as a transition of two regions to avoid excessive interior stress. Hence, the multiple factors work together to improve the mechanical performance of natural materials [3, 10]. In this section, three important factors affecting the performance of natural materials are introduced in detail.

2.1 Chemical Compositions

Chemical composition is one of the most crucial factors for determining the performance of natural materials. Chemical characteristics mainly include mineralization, inorganic ions, biomole-cules and the degree of hydration. Adjusting the type and concentration of the components can have an important effect on the mechanical properties of natural materials. In addition, multiple compositions cooperate to enhance the performance of natural materials rather than a single type of component [16, 17].

There are significant differences in the degree of mineralization among various organisms to obtain specific traits to meet environmental challenges. Through different types and degrees of mineralization, local properties can be precisely and flexibly adjusted [17]. Natural materials with a high degree of mineralization include teeth and nacre. Radular teeth of *chitons* that exhibit increasing mineralization from the posterior to the anterior regions have achieved outstanding overall performance by altering mineralization to ensure smooth feeding without injury induced by abrasion [18, 19] (Fig. 2a). The combination of minerals in biological systems is an interesting subject of research but remains largely unexplored.

In addition to biomineralization, the type, concentration and binding state of biopolymers can also control the mechanical properties of materials [20, 21]. The nereis jaw presents an inhomogeneous distribution of polymers, such as a remarkable variation in the amino acid content at different positions (Fig. 2b). These biomolecules interact with the corresponding ions to regulate mechanical properties. Hence, the mechanical properties of the nereis jaw show a notable gradient, with higher hardness from the base toward the tip [22, 23].

Hydration also plays a significant role in the process of regulating mechanical properties, which mainly depends on the hydration sensitivity of the protein. Water regulates the mechanical properties of natural materials by reducing interactions and interchain space. In addition, water can increase the fluidity of proteins by decomposing and replacing the hydrogen bound to the material inside, thus changing the deformation behavior of protein-based materials. In addition, water is able to constitute a network with protein to serve as plasticizers to reduce hardness [8, 21]. The beak of a squid is an attractive example of tuning mechanical properties with the transformation of hydration (Fig. 2c). The beak is composed of chitin, water and proteins without inorganic components. In addition, it is the hardest and stiffest known biomaterials, comprised of pure organic materials [24, 26]. A 200-fold increase in stiffness exists from the soft beak

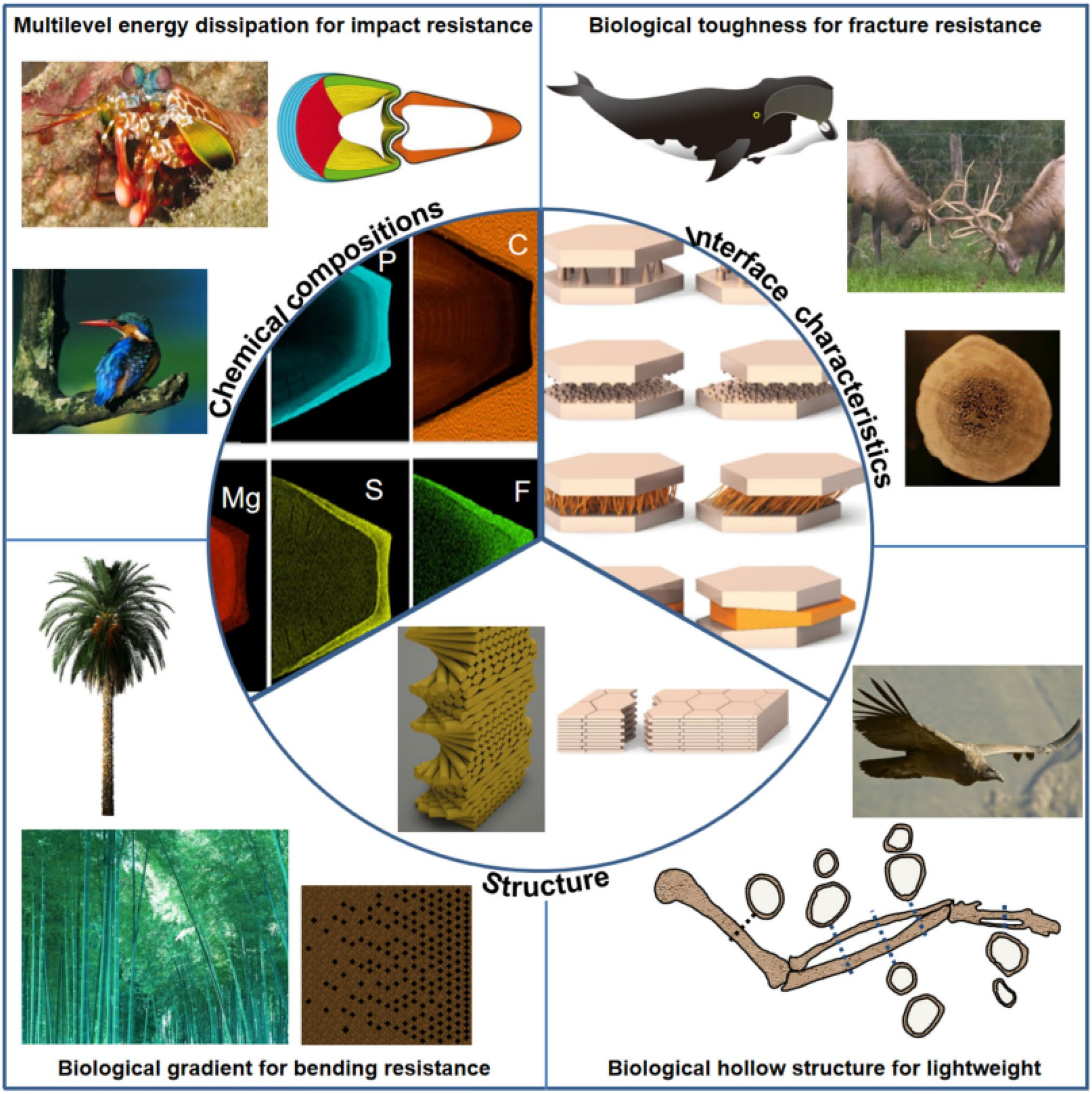

Fig. 1 Specific functions of natural materials are realized by adjusting structure, composition and interface [8, 11–15]

base to the maximum stiffness of the distal rostrum, which is tuned by the level of hydration [24, 27].

Ions can also participate in the enhancement of the mechanical performance of natural materials. Although the content of some ions is low in natural materials, their effect is crucial. In natural materials, the ions that take part in regulation are mainly metal ions, but other inorganic ions at times. Metal ions in natural materials mainly interact with biomolecules to form unique metal coordination bonds, a chemical interaction distinguished by common covalent and non-covalent bonding. This phenomenon is widely found between transition metal ions (e.g., Fe, Zn, Cu, and Ni) and proteins to generate metal coordination complexes. Hence, metal ions play a pivotal role in protein-based natural materials to provide enough protection, abrasion resistance and load-bearing performance. The unique mechanism of the interaction between metal ions and protein provides more possibilities for toughness, hardness and self-healing [16, 28, 29]. The type, concentration and distribution of ions can be adjusted flexibly to determine the mechanical properties

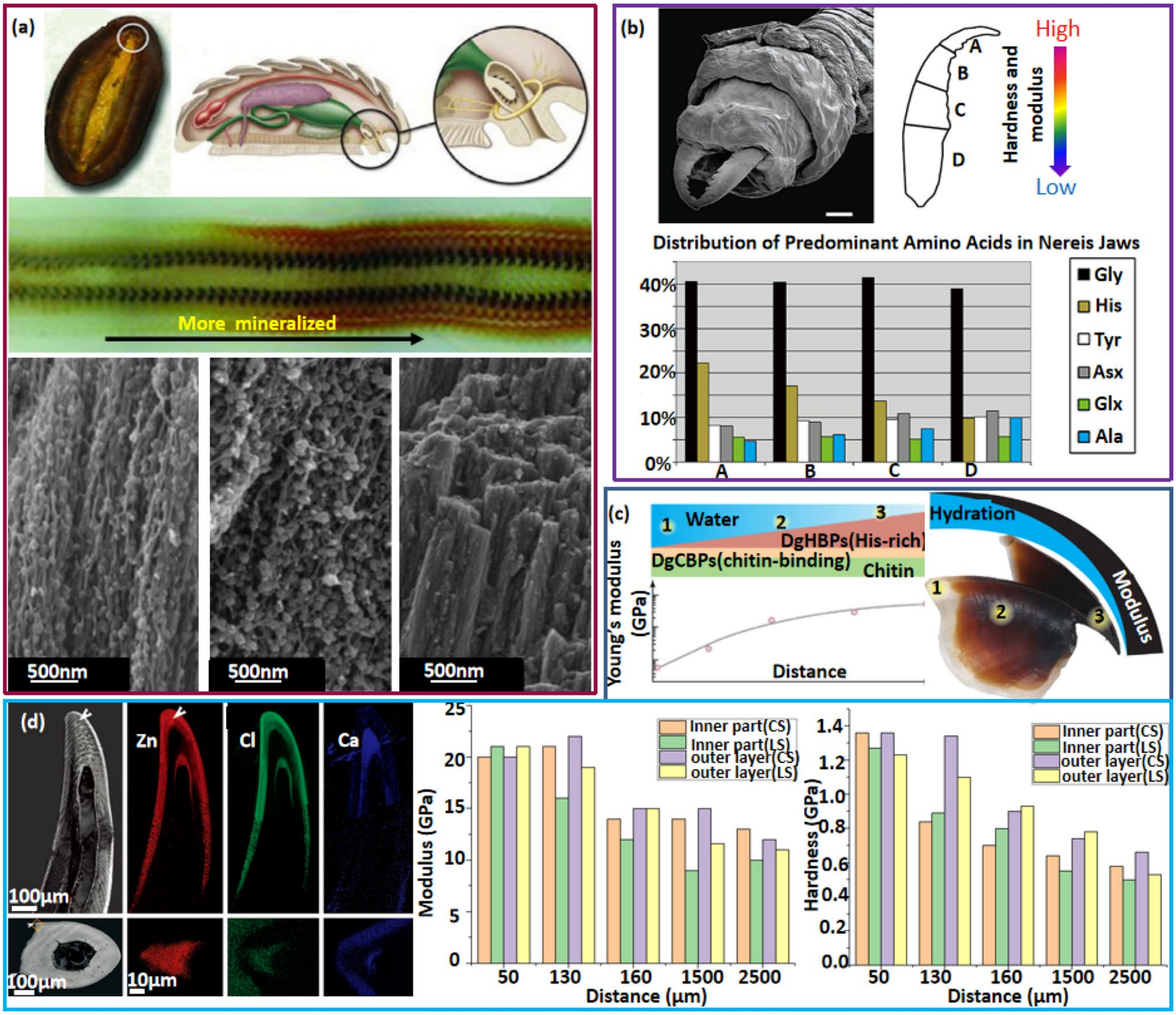

Fig. 2 The regulation of composition to achieve different properties. **a** The gradient mineralization of radular teeth of chiton [18, 19]; **b** The distribution of different type of amino acid in the nereis jaws [22]; **c** The diverse site-specific modulus induced by distinction of hydration [24]; **d** The distribution of different ions in the fang of spiders [25]

[28]. For example, spider fangs obviously exhibit uneven distribution of ions (Fig. 2d). Energy dispersive X-ray spectroscopy mapping reveals the distribution of Zn, Ca and Cl. Specifically, Zn and Cl show the same changing trend; that is, these elements are rich at the fang tip, while Ca is rich at the fang base. The difference in the properties of spider fangs notably corresponds to the distribution of ions [25].

2.2 Structure

In general, the mechanical properties of natural materials with similar compositions may differ because of their structure spans multiple scales. Natural materials mainly use changes in basic features, including arrangement, distribution, dimension, and orientation, to constitute different areas with various structures. In addition, the different structures in diverse regions customarily have different functions and properties, and then various regions combine along a certain sequence to form a unique architecture to satisfy requirements for survival.

