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Review

3D-printed biomimetic structures for energy and environmental applications

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A B S T R A C T

Biomimetic structures involve design and fabrication to mimic the natural world, taking inspiration from the unique shapes, patterns, and functions of biological organisms. This approach has proven to be highly effective in building new functional and efficient structures for many applications. While it is often challenging to fabricate some of the complex biomimetic structures, the development of 3D printing technologies in recent years has made it more feasible, being a powerful tool for fabricating complex structures with high precision and accuracy, at the much reduced use of starting materials. In this review, we will examine the current state of biomimetic structures fabricated by 3D printing techniques and their specific applications in energy and environmental fields for the decarbonization demand. The different selected types of biomimetic structures that have been constructed using 3D printing, the materials used, and the unique properties obtained will be explored. Subsequently, some typical biomimetic structures for energy and environmental applications, such as supercapacitors, zinc-air batteries, oil/water separation, self-cleaning, water collection, droplet manipulation, etc., will be discussed. Finally, the opportunities in this rapidly changing area will be analyzed, hoping to provide insights into the innovative pathways that 3D-printed biomimetic structures can be used to address some challenges in energy and environmental areas.

1. Introduction

With millions of years of evolution, nature has created countless wonderful and complex structures, endowing organisms with unique and superior characteristics and abilities. From lotus leaf surfaces, with superhydrophobic properties that repel water due to the micro-/nanometer-scale papillae structures [1,2], to lobster claw's Bouligand structure and natural nacre's brick-and-mortar structure provides unique functional properties making them mechanically resilient [3–11]. With many of their remarkable properties reported, including mechanical properties [7,12], wetting properties [13–15], and energy absorption capabilities [9,16–19], biomimetic structures have attracted considerable interest. Therefore, biomimicry provided solutions to many practical engineering problems and has been applied in many fields, such as energy, environmental, biomedical, building structures applications, etc. Among them, the most prominent biomimetic structures reported in the literature are relatively simple *nacre*-inspired layered [7,20], helicoidal or Bouligand structures [4], which are mainly manufactured by freeze casting [12,21–24], layer-by-layer (LBL) deposition [25–27], and self-assembly [28,29], spray deposition [24,30], magnetically assisted slip casting [24], electrospinning [13,31]. However, it is rather challenging to lab-fabricate some of the complex biomimetic structures due to the limitations of these conventional manufacturing techniques.

Additive manufacturing (AM), commonly referred to as 3D printing technology, offers a myriad of advantages, revolutionizing the manufacturing industry. These advantages include enhanced design flexibility, rapid prototyping, waste minimization, geometrically induced capabilities, and the ability to manufacture complex micro/structures [32,33]. 3D printing leverages several unique manufacturing strengths. Firstly, it dissects 3D structures into a series of 2D layers, enabling a fundamental principle that allows for the creation of virtually any complex structure. Secondly, this “bottom-up” manufacturing approach facilitates the realization of non-homogeneous materials and functional gradient devices, providing a distinct advantage. Thirdly, the fabrication process occurs directly through printing, eliminating the need for subsequent assembly or joining processes [34–36]. Therefore, the remarkable progress in 3D printing technology over recent years has empowered the manufacturing of complex biomimetic structures. Currently, the available 3D printing techniques for the fabrication of biomimetic structures mainly include digital light processing (DLP), stereolithography (SLA), projection micro stereolithography (PμSL), fused deposition modeling (FDM), and direct ink writing (DIW). For instance, a

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series of 3D-printed biomimetic structures with unique properties have been reported for a wide range of biomedical applications, such as the micropatterned microfiber strut to imitate skeletal muscle cell alignment and fusion, scaffolds for cell spheroid growth, porous cellular structures for bone biomimetic implants [37–42].

In this review, we focus on the current state of 3D-printed biomimetic structures and their applications in the energy and environment fields for the decarbonization demand, as shown in Fig. 1. Starting with exploring the different types of biomimetic structures that have been fabricated using 3D printing, the materials used, and the unique properties thus obtained, with a larger focus on mechanical properties. Following on, discussions are made on typical biomimetic structures for energy applications, such as piezoelectricity, supercapacitor, Zn-air batteries, and environmental applications, such as oil/water separation, self-cleaning, water collection, droplet manipulation, etc. Finally, we discuss the current challenges and opportunities in 3D-printed biomimetic structures, providing new perspectives on future research in this rapidly changing area.

2. 3D-printed biomimetic structures and properties

With the rapid emergence and development of 3D printing technology, countless biomimetic structures inspired by nature's designs have

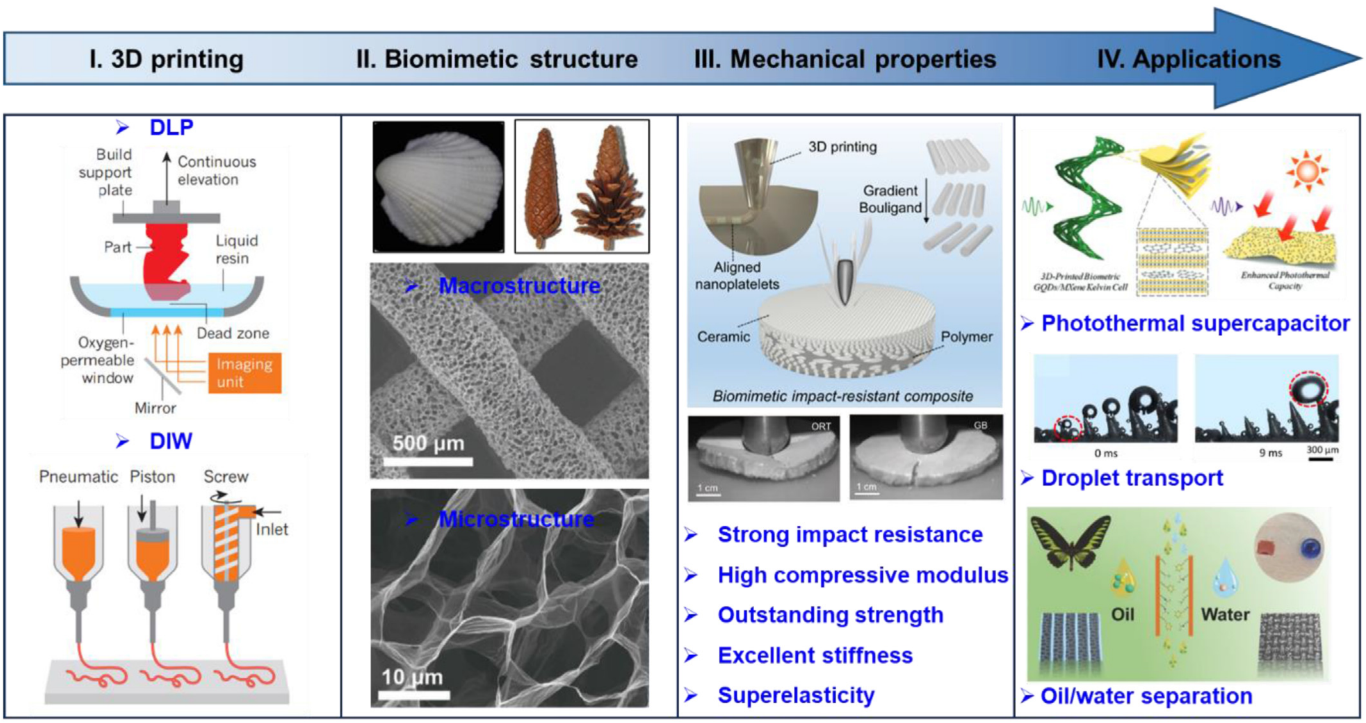

Fig. 1. Overview of this article regarding the perspective of 3D-printed biomimetic structures for energy and environmental applications.