Arrangement is a crucial element in creating diverse structures. For the same structural units, such as fibers, tubes, and plates, the diverse arrangements will directly cause differences in the structure of different locations [30, 31]. As shown in Fig. 3a, the reasonable arrangement of layers with different fiber directions significantly improves the toughness of the material by preventing crack propagation [5]. In addition, the shell of *Chrysomallon squamiferum*

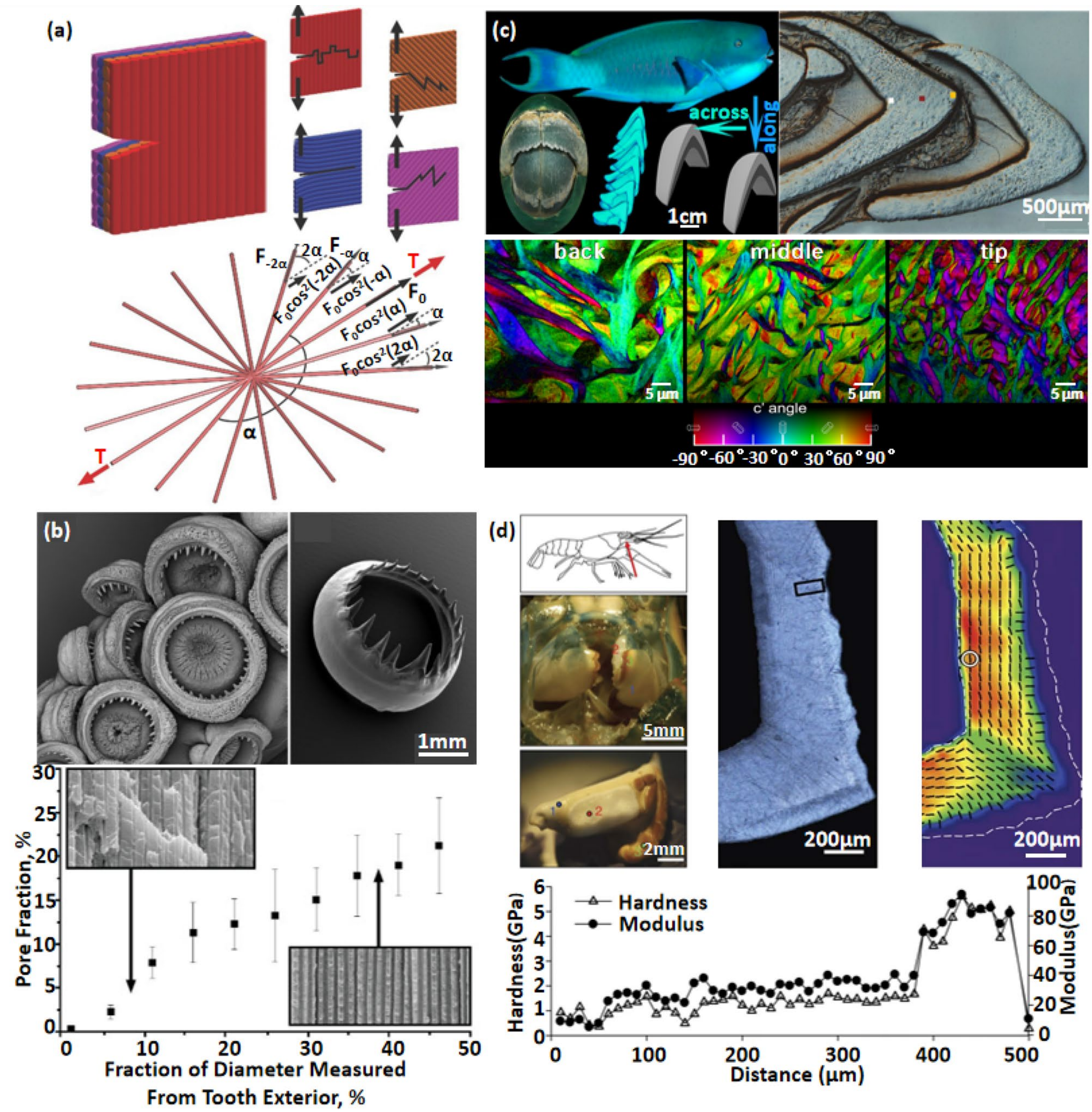

Fig. 3 The different methods regulate the structure of biological materials to achieve different properties. **a** The material toughness is improved by reasonable arrangement of layers with different properties [5]; **b** The squid sucker ring teeth alter the distribution of pores to control the properties precisely [32]; **c** The teeth of parrotfish exhibit diverse properties in different region through altering the orientation and dimension of mineralized fibers [38]; **d** The molar tooth of crayfish with the diverse orientation in distinct areas exhibits different mechanical properties [45]

realizes remarkable mechanical properties by arranging multilayer structures with different mechanical performances and specific functions. In general, various structures with different arrangements have distinct characteristics, such as Bouligand structures that provide toughness and in-plane isotropy and suture structures that control flexibility and strength.

Some natural materials evolve their multiple structure units with helical, layered and tubular structures. The distribution of these structural units is closely related to the performance of natural materials. For instance, the distribution of tubes and pores directly determines the density of natural materials. The rational distribution of tubes and pores will extremely reduce the mass of natural materials without loss of mechanical properties. In addition, the distribution of reinforcements, such as fibers, rods and sheets, has an important influence on the local mechanical properties, which appear at weak locations or high stress areas to make natural materials more durable and robust [10]. Squid sucker ring teeth, which are used as a tool to capture and handle prey, are representative materials that can realize the balance between performance and light weight by altering the distribution of pores (Fig. 3b). The porosity increases notably from the exterior to interior, followed by a decrease in the relative modulus and hardness [32, 33]. The core with more pores combines with a dense periphery, which can clearly enhance bending stiffness. Besides, many biological materials alter the distribution of tubes used as energy-absorbing devices to fit the function of natural materials, such as sheep horns [34, 35], hoof walls [36] and tooth dentin [37].

The dimensions of constituents directly determine the performance and functions of natural materials. Commonly, the variation in lamellar thickness and fiber diameter is mainly responsible for the complex and multiple structures of natural materials. For instance, parrotfish feed by biting stony corals, whose tooth present distinct gradient mechanical properties obviously (Fig. 3c). A schematic representation of the polarization-dependent imaging contrast mapping indicates that the average diameter of fibers presents an clear decrease toward the tip of the tooth (from 5 to 2 μm). Corresponding to this trend, the hardness and stiffness increase from the tooth base to the tip, which improves the wear resistance of the tooth surface. The region that invariably contacts stony corals suffers larger abrasion. This feature of parrotfish makes their teeth more durable under use conditions [38]. In a similar example, a sponge spicule consists of a central core of hydrated silica that is surrounded by concentric layers of silica and a protein material whose thickness decreases from the core to the edge of the sponge spicule [39].

Orientation is another major factor that can form microstructure with different local properties [40]. The orientation of units, such as fibers, platelets, and tubules, commonly exhibits obvious anisotropy, and is closely related to the local properties of natural materials. The preferred orientation of units is the result of natural selection induced by the magnitude and direction of loading. In addition, natural materials are good at utilizing the transformation of the orientation to build a unique architecture with certain roles to enhance the overall performance. The most typical structure is the Bouligand structure which is formed by twisting fibers layer by layer to dissipate energy efficiently and avoid the catastrophic propagation of cracks [41, 42], such as crab [43] and lobster [44]. In another example, the molar tooth of crayfish also utilizes the orientation of fibers to realize outstanding mechanical performance (Fig. 3d). The chitin fibers near the surface run perpendicular to the surface, which is coincident with the direction of the load. By adjusting its surface properties, the preferentially oriented and highly mineralized region with a higher modulus and hardness provides enough support for tearing prey. In contrast, the fibers in the deeper layers are parallel to the surface with low mineralization to dissipate energy to protect the tooth from catastrophic fracture [45].

2.3 Interface Characteristics

Interfaces commonly act as junctions between two regions with diverse compositions and structures to obtain more toughness and durability in natural materials. The natural materials form a continuous transition between different components through ingenious interface design and achieve a smooth transition of properties between diverse components. The interface can effectively reduce the stress concentration and shift the direction of crack extension to improve the toughness of natural materials [46].

Mechanical characteristics at interfaces play an important role in determining interfacial properties. The properties of interfaces can be tuned by adjusting the interfacial mechanical characteristics, including interlocking and altering roughness. Mechanical characteristics commonly depend on the behaviors of the interlayer, such as sliding, shearing and friction, to realize the purposes of energy dissipation. Moreover, crack propagation can be further controlled by only altering the interface (Fig. 4a). Nacre is a typical example of a natural material with excellent strength and toughness owing to its unique “brick-and-mortar” microstructure; this material is commonly imitated to develop artificial composites with outstanding performance [47]. The abundant mineral bridges are embedded in the organic matrix to concatenate the adjacent lamella, increasing energy dissipation during the progress of “pull-out” of mineral bricks. In addition, the interlocking of tablets leads to more deformation during sliding, which endows nacre with the ability to dissipate more energy to increase its toughness. In addition, the nanoasperities on the surface of platelets facilitate energy dissipation through interlayer friction between two rough platelets. Through synergies of several principles, nacre can flexibly tunes its interfacial properties to tolerate damage efficiently [48, 49].

Chemical characteristics of the interface primarily play a role through the way of cross-linking and hydrogen bond. As shown in Fig. 4b, small amounts of ions and minerals (e.g., Zn, Mn, Cu, Ti, Al, and Fe) participate in the assembly of materials and reinforce the delicate structure by the strategy of synergic cross-linking/coordinating. These metal ions cooperate with protein and biopolymer chains, such as chitin and cellulose, to form stochastic helices and coils, generating metal-protein/polysaccharide compounds with high stability, which play a key role in strengthening. Hence,

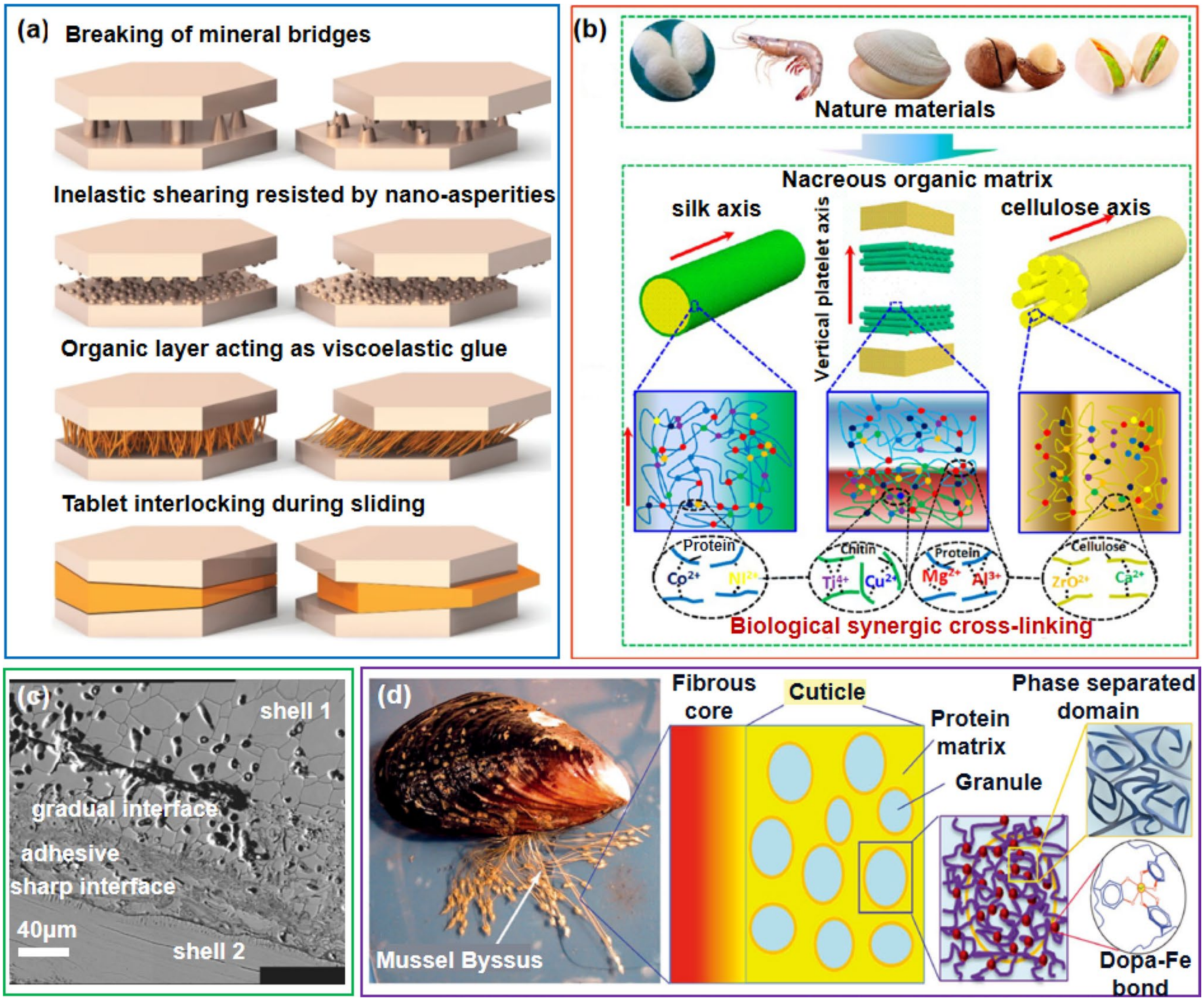

Fig. 4 The interface with ingenious connection to adjust material properties. **a** The multiple mechanical behaviors of nacre are used to enhance the interfacial properties, including breaking of mineral bridge, inelastic shearing of nano-asperities, deformation of biopolymer and tablet interlocking during sliding to dissipate energy efficiently [3]; **b** The chemical characteristic in the interface to promote mechanical performances through cross-linking between metal ions and biomolecules, such as protein, chitin and cellulose [50]; **c** The diverse tiny structures in the different interface in the oyster reefs connected with two shells robustly. One is gradual interface, and the other is sharp interface [51]; **d** The *byssus* cuticle of marine mussels utilizes cross-linking forming Dopa-Fe bond and subtle structures of phase separated domain to obtain the remarkable interfacial properties [52]

natural materials utilize this strategy to manage their local properties wisely. This cross-linking is obviously detected in the materials consisting of silk and cellulose and other organic matrices. In addition, hydrogen bonding is also commonly used to strengthen materials in nature [28, 50]. In summary, chemical characteristics tune the properties of natural materials at the molecular level to achieve strengthening and toughening.

The structure is also a marked characteristic to make a distinction between diverse interfaces. The oyster reef is an excellent example of utilizing unlike interfaces to connect two shells (Fig. 4c). An effective adhesive is used to build reef communities with outstanding performance to confront storms and surges. Backscatter electron imaging is used to show the diverse structures at two shell-adhesive interfaces. However, beyond that, the dimensions of the prisms at the interfaces also exhibit marked differences. The local structures at the interface bring better overall performance to the function of materials [51]. Thus, living organisms build artful junctions between diverse materials by altering the structure at the interface to achieve optimal overall properties.

The interface of natural materials commonly utilizes multiple factors to realize the enhancement of interfacial properties. The diverse factors work together to obtain multifaceted advantages for natural materials meeting the requirements of certain functions. The byssus cuticles of marine mussels are representative examples of biological materials that display excellent mechanical properties due to the unique interface with the ingenious structure and cross-links (Fig. 4d). There are many granular areas in the protein matrix of the byssus cuticle. Under the action of a load, the regions of the micro phase-separated construction deform greatly and dissipate a large amount of energy. In addition, the cross-linking between dihydroxyphenylalanine (DOPA) and Fe ions significantly enhances the properties such as hardness and stiffness in regions [52, 53].

3 Strategies of Natural Materials to Achieve Excellent Mechanical Properties

Different natural materials have evolved various mechanical properties due to the tremendous difference in living environments. The multiple functions of natural materials make living organisms more confident in getting food, resisting enemies and surviving in some special conditions [54]. For instance, the light weight of most birds for flight [13], abrasion-resistant teeth [55] and the protective effect of natural armors [56] are typical examples of natural materials with specific functions for survival. The various functions are realized by ingeniously regulating structures, interface characteristics and chemical composi-tions to confront distinct challenges. In addition, the diverse functions commonly depend on different local properties, so distinct local properties and diverse combinations of site-specific properties make natural materials more flexible and robust to realize specific functions for various working conditions. For instance, the natural material that sustains frequent wearing commonly possesses a higher surface hardness. The natural material suffering from an extremely high local load has a specialized layer to homogenize the stress to prevent stress concentration. Artificial materials can draw lessons from natural materials with specific functions by combining and arranging different regions with diverse local properties for engineering applications in distinct working situations. In this chapter, the strategies of biological materials to achieve specific functions and their potential applications in engineering are introduced.

3.1 Multilevel Energy Dissipation for Impact Resistance

In nature, natural materials inevitably withstand enormous impact forces, such as the smasher of mantis shrimp hammering prey [57–59], the pecking of trees by woodpeckers [60] and the elytra of beetle [61]. The impact loads lead to a substantial impact force directly acting on the surface of natural materials and readily induce a high level of stress concentration. Because the force acting on the impact surface is very large, a high hardness and strength of the impact surface are necessary to resist the direct destruction of the impact. However, a homogeneous component with high hardness and strength is inadequate because of the lack of toughness resulting in fracture. Hence, the region with enough toughness to dissipate impact energy effectively is also indispensable for avoiding catastrophic fracture and increase durability. In addition, the unique areas of some natural materials possessing particular local properties are mainly responsible for redistributing stress and strain to avoid stress concentration and excessive local strain. The smart transition of local properties spanning various areas results in diverse regions with different effects during the impact process and cooperatively resists impact damage. Furthermore, some microscopic characteristics of the inherent properties of components themselves also significantly affect the response behavior to impact loading, such as the crystallographic characteristics of biominerals and the properties of biopolymer chains [62–64]. Similarly, the outstanding impact resistance is also the result of precisely regulating the local properties and functions controlled by multiple factor synergies, such as structure, composition and interface. Multilevel energy dissipation can effectively reduce the impact energy of a single region, thereby improving impact resistance.

The dactyl club of mantis shrimp can destroy the rigid biological armor of mollusks under the impact of a high strain rate, which achieves accelerations over 10,000 g and reaches speeds of 23 ms^{-1} from the rest position [58]. In addition to the contribution of the herringbone and Bouligand structure that has been reported, another important reason for the high impact resistance of the dactyl club of mantis shrimp was recently found to be the impact-resistant nanoparticle coating on its surface [65] (Fig. 5a). The nanoparticle coating is composed of tightly packed ~ 65 nm bicontinuous nanoparticles of hydroxyapatite integrated within an organic matrix. High strain rate impact results in the rupture of nanoparticles into smaller primary grains (~ 10–20 nm), which dissipates part of the impact energy. Differential interference contrast optical micrographs reflect rough surfaces of the clubs after impact, indicating that particle translation and ablation are also the underlying mechanism of energy dissipation [65]. Some microscopic characteristics of the inherent properties of components themselves directly determine the impact resistance of natural materials, especially crystallographic features of biominerals. For instance, during the impact process, deformation twinning and partial dislocations are found in nacre to combat catastrophic fracture under impact loading with a high strain rate [64, 66].

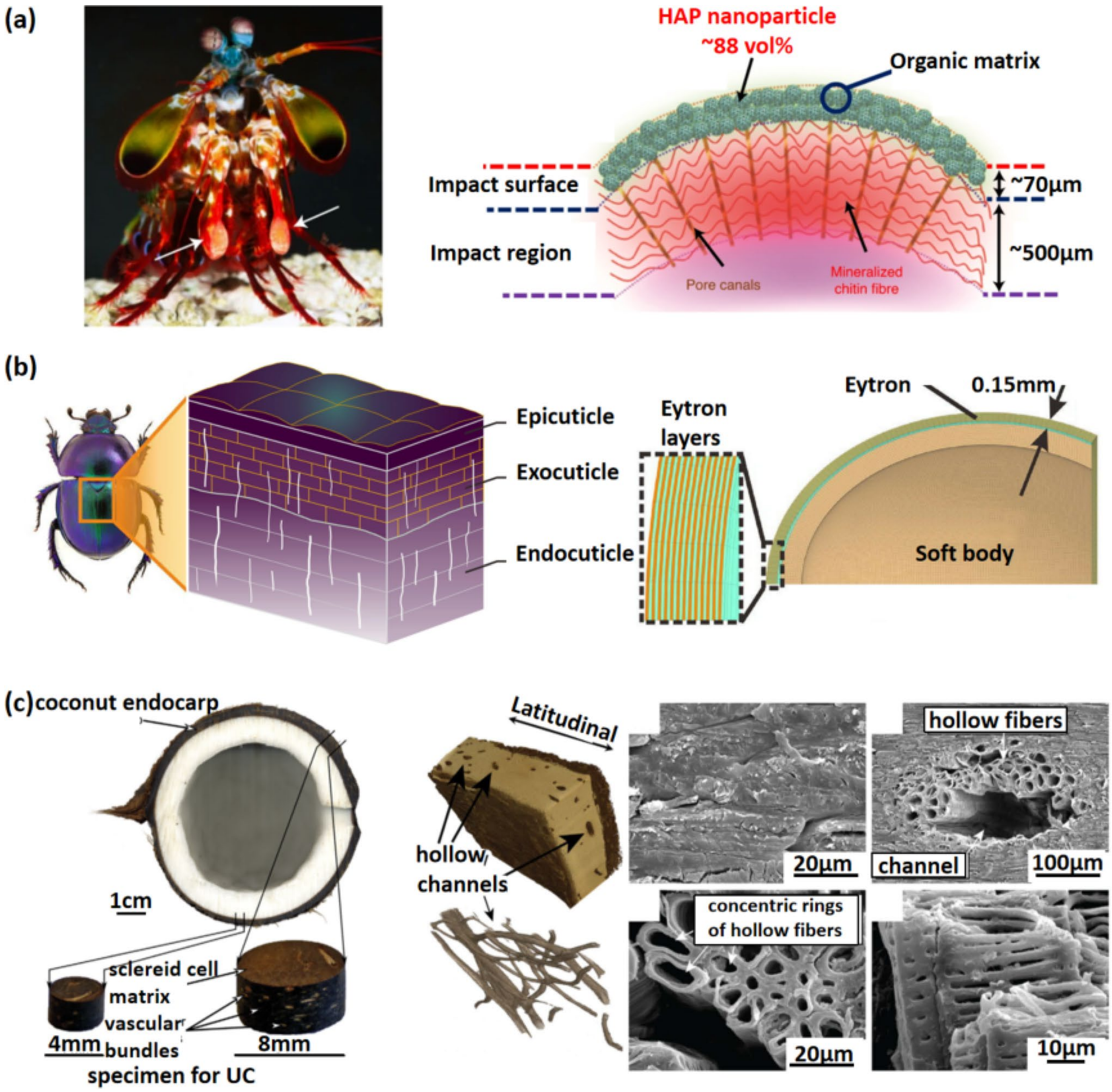

Fig. 5 Natural materials achieve remarkable impact resistance through multilevel energy dissipation. **a** Another important factor for impact energy dissipation of the dactyl club of mantis shrimp is the impact resistant nanoparticle coating on its surface [65]; **b** The layered structure of the beetle cuticle resists impact [69]; **c** The unique structure of coconut protect the internal fruit form the injuring of falling from the tree, mainly including vascular bundles and concentric rings of hollow fibers to dissipate impact energy effectively [72, 73]

Except for the mantis shrimp mentioned above, another classic example of significant impact resistance is the insect cuticle. The insect cuticle has a multilevel laminated structure with different stiffness gradients, which can be used as a defensive armor to resist the impact of predators. Previous studies have shown that the structure of the insect cuticle is usually composed of the epicuticle, exocuticle and endocuticle [67]. In contrast, the epicuticle is stronger and can effectively avoid impact damage to the stratum corneum, while the endocuticle is more flexible, which is conducive to dissipating impact energy and preventing crack propagation. However, the latest research shows that *Pachyrhynchus sarcitis kotoensis* has an inner layer that is stiffer than the outer layer. Researchers have provided the first evidence that a harder endocuticle can increase the mechanical properties of the cuticle, which gives us a deeper understanding of insect cuticles and provides new solutions for the design of biomimetic materials [68]. Besides, Xing et al. revealed the impact resistance strategy by studying the mechanical properties of the layered structure of a beetle cuticle under impact load. The discontinuity at the cuticle interface and the distribution of the stiffness gradient are beneficial for preventing stress wave propagation and improving impact resistance [69] (Fig. 5b). The above research shows that the impact energy can be effectively dissipated among the layers through a reasonable distribution of stiffness between the hierarchical structures, which provides an important inspiration for designing structural materials with higher impact resistance. For example, inspired by the stiffness gradient of insect cuticles, researchers have designed an impact-resistant structure with programmable stiffness [70]. In addition, Rivera et al. investigated the mechanism of how the elytra of *Phloeodes diabolicus* greatly improves impact resistance. In addition to the stiffness gradient on the macroscopic scale, the mechanism highlights the influence of the interface microstructure. Specifically, the ellipsoidal geometry and laminated microstructure provide mechanical interlocking at the interface, thus avoiding catastrophic damage [71]. Therefore, this research provides bionic inspiration for our design of connections in engineering applications. At present, research on beetle elytra has made many achievements, but the structural characteristics of smaller-scale elytra remain to be explored.