Table 1
3D-printed biomimetic structures with reinforced mechanical properties.

Biomimetic prototype	3D printing technique	Materials	Properties	Applications	Refs
Bouligand nanostructure	DIW	Cellulose nanocrystals	Toughness, strength	Architected materials	[4]
Elytrigia repens	DIW	Hierarchical graphene	Exceptional stiffness and superelastic	Compressible electrodes	[52]
Balsa wood	DIW	Epoxy-based ink, silicon carbide	Lightweight, high Young's modulus	Minimize damage	[62]
Pomelo peel	DLP	Photocurable resin, Ti_6Al_4V	Excellent compressibility energy absorption	Metamaterials with high energy absorption	[19]
Mantis shrimp	DLP	Zirconia ceramic	Remarkable toughness, load-bearing capacity	Dental restorations	[49]
Homarus americanus	DLP	Polymer resin, carbon nanotubes (CNTs)	High compressive modulus, tensile strength and strain	Biomedical	[50]
Nacre	DLP	Photocurable resin, boron nitride nanoplatelets	Toughness, flame-retardant properties	Thermal control	[6]
Cortical bone, *nacreous* shell, *peacock*	DLP	Photocurable resin, iron oxide nanoparticles	High toughness modulus	Deflect cracks	[63]
Nacre	DLP	Aligned graphene nanoplatelets in the photocurable resin	Enhanced toughness, impact, compression resistances, and anisotropic electrical property	Biomedical	[10]
Conch shells	PμSL	Polymer resin	Enhanced strength and toughness	Inhibit the propagation of shear bands	[64]
Bivalves, turritella	FDM	PLA polymer	High strength	Failure resistant	[53]
Bamboo	FDM	PLA matrix resin, Basalt fiber	Toughness reinforcement mechanism	Mechanical reinforcement	[65]
Nacre, Bouligand architecture	SLS	Ti_6Al_4V, Mg	High toughening and tensile properties	Biomedical applications	[54]
Crysomallon squamiferum shell	SLS	TiB_2/Ti_6Al_4V	Enhanced flexural strength and ductility	Multi-material additive manufacturing	[66]
chiton scales	PJM	Photocurable resin	Flexibility and protection capabilities	Flexible armor	[67]
Nacre	IJP	Photocurable resin	Impact resistance	Building bricks	[9]

been successfully realized more recently. As summarized in Table 1, various 3D printing techniques such as DIW, DLP, FDM and SLS have been extensively employed to construct these structures. A wide range of different materials, including polymers, carbonaceous, metals, ceramics, and composites, have been utilized as well, where they are made printable. While there have been previous comprehensive reviews on the technical mechanisms and advantages of 3D printing [32–36,43,44], this section aims to introduce some exemplary biomimetic structures constructed through 3D printing, highlighting their unique properties and functions.

2.1. Biomimetic structures

After tens of thousands of years of evolution and development, the natural world has yielded a plethora of structures with unique functions and meanings. These remarkable structures not only serve as a wellspring of inspiration for researchers but also find applications across various fields. As depicted in Fig. 2, some of the selected typical 3D-printed biomimetic structures have been reported in recent years, such as pine needle arrays inspired by *Sabina chinensis* (Fig. 2a) [45], *Cactus*-mimetic spine arrays (Fig. 2b) [46], eggbeater hair structure inspired by *Salvinia Molesta* leaf surface (Fig. 2c). [47], etc. These printed biomimetic structures achieve new functionalities and provide solutions for some specific engineering problems. For example, Feng et al. employed PμSL-based 3D printing to fabricate the needles of *Sabina chinensis*, enabling swift collection and unpowered transportation of fog droplets in the atmosphere (Fig. 2a). The designed *Cactus* spine arrays have demonstrated the ability to efficiently capture and transport fog droplets (Fig. 2b). Li et al. constructed superhydrophobic surfaces that achieved microdroplet manipulation nonloss microdroplet transport and oil/water separation by imitating the ‘egg beater’ structure of *Salvinia Molesta* leaf (Fig. 2c). Inspired by bamboo's morphologies, Zhang et al. fabricated a hollow