Additionally, another typical natural material with excellent impact resistance is coconut, whose fruits are protected by the wall with three layers from impact upon falling from trees, including the exocarp-like leather, fibrous mesocarp and hard endocarp (Fig. 5c). The first two layers mainly provide a function of dissipating energy and buffering the tremendous impact. The ripe endocarp, with a unique structure, directly in contact with the coconut is hard and tough enough to guard the fruit from injury. The structure of the endocarp ingeniously transfers loads to cellulose crystalline nanostructures rather than vulnerable fruits. In addition, the rupture of the vascular bundles provides generous energy dissipation to prevent catastrophic fracture and enhance toughness [72, 73]. The advantage of the coconut shell structure is that it consists of three layers with different structures and functions; this provides a good example to study the control of the impact resistance of multiscale hierarchical shell structure.

Impact damage is very common in the automobile, construction, national defense and sports industries, so how to realize the effective and rapid dissipation of impact energy inspired by biology has great significance for modern engineering. The deep study of natural materials can provide inspiration for the development of new impact-resistant materials.

3.2 Biological Toughness for Fracture Resistance

Fracture is one of the most dangerous modes of failure and can directly result in materials invalid. Hence, it is vital to prevent the emergence and propagation of cracks by altering the structure, composition and interface. The ability to resist fracture is commonly related to the toughness of natural materials. A higher toughness means more energy consumption during the process of failure, which indicates that it is more difficult to drive the propagation of cracks. Natural materials usually adopt intrinsic toughening and extrinsic toughening mechanisms to effectively improve the fracture resistance [74].

According to traditional fracture toughness theory, fracture toughness refers to the ability of a material to prevent crack extension [75]. Generally, crack extension occurs when the crack driving load equals or surpasses the crack propagation resistance of the material. Notably, the crack growth resistance and crack driving force are both dynamic, especially for natural materials with various components and microstructures, which makes the fracture process a complicated and changeable process [75]. The regulation of the local modulus is conducive to fracture resistance [76]. In addition, specific interfaces, such as weak interfaces and sacrificial bonds, also significantly increase the fracture resistance of natural materials. Furthermore, different from the foregoing internal toughening mechanism, external toughening, such as fiber bridging, primarily prevents crack propagation by increasing crack extension resistance [76].

Natural materials generally achieve excellent fracture toughness by combining intrinsic and extrinsic toughening across multiple scales. For instance, the baleen of whales can substitute teeth and serves as a filter for food with outstanding fracture resistance without replacement throughout life [77] (Fig. 6a). The unique sandwich-tubular structure, hydration and gradient mineralization are crucial reasons for its remarkable fracture toughness. In addition, by increasing the interchain space and decomposing secondary bonding, the interaction between water and matrix protein significantly improves toughness. Hence, the combination of various factors contributes to the notable fracture resistance of the whale baleen. In addition to the baleen of whales, the compact bone of the elk antler is another typical example utilizing intrinsic and extrinsic toughening to promote the fracture toughness of natural materials [11, 78] (Fig. 6b). In antler bone, intrinsic toughening is generated by the stretching and unwinding of mineralized collagen at the nanoscale and continuous sliding between collagen molecules and hydroxyapatite particles at the microscale. Extrinsic toughening to resist fracture mainly depends on the deflection and bridging of cracks commonly operating at the micrometer scale and even above [78].

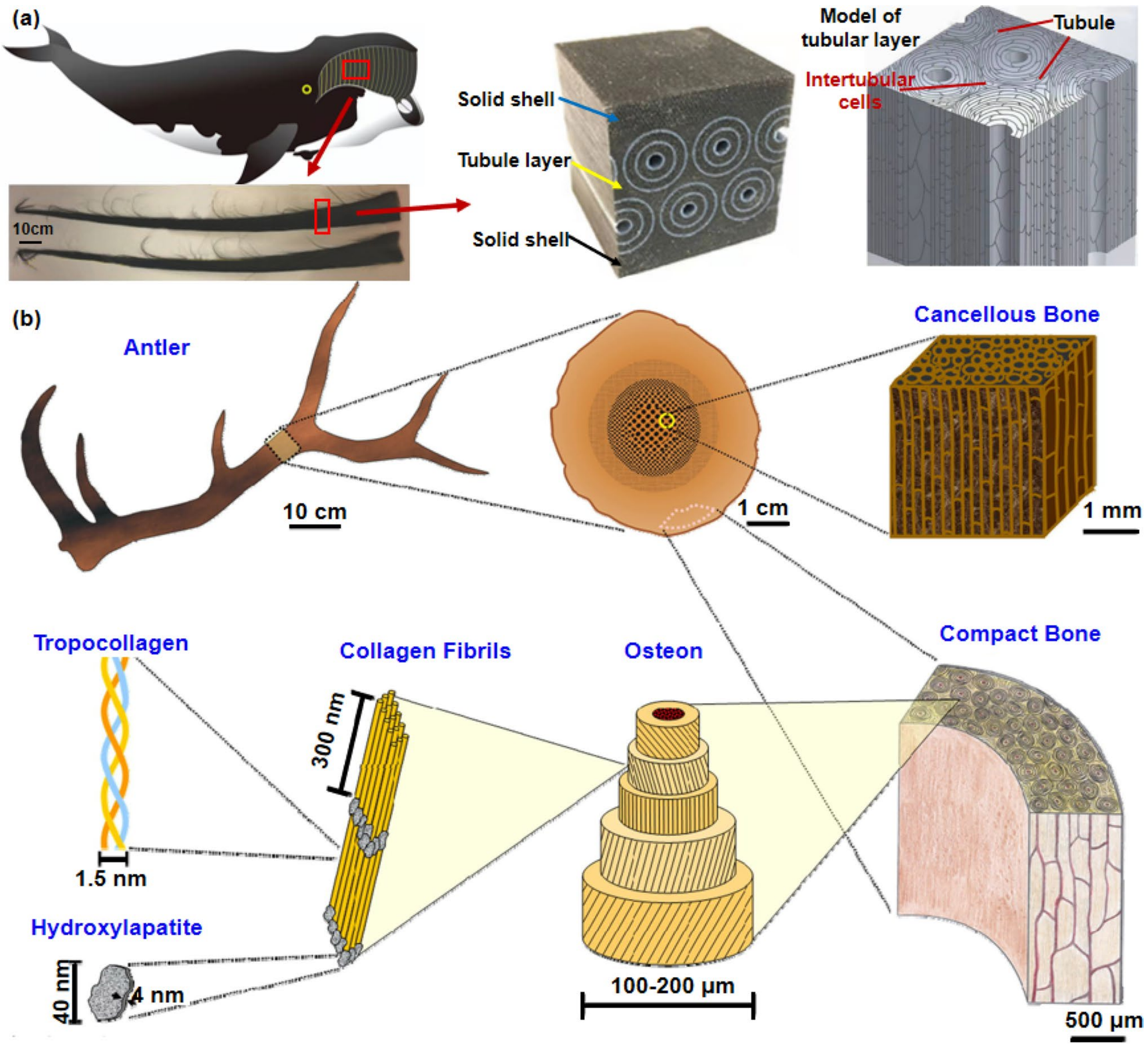

Fig. 6 The natural materials with remarkable fracture resistance. **a** The baleen of whale can resist fracture by utilizing the unique sandwich structure and toughening mechanisms [77]; **b** Hierarchical structure of antlers [11, 78]

The materials mentioned above are initially in a condition without cracking, so the process of failure mainly inhabits the nucleation of cracks in the first step. Instead, some natural materials make use of cracks to realize specific functions ingeniously, such as spiders [31, 79] (Fig. 7a) and scorpions [80, 81] (Fig. 7b). The spiders and scorpions commonly possess a crack-shaped slit near their leg junction to catch extremely weak vibrations. The existence of inherent cracks puts forward the higher requirement of the ability to prevent the propagation of cracks. As shown in Fig. 7b, the slits of scorpions adopt a mechanism to prevent the propagation of cracks spanning multiple scales. The subtle layered structure resembling those of other natural materials near the slits notably promotes fracture toughness. In addition to the layered structure, the unique cuticular membrane covering the slit plays a significant role in avoiding catastrophic structural failure. Compared with the lower modulus, the rational modulus of the membrane makes the elastic modulus of the whole biocomposite steady during the deformation process of, and the opening of slits remains in a certain range throughout the deformation of the membrane. The unique structure with site-specific properties endows the slit sensors of scorpions with an excellent ability to effectively combat fractures [80, 81].

As a quite common and threatening failure mode in the engineering field, fracture seriously affects people's lives and