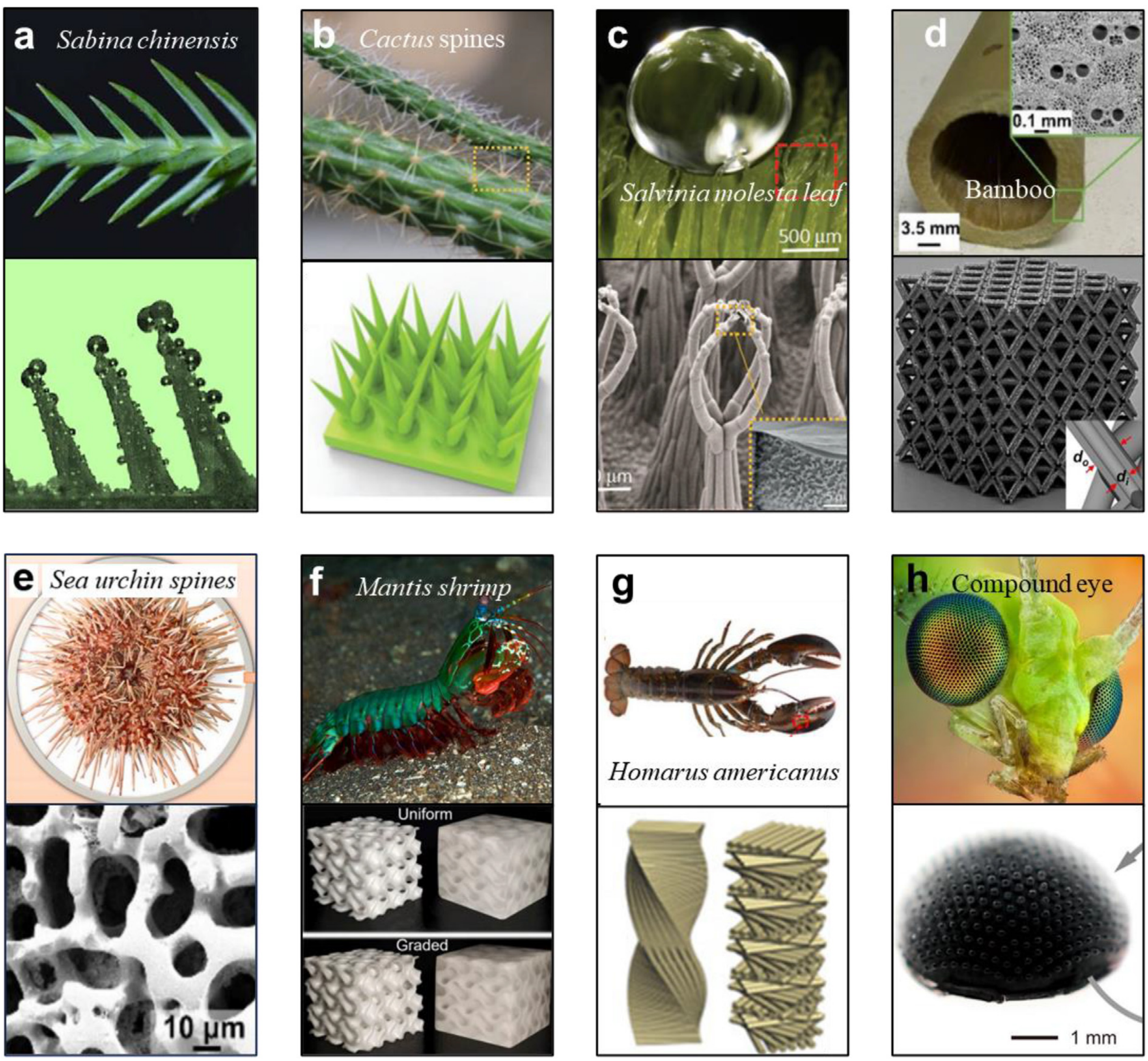

Fig. 2. Typical 3D-printed biomimetic structures. (a) *Pine* needle arrays inspired by *Sabina chinensis*. Reproduced with permissions from Ref. [45], Copyright 2020, American Association for the Advancement of Science. (b) *Cactus*-mimetic spine arrays. Reproduced with permissions from Ref. [46], Copyright 2020, Wiley-VCH. (c) Eggbeater hair structure inspired by *Salvinia molesta* leaf. Reproduced with permissions from Ref. [47], Copyright 2017, Wiley-VCH. (d) Hollow topology structure inspired by *bamboo*. Reproduced with permissions from Ref. [48], Copyright 2022, Elsevier. (e) *Sea urchin spines*' needle-like appearance and internal architecture of graded porosity. Reproduced with permissions from Ref. [42], Copyright 2023, KeAi Publishing. (f) Brick-and-mortar structure inspired by *mantis shrimp*. Reproduced with permissions from Ref. [49], Copyright 2022, Wiley-VCH. (g) *Homarus americanus* biomimetic Bouligand structure. Reproduced with permissions from Ref. [50], Copyright 2020, Wiley-VCH. (h) Biomimetic apposition compound eye structure consisted of countless hexagonal microlenses omnidirectionally distributed across a hemispherical dome. Reproduced with permissions from Ref. [51], Copyright 2021, Nature Publishing Group.

topology structure to achieve lightweight and high-strength materials (Fig. 2d) [48]. By mimicking *Sea urchin spines*, a biomimetic scaffold with excellent strength, permeability, and impact resistance has been printed (Fig. 2e) [42]. The *Mantis shrimp*-inspired brick-and-mortar structure was also successfully printed and was shown to exhibit high roughness and exceptional load-bearing capacity (Fig. 2f) [49]. The *Homerus Americanus* bionic Bouligand structure was designed and printed, exhibiting superior mechanical properties, such as high compressive modulus, tensile strength, and enhanced toughness (Fig. 2g) [50]. Mimicking insect compound eyes, Dai et al. printed a biomimetic apposition compound eye with countless of hexagonal microlenses omnidirectionally distributed across a hemispherical dome, leading to high imaging performance (Fig. 2h) [51]. It can be seen that the utilization of biomimetic structures in various fields is steadily expanding, with ongoing exploration and judicious utilization of their unique structures and properties.

2.2. Unique properties and functions

As briefly mentioned above, biomimetic structures have attracted great attention due to their unique properties and functions. For example, a *Nacre*-inspired structure achieved exceptionally high mechanical and flame-retardant properties fabricated by incorporating 3-(Trimethoxysilyl) propyl methacrylate modified boron nitrate nanoplates (BNs) into a photosensitive resin. By rotating the blades during the 3D printing process, they were able to generate an aligned BN (a-BNs) bridging structure (Fig. 3a). This innovative approach not only led to a lighter structure with higher fracture toughness than the natural pearl layer but also facilitated directional heat transfer. When applied to a fire helmet, this printed structure also exhibited exceptional thermal management capabilities, as demonstrated by a 24-s delay in catching fire [6].

In addition, taking inspiration from the hollow structure of *Elytrigia repens*, an ultralight biomimetic hierarchical graphene material (BHGMs) with exceptional stiffness and superelastic was fabricated by employing an innovative approach (Fig. 3b). This approach involved simultaneously engineering macroscopic hollow structures through DIW and constructing of cellular microstructure induced by the formation of ice crystals. As a result, the BHGMs exhibited remarkable elasticity and stability, with the ability to complete recovery at a 95 % deformation. The successful fabrication of BHGMs showcases the potential of biomimetic 3D printing in producing materials with outstanding mechanical properties, offering new avenues for applications requiring high-performance and lightweight structures [52].

Bivalves and *turritella* shells both exhibit high resistance to fracture and reduction of failure costs and can guide fracture to non-critical parts under compression, which can effectively protect important parts of their bodies [53]. Inspired by this idea, Zhang et al. fabricated biomimetic Mg–Ti composites by utilizing a pressureless infiltration method. Three different biomimetic Ti–6Al–4V scaffolds were first printed, namely the 'brick--and-mortar' structure of *abalone* shell, the Bouligand structure of *mantis shrimp*, and the 'crossed-lamaller' structure of bivalve mollusk shell, then the pure Mg melt was infiltrated into the 3D-printed scaffolds (Fig. 3c). These obtained intermetallic demonstrated exceptional properties such as enhanced toughness, fracture resistance, and crack guidance [54].

Similarly, inspired by the *Mantis shrimp*, Sun et al. first created several graded scaffold structures based on zirconia using a DLP printer, then infiltrated a commercial epoxy polymer into the sintered ceramic

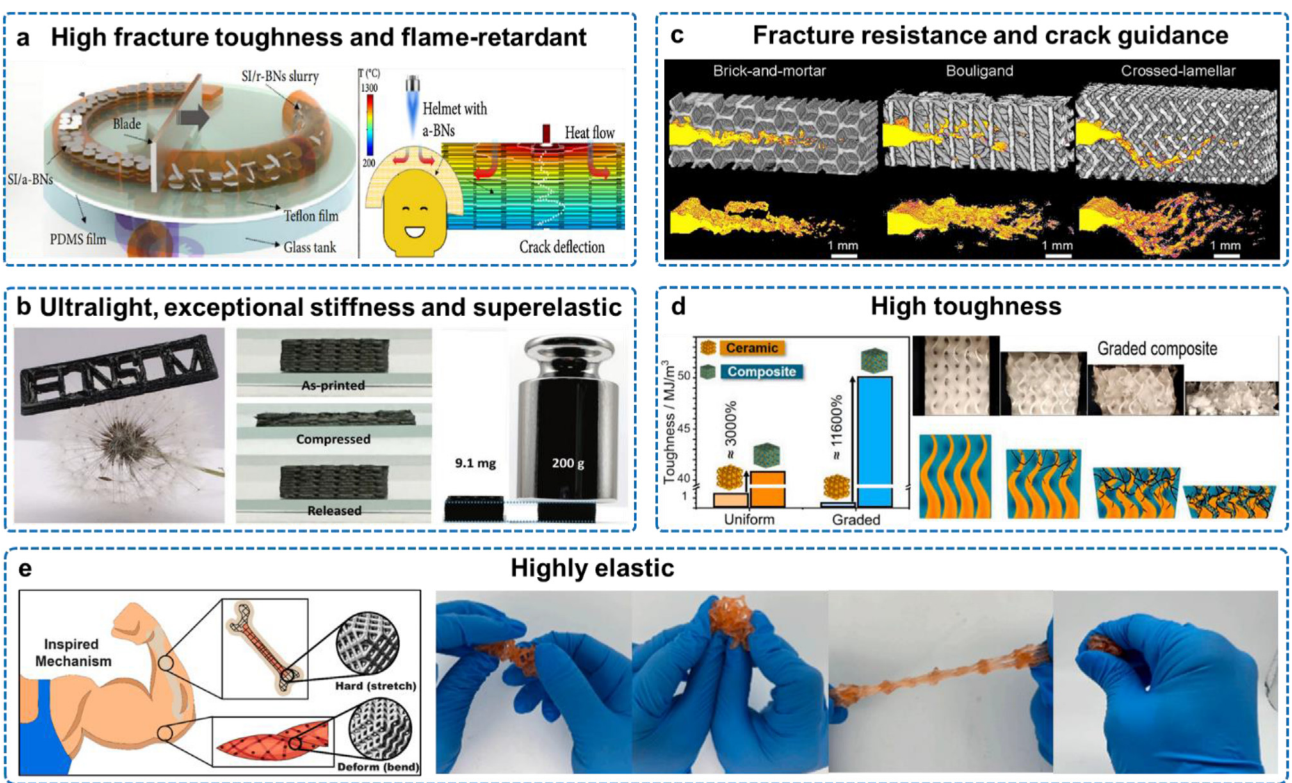

Fig. 3. Properties and functions of 3D-printed biomimetic structures. (a) Exceptional mechanical and flame-retardant properties *via Nacre*-inspired structures. Reproduced with permissions from Ref. [6], Copyright 2022, American Association for the Advancement of Science. (b) Macroscopically hollow scaffold and microscopically cellular of *elytrigia repens* with ultralight, exceptional stiffness and superelastic. Reproduced with permissions from Ref. [52], Copyright 2019, Wiley-VCH. (c) Fracture resistance and crack guidance properties derived from the 'brick-and-mortar' structure of *abalone* shell, the Bouligand structure of *mantis shrimp*, and the 'crossed-lamaller' structure of *bivalve mollusk* shell. Reproduced with permissions from Ref. [54], Copyright 2022, Nature Publishing Group. (d) Hammer-like dactyl club from the *mantis shrimp* structure with higher tough. Reproduced with permissions from Ref. [49], Copyright 2022, Elsevier. (e) High elastic property via bioinspired hierarchical elastomeric lattices. Reproduced with permissions from Ref. [55], Copyright 2023, Elsevier.

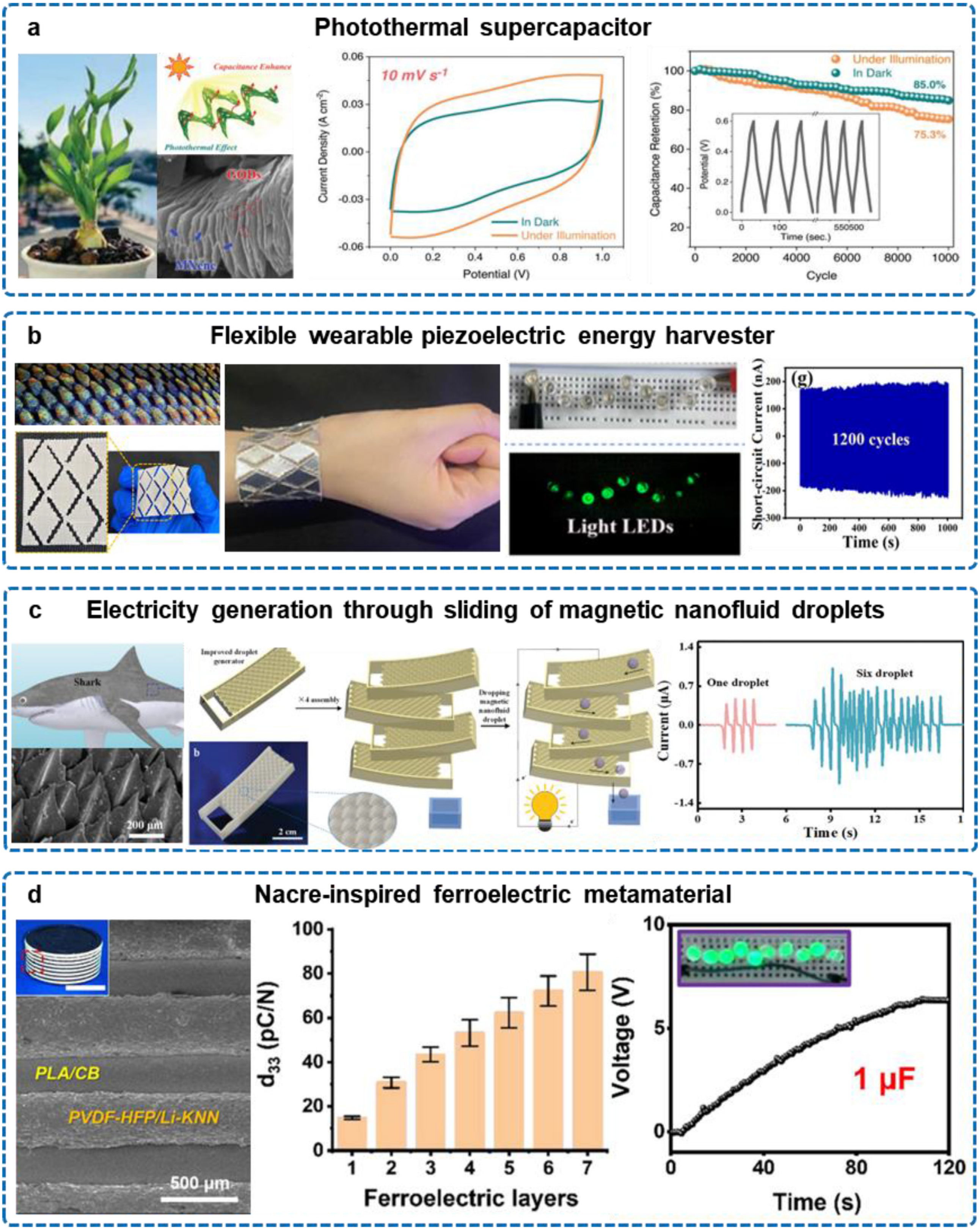

Fig. 4. 3D-printed biomimetic structures for energy applications. (a) Biomimetic 3D-printed photothermal supercapacitors with large-capacitance high-photothermal conversion and exceptional capacitive performance. Reproduced with permissions from Ref. [68], Copyright 2022, Wiley-VCH. (b) Biomimetic wearable fish-scale PVDF materials for piezoelectric energy harvesters. Reproduced with permissions from Ref. [69], Copyright 2022, American Chemical Society. (c) 3D-printed shark skin for electricity generation. Reproduced with permissions from Ref. [70], Copyright 2021, Wiley-VCH. (d) Bio-inspired lamellar ferroelectric metamaterial for piezoelectric application. Reproduced with permissions from Ref. [71], Copyright 2021, American Chemical Society.

scaffold, and finally obtained the zirconia/epoxy composites. As shown in Fig. 3d, by tuning the ceramic wall thickness progressively, this structure effectively improved the toughness and fracture resistance of the material, resulting in 116 times improvement in toughness compared to the uniform ceramics composite [49].

In addition to providing higher mechanical properties, such as toughness, hardness, and strength to the biomimetic structures, ultra-high elasticity properties were also designed by inspiring strong and tough biological systems with soft behavior. Fig. 3e displays the mechanically tunable properties of the printed hybrid-architected lattices with high twistable, foldable, stretchable and compressible abilities [55].