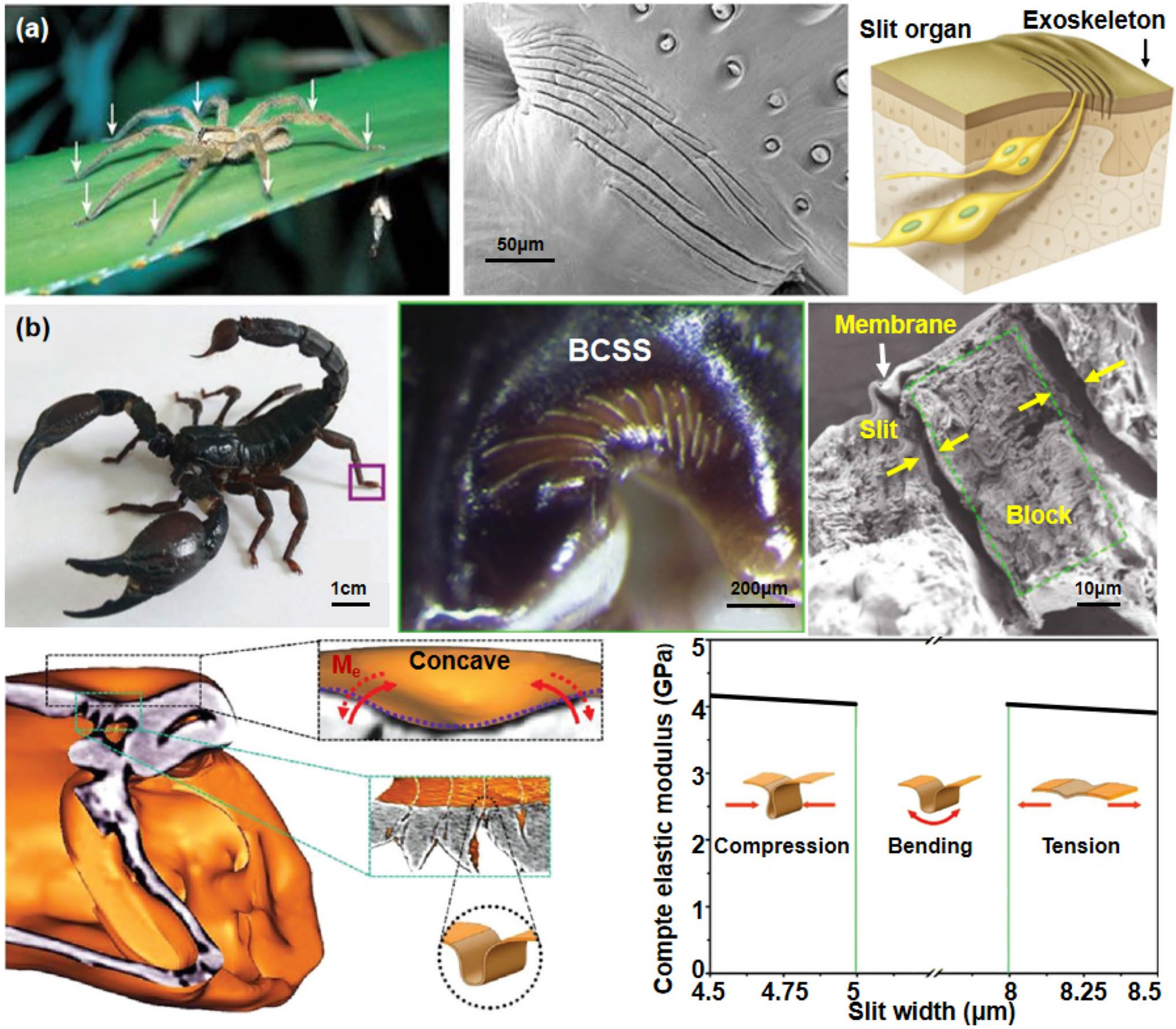

Fig. 7 Living organisms utilize crack-shaped slit to sense tiny vibration and ensuring safety of materials simultaneously. **a** The crack-shaped slit in spider legs to sense vibration in case of ensuring safety of crack-shaped slit [31, 79]; **b** The basitarsal compound slit sensilla of scorpions prevent the propagation of crack-shaped slits through the unique structures and the membrane ensuring the safety of their sense organs [80]

production, causes great economic losses, and even threatens personal safety. Therefore, it is extremely important to improve the fracture toughness of engineering materials inspired by natural materials.

3.3 Biological Gradient Increases the Area Inertia Moment for Bending Resistance

Many natural materials are susceptible to failure due to bending and buckling, such as beams and poles with a high aspect ratio. Although recoverable bending does not result in irreversible failure, large bending also means that natural materials cannot be used properly for a period of time. In addition, excessive buckling will directly lead to the instability of materials. Therefore, bending and buckling must be controlled effectively for normal use and to avoid failure. Natural materials can normally obtain remarkable flexural strength through biological gradient structures [82]. The deflection y can be calculated by Eq. 1:

$$\frac{dy^2}{dx^2} = \frac{M}{EI} \tag{1}$$

where E is the elastic modulus, M is the bending moment, and I is the area moment of inertia. In addition, Euler's buckling equation is typically used to evaluate the level of buckling. The overall buckling under loading is generally satisfied by Eq. 2:

$$P_{cr} = \frac{\pi^2 EI}{(kL)^2} \tag{2}$$

where P_{cr} is the critical load, L represents the length of the biological materials and K is a constant dependent on the column-end conditions. Hence, the bending and bulking resistance is tightly related to the local modulus and area moment of inertia. The elastic modulus is commonly tuned by altering the components of materials, while the area moment of inertia is determined by the distribution of mass. In other words, the local density directly determines the area inertia moment and further inflects bending and bulking resistance. In terms of the above expression, a larger area moment of inertia means a greater capacity to withstand bending but worse bucking resistance. Therefore, there is a contradiction between bending and buckling. In nature, many materials utilize gradient methods to distribute their mass ingeniously, obtaining remarkable stiffness with a light weight to resist deflection with a hollow core and foam. On the other hand, the problem of bulking resistance is solved by adding the reinforcement, such as disks, struts and stiffeners, at a proper location to resist excessive local bucking [83].

Flight feathers, composed of a cortex of a solid keratinous shell, enclosing the medulla of a foamy core, are mostly subjected to bending during flight. The cross section of a seagull feather from calamus to rachis shows that the shape of the cortex changes from circular to rectangular (Fig. 8A). Compared with the circular hollow beam, the hollow beam with rectangular cross sections has advantages of higher bending stiffness per unit area and a stronger resistance to changing cross-sectional shape. The cortex of the rachis is similar to an I-beam that distributes material to the area of the maximum area inertia moment to resist bending deformation [84]. Similarly, feather shafts of other volant birds, such as pigeon and bar owl, also exhibit such a shape factor gradient [85]. This variable cross-sectional structure of feather shafts not only resists bending deformation but also has the advantage of light weight.

The stem of a palm is a typical example of using the gradient method to gain bending stiffness (Fig. 8b). Palms acquire excellent overall resistance to bending and buckling by controlling their local density. The relationship between mechanical strength σ_c and r can be described as $\sigma_c \propto r^4$, where r represents the radius of the palm and stress σ complies with the $\sigma \propto r^6$ relationship. Besides, palms show the trend that the exterior density is higher than that in the interior by utilizing the uneven porosity. Compared with homogeneous materials of equal quality, the overall bending stiffness is increased by 2.5 times [4].

Figure 8c demonstrates that the distribution of fibers across the thickness of bamboo is nonuniform, resulting in the outer portion of the bamboo being more dense than the inner portion. This hierarchical architecture induces functionally local properties along the direction of thickness. For instance, the stiffness increases toward the surface, resulting in more flexible rigidity of the stem [86–89].

Bending and buckling are common in machinery, such as the drive shafts of cars and machine tools, which seriously reduce the transmission accuracy and even cause mechanical failures, threatening personal safety. Therefore, it is significant to learn strategies for resisting bending and bulking of natural materials to improve mechanical properties.

3.4 Biological Hollow Structure for Lightweight Materials

Natural materials generally have excellent mechanical properties and are lightweight to satisfy the needs of survival. For example, the demand for flight requires a bird with lightweight wings and bone to satisfy relevant aerodynamic requirements [90]. Living organisms utilize all kinds of methods to decrease quality under the prerequisite of ensuring related mechanical performance. Hollow structures, such as pores and holes, can significantly reduce the quality of the material. However, if the distribution of hollow structures is unreasonable, then the mechanical properties of materials will be inadequate. Therefore, some ingenious strategies should be employed to adjust the properties of materials [91].

Many birds have hollow bones for the purpose of decreasing the mass to ensure flexibility of flight [92]. The wing bone of a bird is a typical case that adjusts the local structure of materials to realize lightweight whole materials on the macroscopic scale [13]. The cross sections of wing bones of *Turkey vultures* show that the cross-sectional shape of the wing bone changes significantly with position (Fig. 9a). The cross-sectional shape is observed as a hollow circular section, which varies toward the end of bones. The various cross-sectional shapes of bone ensure the mechanical performance of different locations to withstand unequal forces. The wing bone of birds obtains excellent performance in responding to severe environmental challenges through precise control of the cross-sectional shape.

Cellular structures are widely found in nature, such as wood [93] and cancellous bone [94]. Because of their high porosity, these natural materials commonly possess a very low density. However, the low density due to the porous structure is usually at the expense of mechanical properties. To overcome this challenge, natural materials utilize ingenious cellular structures to dramatically improve their mechanical properties with relatively light weight. The precise control of multiple factors, such as arrangement,

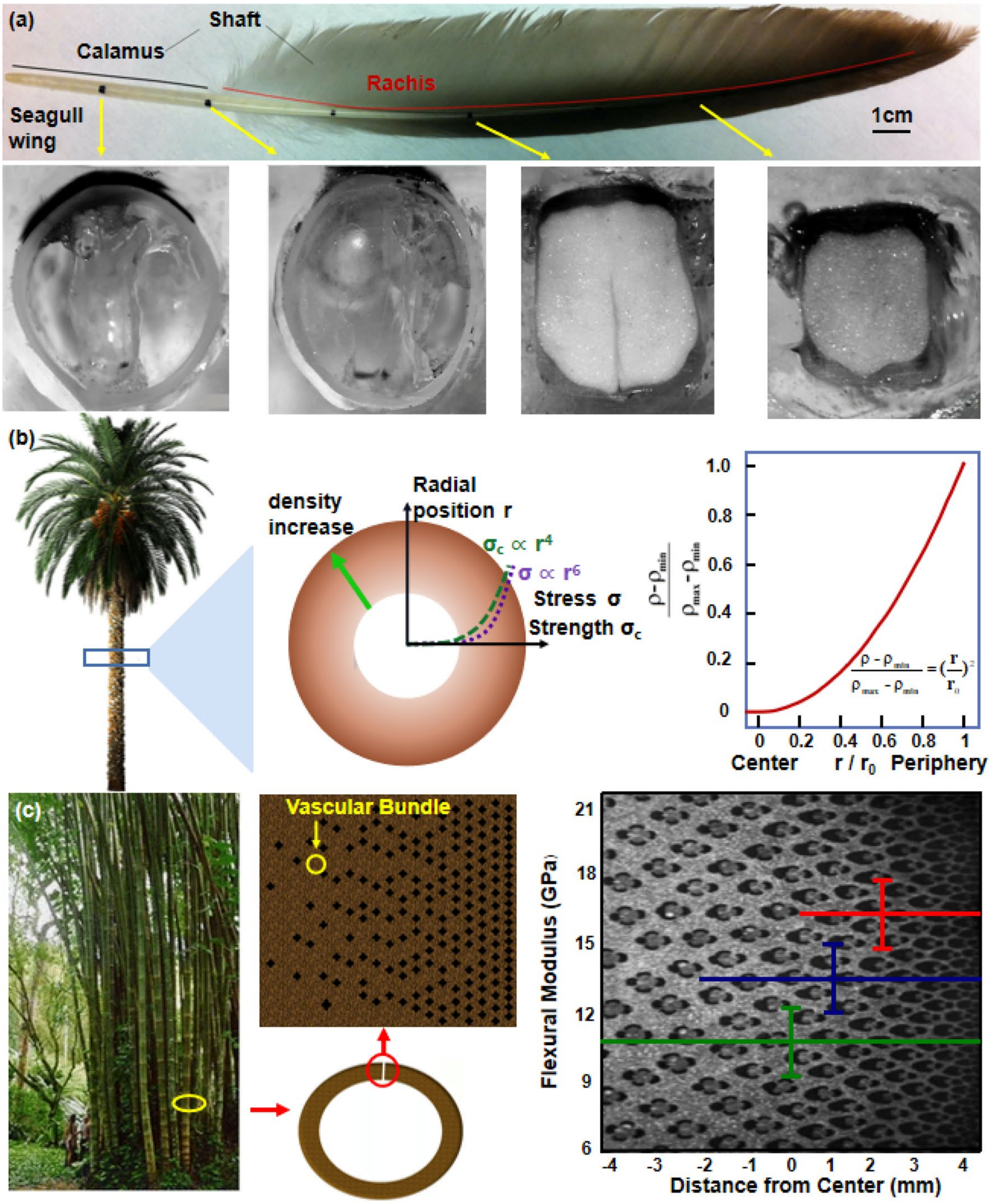

Fig. 8 The gradient strategies of natural materials for achieving outstanding bending resistance. **a** The cross section of seagull feather gradually changed from round to rectangular to resist bending [84]; **b** The stem of palm exhibits the increase in relative density from center to surface, resulting in the different strength to resist bending [4, 8]; **c** The bamboo tunes the distribution of fibers resulting in the gradient flexural modulus to confront bending with a low mass [88, 89]

dimension and distribution, results in complex structures to realize lightweight materials with outstanding mechanical properties [95]. Wood, which acts as one of most common natural structural materials, is a representative example of utilizing cellular structures to realize lightweight and high-strength properties simultaneously. The unique hierarchical cellular structure similar to a honeycomb endows wood with admirable mechanical properties [96] (Fig. 9b). Hence, the unique cellular structures of natural

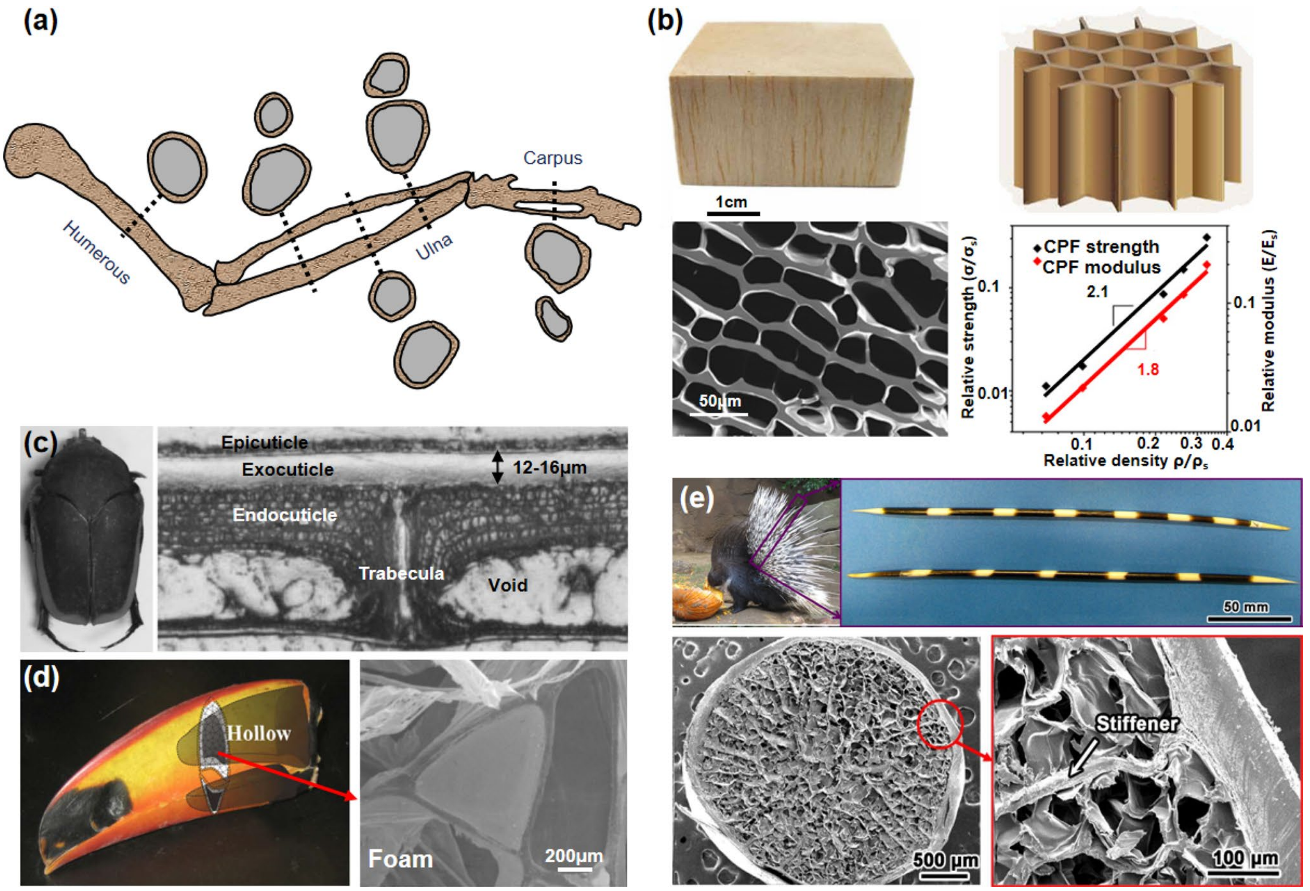

Fig. 9 The hollow structure strategies of biological materials realize lightweight with excellent mechanical properties. **a** The wing bones of *Turkey vulture* realize the unity of lightweight and strength by adjusting the shape of hollow area [13]; **b** The wood with the smart cellular structure combine outstanding mechanical properties and lightweight simultaneously [96]; **c** The rational distribution of pores and columns endow beetle exoskeleton ultra-lightweight and remarkable mechanical properties [97]; **d** The toucan beak realize lightweight with the rational distribution of hallow areas and foam cores [102]; **e** The porcupine quills utilize the foam of the core to reduce their mass and the stiffer in local positions sustained higher load to reinforce the local properties [101]

materials spanning multiple scales effectively improve their mechanical properties with lightweight.

Tubules and cavities are widely found in natural materials as common structural units that directly reduce the mass of materials. Therefore, the distribution of these units directly determines whether the materials have excellent mechanical properties with light weight to resist complicated and changeable environments. Compared with solid materials, tubules and cavities are commonly added to materials to reduce mass. The reinforcements in hollow areas make natural materials combat local failure with a minimum weight penalty. For instance, the periodic disks in hollow tubes and reasonable distribution of hallow vascular bundles provide bamboo enough support to sustain local buckling at prescribed distances with a light weight [86, 87]. In addition, the beetle exoskeleton is a successful combination of pores and reinforcement [97] (Fig. 9c). The rational distribution of pores and columns endow it with ultralight weight and remarkable mechanical properties [98, 99].

Another method to realize the goal of weight reduction is the skillful application of foam. Numerous natural materials, such as porcupine quills [100, 101], toucan beaks [102], hedgehog spines [103, 104] and feather rachises of most birds [105], are sandwich-structured composites composed of stiff solid shells filled with lightweight foam to realize the goal of being lightweight. The beaks of most birds are short and thick or long and thin except the toucan beak, which is one-third of the whole length of the toucan. Therefore, the beak of toucans must have lower density than common beaks of other birds to ensure flexible and steady flight (Fig. 9d). The unique structure makes beak only 1/30 of the overall bird's mass with outstanding mechanical properties. The external part of the beak is stacked with keratin scales, which are stiff and hard. The core consists of a cell-closed foam composed of rod-like trabeculae and thin membranes [102]. Compared with hollow structures, foam-filled structures can effectively raise the bending resistance of natural materials with minute mass additions [106].

In general, the light weight of natural materials with outstanding properties is not the contribution of a single factor but the result of multiple strategies acting together. The synergy of various methods perfectly provides enough resistance to local loading with a minimum weight. For example, porcupine quills are strong enough to resist enormous compression and flexure loads with lightweight by the coordination of cortex, foam and stiffener [101] (Fig. 9e). Under a significant load, the cortex with a high modulus mainly provides most of the buckling resistance to enhance the stiffness of materials. However, this does not mean that the role of foam can be ignored. Although the foam with a relatively low modulus cannot contribute to the stiffness directly, the foam of the quills can absorb amounts of elastic strain energy by deforming extensively to delay the occurrence of buckling [107].

For vehicles such as cars, trains and planes, lightweight means higher energy efficiency and lower economic cost. Therefore, the realization of lightweight under the premise of ensuring strength has great engineering value. The ingenious strategy of natural materials to achieve lightweight provides inspiration for our design and manufacturing.

4 Preparation and Application of Biomimetic Materials

Some traditional methods of manufacturing biomimetic materials require harsh conditions such as high temperature and high pressure, rather than the mild external circumstances [17, 108]. Therefore, the use of environmentally friendly biological strategies to prepare biomimetic materials for the purpose of obtaining artificial materials with superior performance under mild conditions has attracted the attention of more and more scientists. Generally, the biological methods for obtaining materials with excellent performance mainly contain the following aspects. The first method is bionic mineralization inspired by the synthesis process of biological materials. The second strategy is to use advanced manufacturing techniques to mimic the multiscale structure of natural materials. The last means is to modify natural materials through physical or chemical methods.

4.1 Methods for Preparing Biomimetic Materials with Excellent Mechanical Properties

4.1.1 Bionic Mineralization

Biomineralization is an important tactic by which biological organisms produce hierarchically structured minerals with marvelous functions [109, 110]. Bionic mineralization is a method to prepare materials by imitating the process of biomineralization. At present, chemical minerali-zation technology has produced highly mineralized structural composites, but the free control of mineral orientation cannot be realized [111, 112]. Therefore, it is a severe challenge to make highly mineralized structural composites with freely controlled mineral orientation. Nature is the source of inspiration for the design of composite materials. Inspired by the process of constructing mineralized composite materials by mollusks or articulates, Xin et al. proposed a method to prepare ordered highly mineralized composite materials using bacteria-assisted mineralization in a polymer lattice that was 3D printed [113] (Fig. 10a). The superiority of this method is that the arrangement of polymer phases and mineral fibers is controlled by a 3D-printed lattice structure, which enables the creation of complex arrays of structural composites, such as Bouligand and layered structures. Similarly, researchers have designed a hydrogel biomimetic mineralization model for regenerating enamel prismatic tissue. Hydrogels regulate the habit, size and mineral phase of growing crystals by synergistic action with calcium, phosphate and fluoride ions. The regenerated apatite crystals were found to be highly oriented along the c axis with good crystallinity. The elastic modulus and nano-hardness of this material are similar to those of natural enamel, which has broad application value in clinical dentistry [114] (Fig. 10b). In addition, some researchers have proposed a method of mesoscale "assembly and mineralization" to obtain a synthetic nacre with excellent performance inspired by the mineralization process of the synthetic nacre of mollusk [112].

Although this approach is inspired by the synthesis process of natural materials and can accurately mimic the properties of natural materials compared to other technologies, it is difficult to fully inherit the structure and properties of natural materials because existing technologies cannot fully mimic biominerali-zation and other synthesis processes controlled by living organisms. At the same time, improving the time efficiency of the synthesis and growth of natural materials is also a serious challenge.

4.1.2 Advanced Manufacturing Technology

The multiscale structure of organisms enables them to adapt to complex environments. Imitating the structure of organisms directly through advanced manufacturing technology is also a strategy for the biomimetic design of new materials.

Additive manufacturing is an effective method to manufacture customized parts with complicated structures [115]. The recent development of 3D printing technology, such as 3D magnetic or electrical printing [116] and slip-casting [117], allows researchers to model sophisticated bioinspired structures. Yang et al. presented a method termed electrically assisted nano-composite 3D printing that can dynamically align multiwall carbon nanotubes by controlling a rotating electrical field for the preparation