It can be seen that some of the aforementioned structures are at the micro/nano level, made achievable through the exceptional precision of 3D printing. The versatility of 3D printing technology, allowing for the use of diverse materials like metals, polymers, and ceramics, also exemplifies its unparalleled advantages. As briefly summarized in Table 1, a plethora of 3D-printed biomimetic structures show remarkable characteristics, including lightweight, toughness, fracture resistance, high hardness, impact resistance and elasticity. Of these, the common ones are *mollusca* shells inspired structures that are mainly composed of calcium-carbonate ceramics or hydroxyapatite crystals typically. These brittle minerals and a small number of flexible polymers are alternately stacked like 'brick-and-mortar' or Bouligand structure, forming a unique layer structure, giving shells the excellent mechanical properties that exceed their components by several orders of magnitude [18,56–61]. Using this efficient mechanical reinforcement approach, many devices are designed and applied, such as body armour materials and assemblies, turbine blades, airplane wings, bone biomimetic implants and dentures. Biomimetic 3D printing not only enhances the mechanical performance of the printed structures but also opens up avenues for implementing new functions and solving more practical engineering problems. The following sections will provide a detailed explanation of the application of biomimetic 3D printing in the fields of energy and environment.

3. Energy applications

With the support of 3D printing technology, a large number of biomimetic structures have been reasonably designed and successfully fabricated. Remarkably, by implementing biomimetic design solely on the structure while preserving the original material composition of the device, significant enhancements in device performance have been realized. Recent years have witnessed significant interest and research dedicated to energy-related devices, including batteries, supercapacitors, piezoelectric devices, flexible wearable devices, and sensors.

Photovoltaic technology is one of the best-known means of harvesting renewable green energy. Taking inspiration from the unique light-trapping effect observed in wide-leaf spiral grass, Peng et al. embarked on the printing of a biomimetic structural photothermal energy storage system, aiming to enhance the improvement of solar thermal-driven pseudo capacitance [68]. As illustrated in Fig. 4a, to gain deeper insights into the impact of solar irradiation on the performance of the biomimetic photothermal supercapacitor (SC), a comparison was made between the cyclic voltammetry (CV) profiles under dark conditions and solar light illumination. Notably, irrespective of the scan rate, the CV curves under solar light illumination exhibited characteristic pseudocapacitive behavior similar to those in the dark, yet with higher current responses and larger integrated areas. Further investigations revealed that even after 10,000 cycles at a current density of 200 mA cm^{-2} under dark conditions, the symmetric GQDs/MXene-720° SC demonstrated remarkable capacity retention, maintaining an impressive 85.0 % of its initial capacity.

Other energy harvesting devices are also of great interest to sustainable development. For instance, Pei et al. printed a high-performance biomimetic wearable piezoelectric nanocomposite energy harvester with a biomimetic fish scale-like metamaterial (Fig. 4b). Their results indicate that flexible piezoelectric materials have excellent output voltage, output current and number of cycles. The flexible piezoelectric devices can also be easily worn on the wrist and are capable of lighting up 9 LEDs [69]. Inspired by shark skin, Huang et al. prepared an underwater magnetic nanofluid droplet-based generator (UMNGD), collecting the mechanically sliding energy of droplets and converting it into electrical energy (Fig. 4c). The UMNGD can produce a peak voltage of 85.2 μV. In addition, experiments have shown that the sliding of multiple droplets can generate the accumulation of current, leading to a maximum current of 1.1 μA [70]. Imitating the hierarchical structure of *nacre*, Li et al. created a class of laminar ferroelectric metamaterials with exceptional piezoelectricity and fracture toughness (Fig. 4d) [71]. Each layer of the ferroelectric layers can bring about a linear increase in the longitudinal piezoelectric charge coefficient (d_{33}) of approximately 11 pC N^{-1}. The 7-ferro-layer metamaterial (d_{33} reached 80.6 pC N^{-1}) can simultaneously light up 10 LEDs.

Table 2 presents a range of energy applications that utilize biomimetic 3D printing, leading to much improved electrical and mechanical properties as compared to those produced using other conventional manufacturing methods. For example, bioinspired bone structures of poly(vinylidene fluoride) (PVDF) were successfully fabricated with 13 V output voltage and 0.27 μA/cm^2 maximum current density, which outperforms most of the PVDF piezoelectric energy harvesters reported so far [72]. Although there is still limited research on biomimetic 3D printing in the energy field, the integration of biomimetics with 3D printing technology holds promise for further advancements in various properties of energy devices.

Table 2
3D-printed biomimetic structures for energy applications.

Biomimetic prototype	3D printing technique	Materials	Properties	Application	Refs
Bean-pod	DIW	Graphene oxide (GO) ink	High energy storage efficiency, thermal reliability and stability	Solar-thermal energy harvesting and storage	[73]
Shark skin	SLA	Photosensitive resin	Reduce the solid/liquid adhesion	Converting sliding energy to electricity	[70]
Albuca namaquensis baker	DLP	Photocurable preceramic polymer, GQDs, MXene	Large-capacitance, high-photothermal conversion	Solar thermal systems, energy storage devices	[68]
Nacre	FDM	Li–KNN, PVDF-HFP, CB, PLA	High piezoelectricity and fracture toughness	Small electronics, self-powered sensors	[71]
Biological bone	FDM	PVDF, azodicarbonamide foaming agent	Superior compressibility and stability	Piezoelectric energy harvester	[72]
Alveolus	FDM	Acrylonitrile-butadiene-styrene	Higher and more stable performance	Direct methanol fuel cells	[74]
Fish-like metamaterial	FDM	PVDF, TPPC, $BaTiO_3$	Piezoelectric and durability	Wearable devices	[69]
Lung	DMLS	Stainless steel powder	Uniform reactant distribution across the electrodes	Fuel cell	[75]
Xylem with aligned channels	SLM	Metal powder	High power density, open-circuit voltage	Zinc-air battery	[76]

Table 3
3D-printed biomimetic structures for environmental applications.

Biomimetic prototype	3D printing technique	Materials	Properties	Application	Refs
Plant-based hierarchal structure	DIW	GO-based ink	Wide spectra sunlight absorption, rapid water transportation	Solar steam-generation	[82]
Mushroom	DIW	Polysiloxane, graphene, PEDOT:PSS, cyanobacterial cells	Photosynthetic bioelectricity of cyanobacterial cells	Photosynthetic bioelectricity	[83]
Needles of *Sabina chinensis*	SLA	Photosensitive resin	Ultrafast transport of fog droplets	Collection of fog, directional transportation of water	[45]
Cactus-inspired spine	SLA	Photocurable resin, multiwall CNTs	Fast water transportation along the spine	Efficient water harvesting and transportation without energy input	[46]
Rice leaf	SLA	Photocurable resin-type clear	Superhydrophobic	Fog-harvesting, anti-fouling, drag reduction	[84]
Peristome surface of *Nepenthes alata*	DLP	UV-curable acrylic ester resin, carbon nanofibers	Superior solar water evaporation, solar desalination, salt-rejecting	Real-time and on-demand crop growth	[85]
Bird beak, *pitcher* plant	DLP	UV curable resin	High water evaporation, excellent stability under high salinity	Solar evaporator	[86]
Salvinia molesta leaf	DLP	Photocurable resins, Multi-walled CNTs	Superhydrophobic property, petal effect, tunable adhesion	Water droplet manipulation, 3D cell culture, microreactor, oil/water separation	[47]
Fish gill	PμSL	Photosensitive resin	Anti-fouling	Membrane, biomedical engineering	[87]
Wheat awn	PμSL	Photocurable resin	Fogdrop capture	Fogdrop collection and transport	[88]
Geckos	PμSL	Photosensitive resin	Strong attachment, easy detachment, self-cleaning	Reusable adhesives, climbing robots	[89]
Mushroom-like geometry	PμSL	Photosensitive resin	Strong mechanical robustness	Droplet transport, flexible interfacial structures	[90]
Springtail cuticle	PμSL	Hydrophilic photocurable resin	Wettability	Droplet-based microreactors, water transportation	[91]
Fish spine and *rice* leaf,	PμSL	Photocurable resin, SiO_2 nanoparticles	Ultrafast and continuous oil transport underwater	Water remediation, oil extraction	[92]
Hand-like	PμSL	Low-viscosity photopolymer	Efficiently grasping and releasing droplets	Fogdrop collection and transport	[93]
Araucaria leaf	PμSL	Acrylic photosensitive resin	Well-controlled directional steering, self-propulsion	Oil/water separation, unpowered water transportation	[94]
Cross-sectional vessels in trees	PμSL	Photocurable resin	Antigravity step lifting and elevating water	Unpowered water transportation	[95]
Springtails	TPP	Photoresist resin	Superrepellence to various liquids, anti-adhesion behavior	Directional liquid flow	[96]