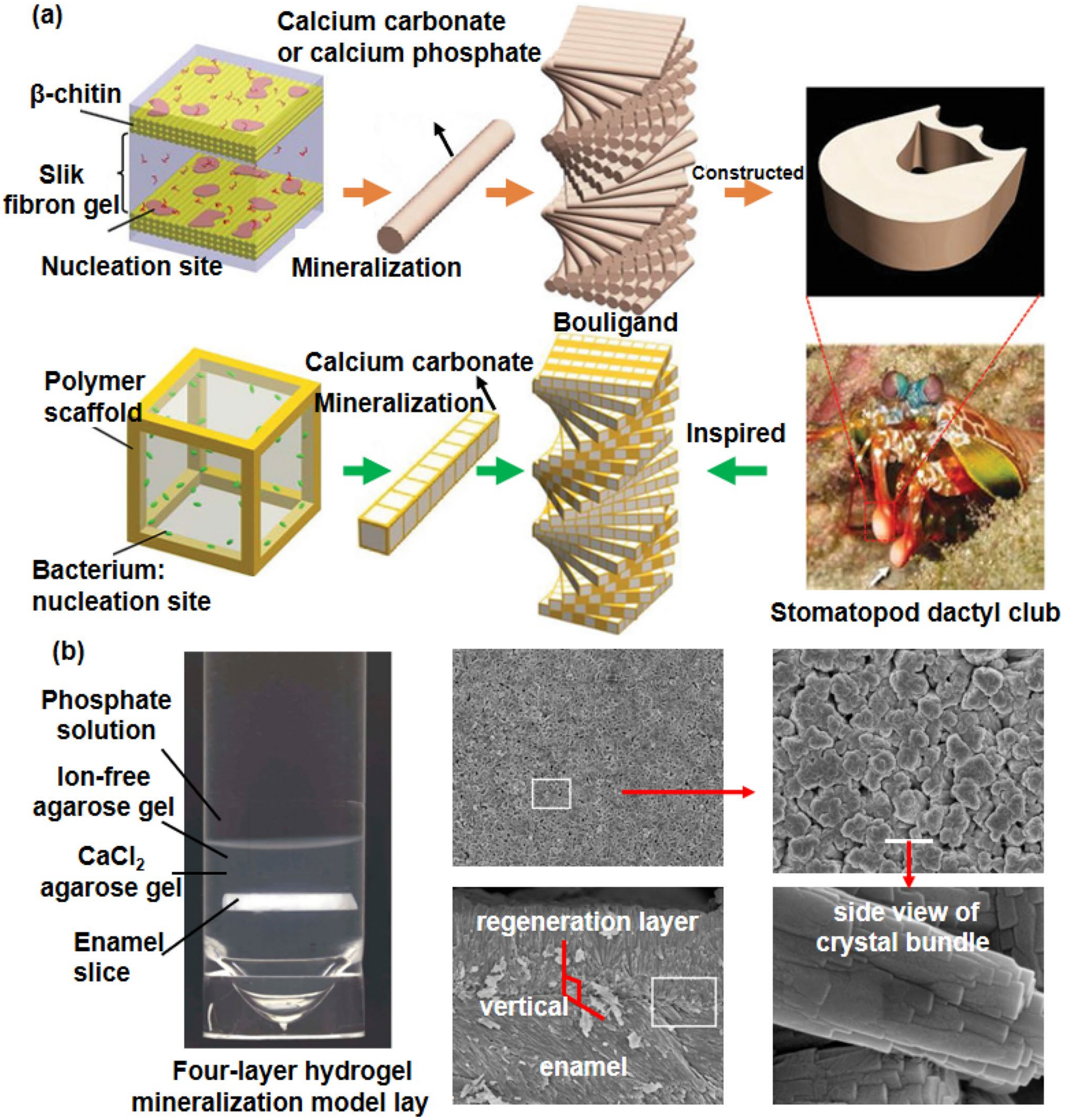

Fig. 10 Bionic mineralization fabricates biomimetic materials. **a** The highly mineralized composites are fabricated by bacteria-assisted mineralization in a 3D-printed polymer lattice [113]; **b** Biomimetic mineralization for the regeneration of enamel prism-like tissue [114]

of a bionic Bouligand structure [118]. The use of electric fields is limited by fillers with specific electrical properties, so it is still a challenge to expand the types of fillers for electric field-assisted 3D printing [119]. In addition, electrospinning has a great advantage in the preparation of nanofibers that can produce nanofibers with ultrafine diameters, high aspect ratios and controllable morphologies [120]. Chen et al. designed an electrostatic spinning system to better control the array of nanofibers through the fine design of electrodes and the control of applied voltage, obtaining a kind of impact-resistant composite film with spiral structure, which can effectively release impact energy and significantly improve the impact resistance (Fig. 11a). This method can control the direction of the

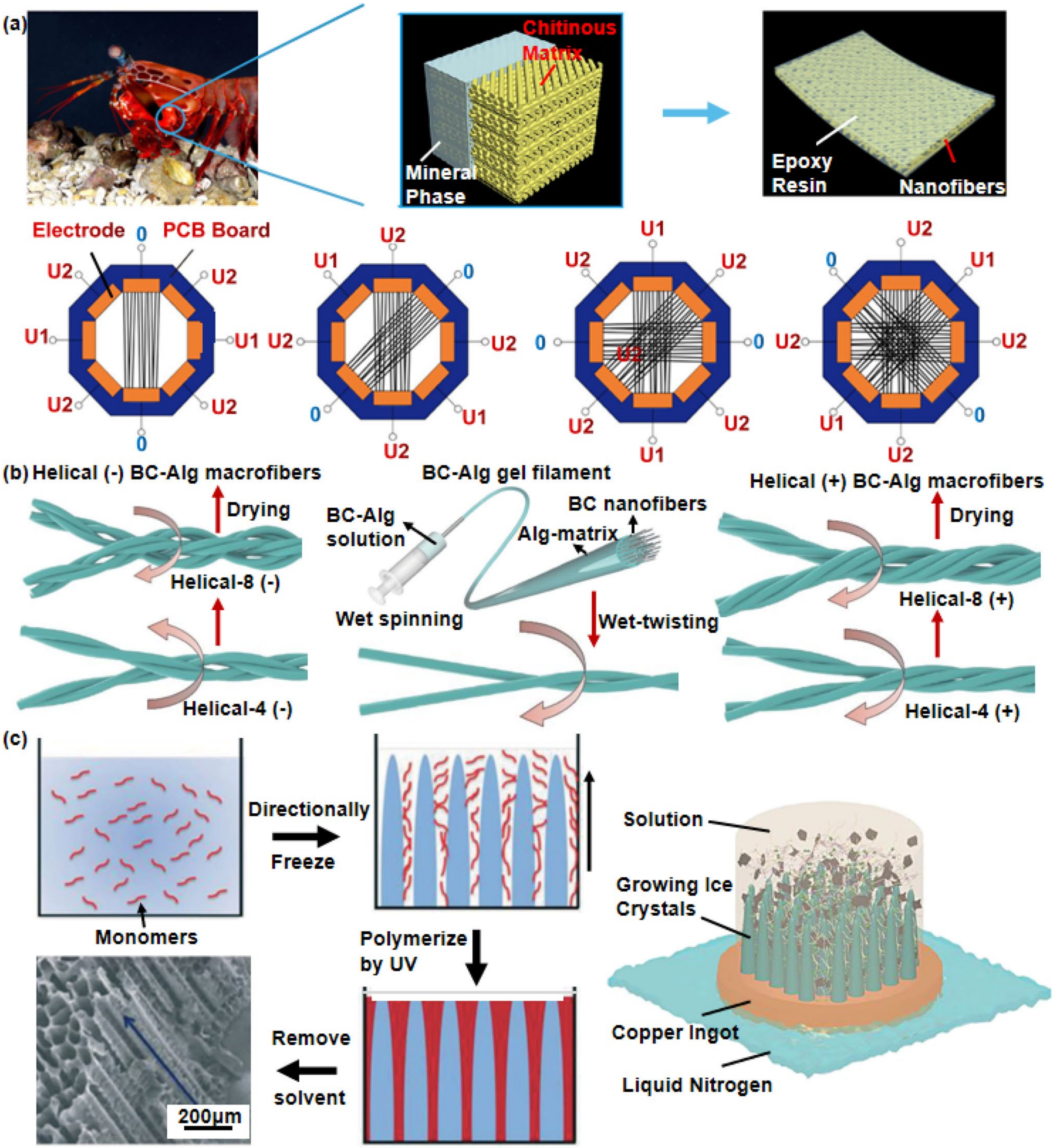

Fig. 11 The preparation of biomimetic materials utilizes advanced technology. **a** Periodic spiral nanofiber reinforced impact-resistant composite films are fabricated by controlling the arrangement of electrospinning nanofibers [7]; **b** Bioinspired hierarchical helical nanocomposite macrofibers are prepared by combining a facile wet-spinning process with a subsequent multiple wet-twisting and drying procedure. Helical-4 and 8 represent the number of original filaments and the symbol indicates the twist direction at each level [121]; **c** Artificial wood is manufactured by a combination of directional freeze casting and in situ polymerization by ultra-violet [122]

fiber flexibly, which provides us with bionic inspiration for the design of composite material protective layers with broad application prospects [7]. In addition, inspired by the hierarchical spiral and nanocomposite structural features widely present in biosynthesized fibers, researchers have transferred the structural and mechanical properties of natural fibers to the designed artificial fibers by combining a facile wet-spinning process with a subsequent multiple wet-twisting procedure that successfully obtained biomimetic hierarchical helical nanocomposite macrofibers based on bacterial cellulose nanofibers [121] (Fig. 11b). The significant advantage of this method is that it is based on biosourced nanocellulosic materials that are degradable, renewable and rich in reserves. Furthermore, wood, as one of the most common natural materials, has attracted much attention due to its light weight and high strength. Artificial wood can be manufactured by a combination of directional freeze casting and in situ polymerization by ultraviolet radiation, in which factors affecting the structure of artificial wood include the initial freezing temperature, freezing rate, polymer content and curing temperature [122] (Fig. 11c).

Notably, it is difficult to achieve the excellent properties of natural materials only by imitating biological structures because the properties of materials are related not only to the structure but also to the interface gradient and chemical composition. Therefore, the preparation of structural composite materials that imitate or even surpass natural materials poses a higher challenge for advanced manufacturing technology.

4.1.3 Modification of Natural Materials

The third strategy is to modify natural materials directly through chemical or physical methods to enhance their original performance or give them some new functions [123–125]. The significant advantage of this method is that it is based on sustainable and renewable biosourced materials, such as wood and bamboo, which are more environmentally friendly. Natural bamboo has been processed into structural materials with excellent mechanical properties through a two-step process of partial delignification and microwave heating (Fig. 12a). The reasons for the excellent mechanical properties of modified bamboo are as follows: the structure of bamboo with partially removed hemicelluloses and lignin components becomes more porous and softer. Meanwhile, microwave heating induced rapid and uniform shrinkage of the bamboo structure by quickly driving out water [126]. Similarly, some researchers have successfully prepared strong and tough bulk materials through a three-step process of delignification, drying-induced assembly, and water molecule-induced hydrogen bonding under compression, showing enhanced tensile strength (352 MPa *vs.* 56 MPa for natural wood) and toughness (4.1 MJ m^{-3} *vs.* 0.42 MJ m^{-3} for natural wood) (Fig. 12b). The compression compactness

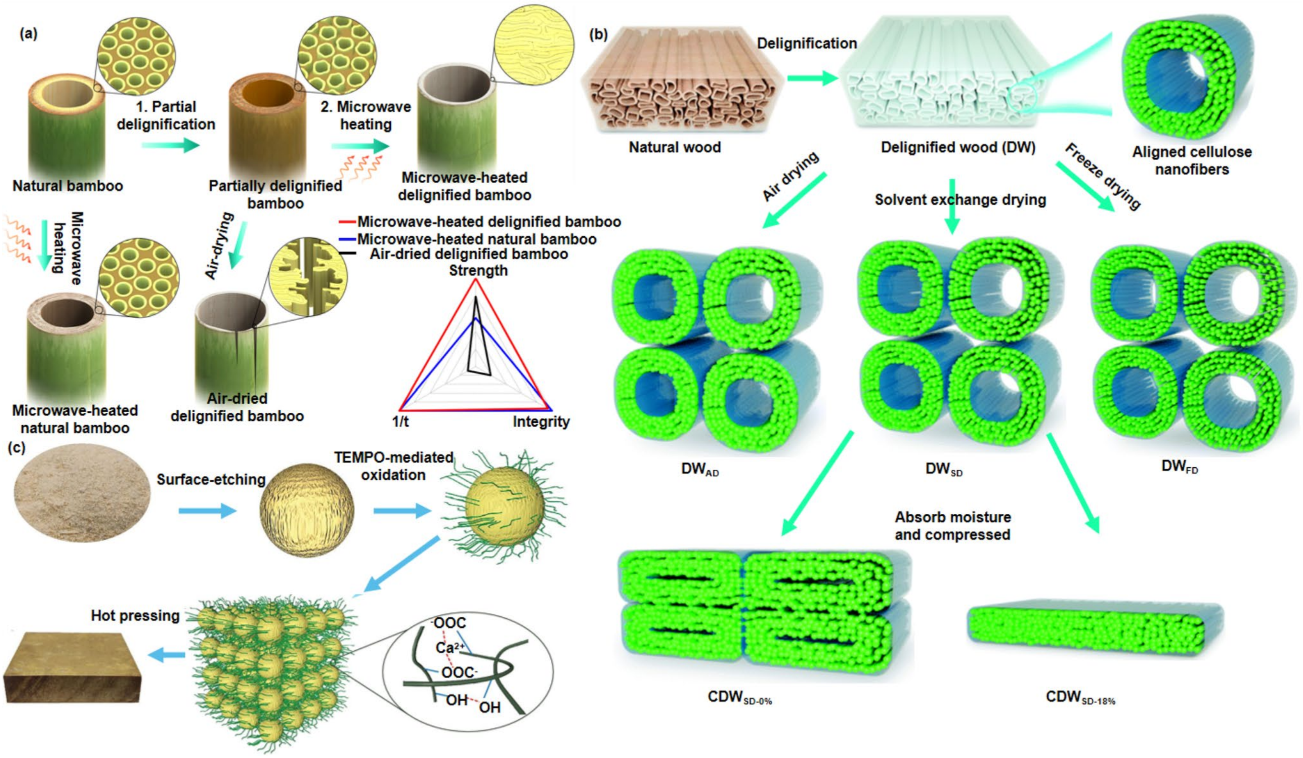

Fig. 12 Obtain materials with excellent performance through modification. **a** The structure materials with excellent mechanical properties are fabricated through a two-step process of partial delignification and microwave heating of natural bamboo [126]; **b** The preparation process of cellulose nanofibers bulk material includes delignification, drying-induced assembly, and compression [127]; **c** The natural wood particles are processed into isotropic wood [128]