4. Environmental applications

The application of 3D printing in the field of environmental science is undergoing rapid expandsion [77]. Notably, the exploration of 3D-printed biomimetic structures has garnered significant research attention in the past few years, finding diverse applications in environmental contexts, such as liquid collection and transportation, water and air purification [78], environmental monitoring and sensing [79], air vehicle wing [80], green building [81]. As outlined in Table 3, we have summarized some state-of-the-art studies on 3D-printed biomimetic structures in the environmental field. High-resolution 3D printing techniques such as two-photon polymerization (TPP) and PμSL are often needed to fabricate micro/nano structures closer to nature. It can be found that some natural structures, despite originating from entirely different species, exhibit remarkable similarities, suggesting that material composition may not be the primary determinant of their functionality. For instance, both the lotus leaf surface and the springtail worm feature an abundance of surface micro protrusions that collectively confer hydrophobic properties. Water treatment represents one of the most extensively researched areas within this field. Consequently, this section provides a more comprehensive focus on advancements in water treatment through the application of 3D-printed biomimetic structures.

4.1. Superhydrophobic and hydrophilic/lipophilic functions

Throughout the course of nature evolution, many animals and plants have developed unique hydrophobic structures that serve various functions. They include some of the most well-known self-cleaning effects exhibited by lotus leaves [1], the superhydrophobicity of *water strider* legs [97], the presence of superhydrophobic structures on *cicada* wings [98], and the intricate microstructure found on *gecko* toes [89]. These natural phenomena arise from the intricate arrangement of small grooves and nano-columnar structures on the surface, which contribute to the object's superhydrophobicity and self-cleaning properties. By harnessing the potential of 3D printing technology to replicate these natural structures, it becomes possible to impart superhydrophobic properties to the surfaces of manufactured products as well [99–101].

A good example is triple reentrant structures designed from nature's *springtail* insects and created by a two-photon polymerization printing technique, which closely reassembles the insect's surface [96]. These structures exhibit super-repellency to water and various organic liquids. Building upon these triple reentrant structures, micro-open capillaries were constructed to enable controlled and directional liquid spreading. As shown in Fig. 5a, the triple re-entrant array can effectively prevent the diffusion of liquids, and the open channels led to the directional flow, creating a 'SEU' sign.

In addition, Yang et al. successfully replicated the 'eggbeater' structure inspired by the leaves of *Salvia molesta* using 3D printing technology, achieving several intriguing hydrophobic characteristics [47]. The research findings reveal that hydrophilic materials can be made to exhibit macro-level superhydrophobicity while still having adhesion to water (Fig. 5b). In nature, the 'eggbeater' structure typically consists of four arms. By manually adjusting the number of arms, the adsorption capacity for water can be controlled artificially, enabling droplet separation and non-destructive transportation (upper right). Additionally, the material demonstrates lipophilicity, as observed when the 'eggbeater' structure is brought close to oil droplets in water, resulting in rapid suction of the oil droplets within just 1 s (middle). When droplets of an oil-water mixture are placed on the 'eggbeater' structure, they can be effectively separated within 6 s.

4.2. Water collection and transportation

Water filtration, collection, and transportation play a crucial role in water resource utilization, conservation and environmental protection.

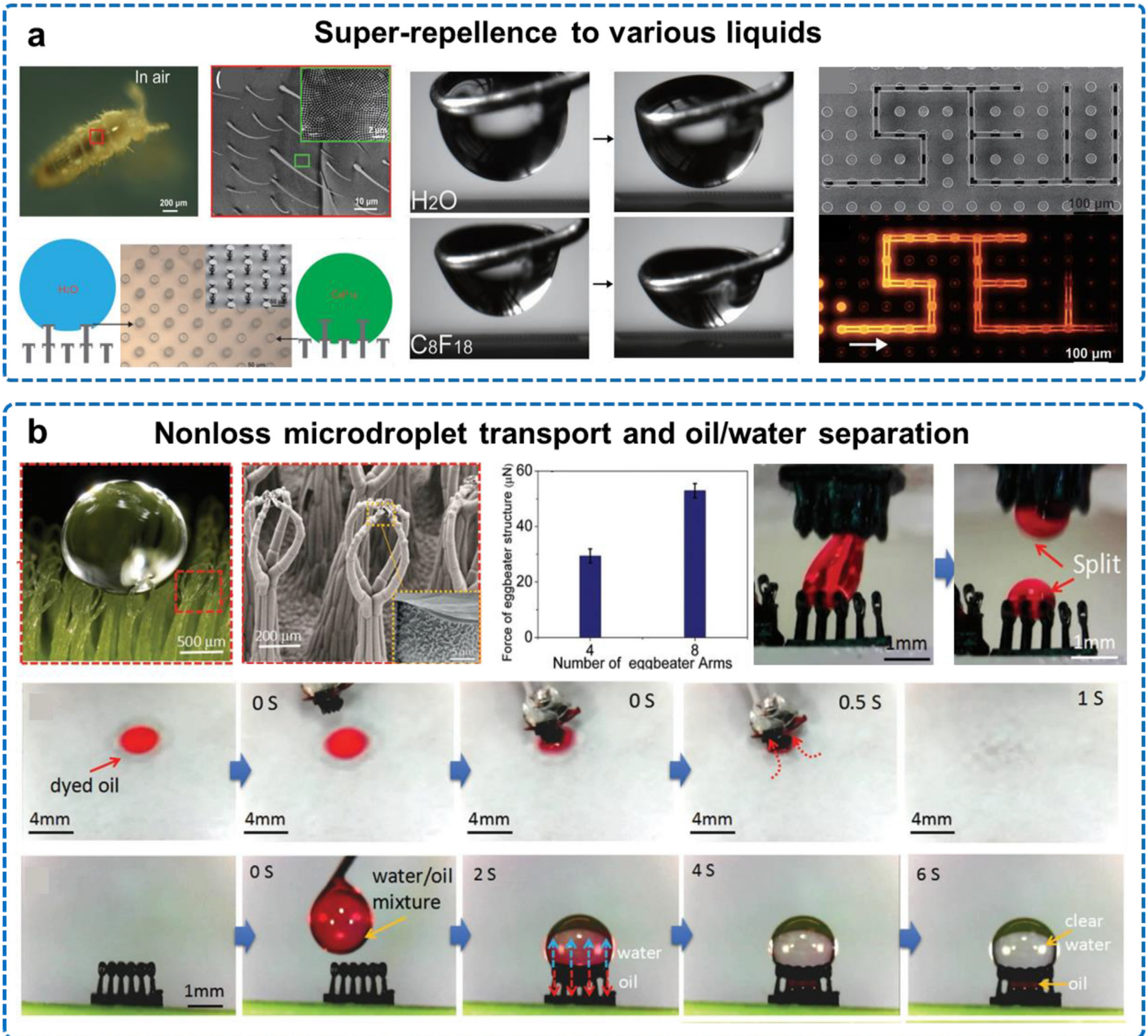

Fig. 5. 3D-printed biomimetic structures for superhydrophobic applications. (a) 3D-printed *springtails*-inspired structure with super-repellence to various liquids. Reproduced with permissions from Ref. [96], Copyright 2018, Wiley-VCH. (b) 3D-printed *Salvinia molesta* leaf structure realizes the nonloss microdroplet transport and oil/water separation of liquid. Reproduced with permissions from Ref. [47], Copyright 2017, Wiley-VCH.

In nature, there exist remarkable water collection structures, such as the cacti found in deserts, which have evolved natural clusters of branched spines to maximize water harvesting. The replication of such intricate structures has been made possible through the use of 3D printing technology. For instance, Li et al. have successfully designed and fabricated different artificial thorns that mimic the efficient water harvesting mechanism observed in nature. These artificial thorns demonstrate the ability to collect water without the need for additional energy input [46]. Similarly, Wang et al. used PμSL to copy cross-sectional vessels in trees, creating a structure with microfluidics ability consistent with real trees and excellent anti-gravity water transport performance [95]. Except for plants, animals also have structures with varying degrees of hydrophobicity toward liquids. Liu et al. achieved programmable liquid adhesion on micro doubly re-entrant arrays inspired by *springtail* skin and *gecko* feet. By adjusting the center-to-center distance and the diameter of the top cover, three distinct Cassie adhesion behaviors were achieved, including no residue adhesion, tunable adhesion, and absolute adhesion [102].

Droplet capture and efficient transmission are among the critical features of high-performance droplet collection systems. Inspired by the remarkable fog droplet collection ability of *wheat* awns, Xiao et al. developed artificial hierarchical systems that mimic the structure of wheat awns [88]. These systems consist of conical spines, gradient microgrooves, and oriented thorns, as shown in Fig. 6a. The presence of such a hierarchical structure facilitates the transformation of droplet collection from a dropwise mode on the thorns to a filmwise mode on the spine. Notably, even when placed vertically, droplets can be directed and driven from the tip of the needle to the base of the spine (middle). The collection rates of the five manually designed fog collection systems vary, allowing for the design of different appearances for specific applications (lower). These findings demonstrate the potential of biomimetic design in creating efficient fog droplet collection systems.

Furthermore, as shown in Fig. 6b, the 'tip-induced flipping of droplets' on Janus pillars was realized regarding the behavior of droplets on needles of *Sabina chinensis* [45]. This local effect, driven by the geometry

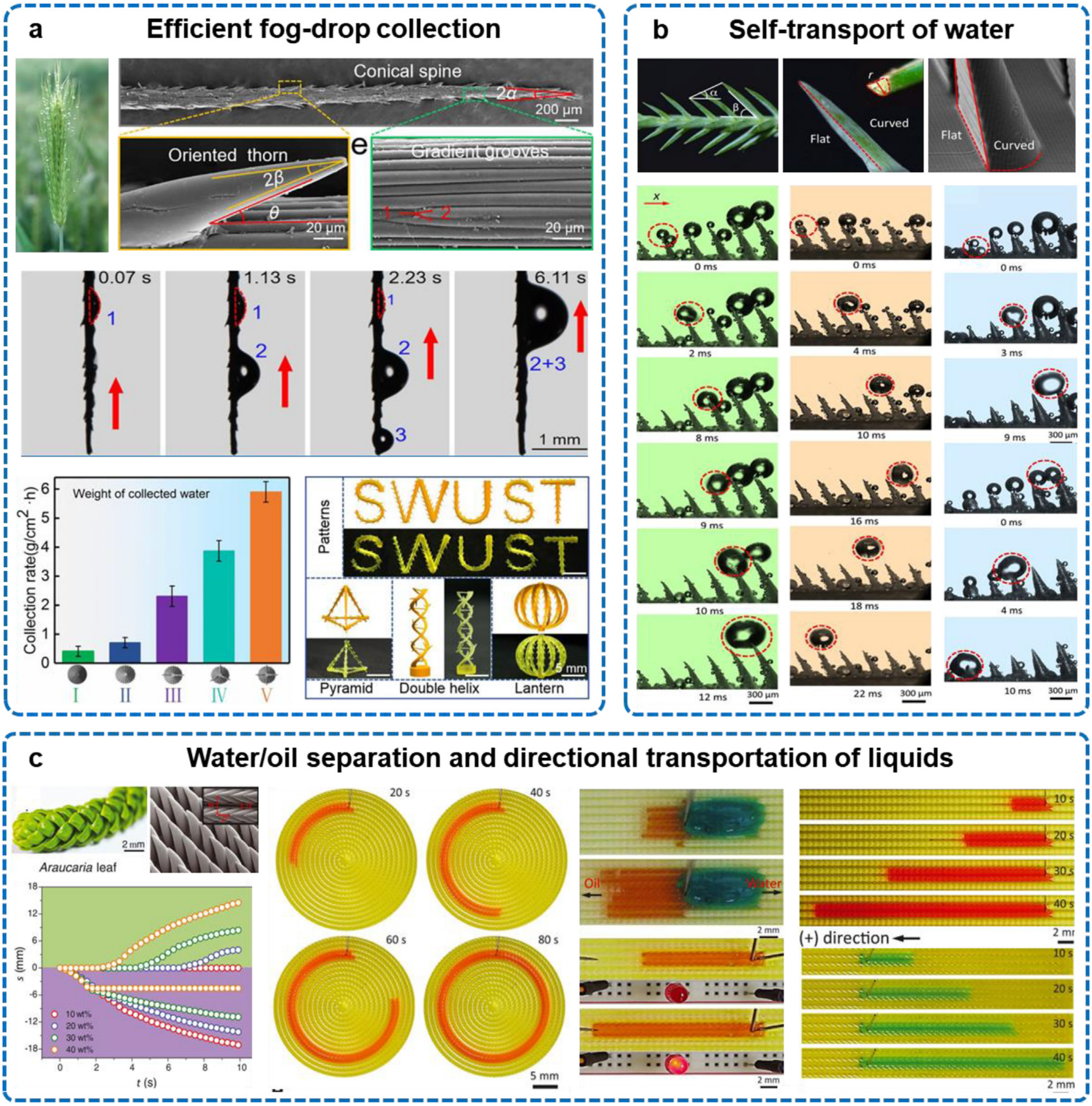

Fig. 6. 3D-printed biomimetic structures for liquid collection and transportation. (a) Programmable 3D-printed wheat awn-like system for high-performance fogdrop collection. Reproduced with permissions from Ref. [88], Copyright 2020, Elsevier. (b) 3D-printed pine needle for self-transport of water. Reproduced with permissions from Ref. [45], Copyright 2020, American Association for the Advancement of Science. (c) Water/oil separation and directional transportation of liquids by 3D-printed *Araucaria* leaf. Reproduced with permissions from Ref. [94], Copyright 2021, American Association for the Advancement of Science.

of the pillars, leads to remarkable global consequences. Vast arrays of Janus pillars enable the continuous, long-range, and rapid self-transportation of water collected from fogs, enabling the collection and concentration of droplets at various scales. The droplets gather on the asymmetric needle tip of a 3D-printed structure and move toward the other side, ultimately converging together. This droplet transport mechanism, which operates without the need for energy input, can significantly enhance the rectification efficiency of materials. These findings hold practical and promising applications in microfluidic devices and water collection systems.