of natural wood and the hydrogen bond formed by water molecules to bridge adjacent cellulose nanofibers are the main reasons for its excellent mechanical properties [127]. In addition, some researchers have proposed a bottom-up design method for micro/nano structures to regenerate isotropic wood from natural wood particles, which is a high-performance sustainable structural material, by exposing cellulose nanofibers in natural wood chips to the surface and facilitating cross-linking with each other (Fig. 12c). This kind of artificial wood breaks the limit of anisotropic natural wood, with an isotropic flexural strength of ~ 170 MPa and a flexural modulus of ~ 10 GPa. This preparation method is of great significance in the large-scale manufacture of isotropic materials [128].

Environmental protection is the greatest advantage of the modification strategy of natural materials. However, it is difficult to extend the modification method from one natural material to others due to the obvious differences in structure and composition among different natural materials. Therefore, it is necessary to explore specific processing methods for various natural materials.

In short, each of the three strategies has advantages and disadvantages. Therefore, we should consider all kinds of factors when preparing biomimetic composite materials to choose the most suitable method.

4.2 Biomimetic Materials Designed for Engineering Application

The ultimate goal of bionic design is to solve the practical problems in human production and life. Therefore, bionic design should be application-oriented to guide the manufacture of engineering materials such as laminated boards [129], beetle boards [130] and body armors [131], which are widely used at present.

The sandwich panel inspired by biological structures has the advantages of being lightweight and having high strength and energy absorption. Inspired by the dual role of the beetle forewing in protecting the trunk and facilitating flight, some researchers have proposed a beetle elytron plate structure with small columns at the junction of honeycomb walls and analyzed the mechanism of its high compression-resistance performance [132, 133] (Fig. 13a). In addition, the sandwich panel mimicking the turtle shell structure and mantis shrimp's unique structure has excellent impact resistance and energy absorption capacity, which can be used as anti-collision materials in automobiles [134, 135]. A bionic sandwich plate with high compression stiffness combined with topology optimization technology was proposed based on tree leaves with fractal distributed veins. The results showed that the combination of bionic thought and topology optimization is a promising technique for designing engineering materials with excellent mechanical properties [136]. The intermediate structure of the sandwich panel can be designed into different forms according to different application conditions to meet the needs of different mechanical properties. Engineering applications under some extreme conditions have put forward higher requirements for sandwich panels.

In addition, there is a high demand for glass in production and life, but it has the shortcomings of low toughness and poor impact resistance. Tempering and laminating, as a conventional way to improve the impact resistance of glass, cannot effectively solve the problem of glass fragility. Yin et al. designed a laminated glass inspired by the brick-and-mortar structure of the nacre of the mollusk shell [137]. The impact resistance of the glass was significantly improved by utilizing the relative sliding between microscopic mineral tablets bonded together by biopolymers; at the same time, the high rigidity, bending strength and transparency were retained. Furthermore, the microstructures of fish scales and the cuticle of arthropods can also be used as laminated structures of glass to prepare strong, tough and transparent glass. Researchers have utilized laser engraving to fabricate glass with four bionic structures: crossply, Bouligand, segmented Bouligand and nacre-like. The impact tests of bionic glass show that the mechanical properties of glass can be significantly improved by regulating the dimensions of glass building blocks and adopting a mixed design combining plain layers and building layers [138] (Fig. 13b).

The design and manufacture of lightweight and tough body armor have attracted widespread attention with the rapid development of military technology. To date, fish scales, nacre, conches, crustaceans, exoskeletons and cortical bone have been investigated for the application of bullet-proof components [139]. Studies have shown that the sheet-like overlapping structure of fish scales can disperse external destructive forces to a larger area, which can ensure flexibility and effectively avoid projectile penetration. Hence, the unique structure of fish scales can be used to design flexible and tough body armor by considering the actual application environment [140]. In addition, pangolin scales are arranged in an overlapping hexagonal shape around the central scale, which has important guiding significance for the design of protective armor. Moreover, at the nanoscale, the adjacent lamellae of the scales form an interlocking interface due to the suture-like cell membrane complex between keratinized cells [141] (Fig. 13c). A higher requirement for biomimetic engineering materials is needed to meet the integration of multiple functions in the field of military protection.

In other respects, a new type of crash box mimicking human tibia was prepared, which is composed of a concave structural shell and an inner core filled with negative Poisson's ratio structural material [142]. Inspired by the sinusoidal structure of the impact region and the spiral structure of the periodic region of the dactyl club of mantis shrimp, Han et al. made a novel helical-fiber sinusoidal structure laminate

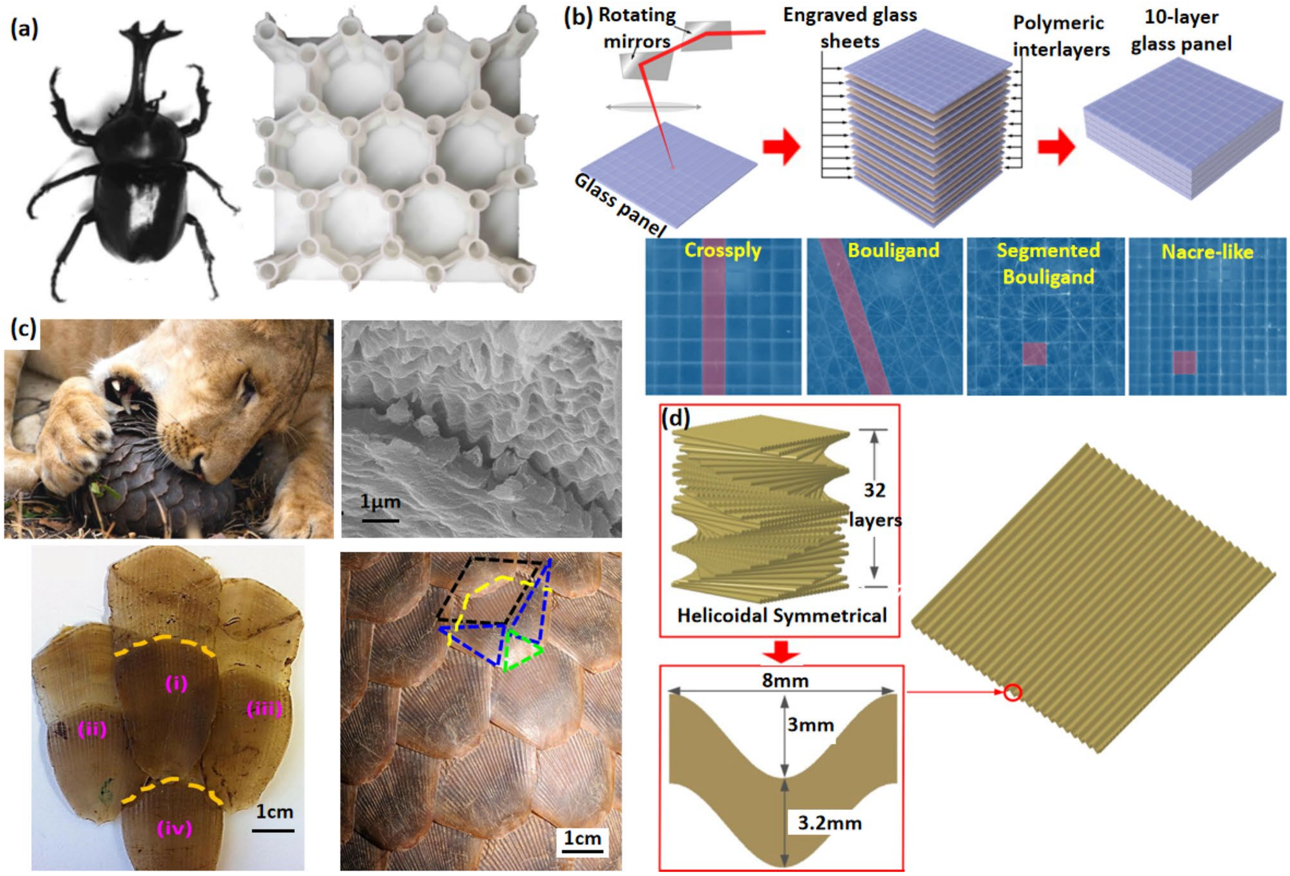

Fig. 13 The application of biomimetic materials. **a** The beetle plate with high compression resistance inspired by beetle forewing structure [132, 133]; **b** Four kinds of bionic glass structures are made by laser engraving technology [138]; **c** The armor mimics pangolin scales which have overlapping structure and interlocking interface [141]; **d** The novel dactyl-inspired helical-fiber sinusoidal-structure laminate was manufactured based on the Bouligand and herringbone structure [143]

by coupling the two structures together that can be used for aircraft wings and car shells to improve their impact resistance [143] (Fig. 13d).

In general, bionic design provides a steady stream of inspiration for the design and manufacture of engineering materials. However, it is a severe challenge for designing and manufacturing engineering materials to achieve the unity of excellent mechanical properties and particular functions by imitating natural materials.

5 Conclusion and Perspective

Natural materials achieve outstanding mechanical properties by adjusting the three basic factors of structure, composition and interface to satisfy diverse requirements for survival [10]. Although natural materials are made from a limited number of materials, they tend to exhibit excellent mechanical properties many times better than the individual components due to the components of rational distribution, structures of ingenious arrangement and interfaces of precise junctions. Nature has provided us with many successful examples of organisms with specific functions, which adjust the properties of the material through the three basic factors to further achieve the desired specific function. Hence, the strategy of achieving high performance of natural materials can inspire us to design and manufacture structural materials with remarkable mechanical performance, such as high strength, high impact resistance and lightweight. However, the design and preparation of biomimetic materials still face numerous challenges.

First, it is extremely important to conduct more in-depth research on the mechanism of natural materials with excellent properties. The chemical compositions, structures, interface characteristics, and resulting mechanical and functional properties under living conditions still remain to be explored for a wide range of natural materials.

Second, although recent advances in materials and manufacturing have led to new synthetic materials exceeding the performance of their natural counterparts, most manufactured biomimetic materials lag far behind the performance of their natural materials [144]. Further advances in nanoscale material manufacturing and other advanced manufacturing technologies may provide new opportunities for the development of biomimetic materials, but new technologies also face the problem of large-scale production.

Third, living organisms can actively respond to external stimuli. Therefore, we should not only imitate their excellent mechanical properties but also imitate their self-healing and self-adaptation properties, which puts forward higher requirements for the design of the next generation of intelligent composite materials with multiple functions [145].

In short, the development of bionic composite materials is full of opportunities and challenges. On the one hand, with the continuous development of advanced manufacturing technology and equipment, the mechanism of the excellent performance of natural materials will be more deeply revealed. On the other hand, the existing preparation methods still face a series of problems, such as immature processing technologies and difficulties in large-area preparation. In the future, the intelligence of biomimetic composites should also be considered to make real use of biological intelligence, and there is still a long way to go before practical engineering application.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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