In addition, a liquid transport behavior on a 3D-printed *Araucaria* leaf-inspired surface (ALIS) was also established, where the surface features 3D ratchets with transverse and longitudinal reentrant curvatures (Fig. 6c) [94]. Low-surface-tension liquids preferentially follow a pathway along the direction of ratchet tilting, while high-surface-tension liquids choose the opposite direction. By studying the movement patterns of water-ethanol mixtures with different mass fractions on ALIS, interesting behaviors were observed. For the mixtures with a mass fraction of $c \leq 10$ %, the liquid aggregates only in the feedback direction. For those mixtures with $10 < c < 40$ %, the liquid transport is bidirectional. And for mixtures with $c \geq 40$ %, the liquid propagates exclusively in the forward direction (lower left). These findings have practical implications, particularly in the design of oil/water separation devices. By placing an oil-water mixture on ALIS, the oil and water can be transported in opposite directions, achieving complete separation without relying on gravity (right). This innovative approach provides a promising solution for efficient oil/water separation.

4.3. Water purification

Seawater desalination is a crucially important technology for obtaining clean water resources, especially in arid desert areas and coastal cities, contributing to economic and social development. Among desalination techniques, solar-driven interfacial evaporation is an emerging technology, owing to its eco-friendly and cost-effective characteristics in freshwater production [103]. In order to improve the distillation efficiency, distillation speed, and ensure that the device is not contaminated by salt, biomimetic technology is also used in this field [104–107]. For example, Song et al. synthesized biomimetic Au nanosphere assemblies and nanostars assemblies with a photonic structure successfully replicated from *Papilio Paris* butterfly forewings. As a result, the structure exhibits a high evaporation rate (1.30 kg m^{-2} h^{-1}) and evaporation efficiency (83.3 %) under 1-sun irradiation [104]. It is worth noting that due to the high design freedom and controllable microstructure of 3D printing technology, the three biomimetic solar evaporators using 3D printing technology in Fig. 7 can achieve even much better energy conversion rate and evaporation rate.

Building upon the transpiration phenomenon in nature, Wang et al. developed a 3D graphene oxide-based biomimetic solid steam generator (GOSG) by combining the natural migration phenomenon and origami configuration. As shown in Fig. 7a, the GOSG exhibited impressive performance characteristics. It achieved a high solar-thermal conversion efficiency of 94.5 % under one sun illumination. Additionally, the GOSG demonstrated a superior steam generation capacity of 0.46 kg m^{-2} h^{-1}. Moreover, the GOSG exhibited an exceptional solar absorption capability, with a value exceeding 99.90 %, indicating its great ability to effectively capture and utilize solar radiation for energy conversion (middle). Furthermore, the prototype GOSG device was tested for its desalination capabilities using water from the Bohai Sea. The concentrations of Na^+, K^+, Ca^{2+}, and Mg^{2+} in the treated water were significantly reduced, meeting the World Health Organization's (WHO) recommended standard for drinkable water, thereby achieving water purification goals [82].

In addition, Zou et al. have proposed a 3D-printed biomimetic solar evaporator with the ability for long-term salt rejection by taking inspiration from the superfast water transportation mechanism of the *Nepenthes alata peristome* surface and the continuous bridge-arch design. This multifunctional evaporator exhibited superior performance in solar-driven water evaporation (1.64 kg m^{-2} h^{-1}, 91 % efficiency for pure water), efficient solar desalination, and long-term salt-rejecting capability (continuous 200 h in 10 wt% saline water) without the need for post-process cleaning (Fig. 7b). Evaporation experiments were conducted on water containing various ions, and the ion content of the purified water obtained also met the WHO standard for drinkability (right) [85].

Interestingly, Wu et al. constructed a novel multi-bioinspired biomimetic structure for solar evaporators by combining the asymmetric capillary ratchet of bird beaks and the peristome surface of *pitcher plants*. The obtained evaporator achieved a high water evaporation of 1.17 kg m^{-2} h^{-1}, a high solar-driven water evaporation of 2.63 kg m^{-2} h^{-1}, and a high energy efficiency of 96 % under 1-sun illumination, which performs better than previous examples. As shown in Fig. 7c, it exhibited excellent stability even under high salinity conditions. After desalination, the Na^+ concentration is significantly decreased to 3.6 mg L^{-1} (lower right), meeting the WHO drinking water standards as well [86].

4.4. Other environmental applications

In addition to the aforementioned applications, biomimetic structures have also been widely used in other environmental fields, such as sewage treatment [87], photosynthesis bioelectricity [83,108], and spilled oil absorption [47,94,109]. For example, sewage treatment plays a crucial role in industry, environmental protection and ecological governance, while a major challenge lies in preventing blockages and pollution in filtration devices. To address this issue, Li et al. introduced a novel type of 3D-printed membrane filter that offered sustainable and chemical-free water treatment. Taking inspiration from aquatic creatures, they incorporated fish-mimicked structures, metallic micromesh, and polymeric membranes into a single 3D-printed functional filtration device which exhibited outstanding anti-fouling and clogging properties [87].

Coral reefs are among the best-known ecosystems, with their vitality relying on the symbiotic relationship between the coral and algae. Interestingly, despite the common expectation that light should quickly decay when it enters coral, the presence of coral skeletons directs light deeper into the originally dark regions. This phenomenon facilitates photosynthesis and energy generation by the algae residing deep inside the coral. In this connection, Wangpraseurt et al. conducted imaging and compositional analyses of corals, subsequently utilizing 3D bioprinters to create intricate structures that mimic real corals. These printed structures consist of cellulose and other biological materials, housing embedded algae that thrive exceptionally well-up to 100 times denser growth than in conventional experimental conditions. Such research findings hold promise for mitigating the ongoing degradation of coral reef ecosystems worldwide [110].

Joshi et al. have successfully printed an artificial mushroom by integrating cyanobacterial cells with graphene nanoribbons onto the pileus of the mushroom, enabling photosynthetic bioelectricity generation. This 3D-printed bionic mushroom architecture represents an environmentally friendly and sustainable source of photosynthetic bioelectricity [83]. Inspired by mussels and oysters, Li et al. designed a Soy protein isolate-based underwater adhesive, which has good antibacterial, mildew resistance, and fire resistance. It can be used in various fields such as sealing and repairing underwater or wastewater structures [108].

Oil spills resulting from events like ship sinking and improper handling of oily wastewater pose significant environmental challenges. Polydimethylsiloxane (PDMS) sponges have been used for absorbing and separating spilled oil, but there is a need to improve the absorption capacities to make the separation process more effective. Based on this point, Shin et al. proposed a novel design for PDMS sponges that mimic *cacti*. By incorporating a hollow and bio-inspired design, the bio-inspired PDMS sponge demonstrated an absorption capacity 3.7 times higher than that of the non-hollow and conventional PDMS sponge. This bio-inspired approach offers a promising solution for improving the effectiveness of PDMS sponge absorbents to resolve global oil contamination issues [109].

5. Summary and outlook

In summary, we have provided an overview of the current state of 3D-printed biomimetic structures and their applications in energy and environment. They include selected examples, such as piezoelectricity, supercapacitor, oil/water separation, self-cleaning, water collection, and droplet manipulation. We have discussed different types of biomimetic structures, the 3D-printed materials, the 3D printing technique used, and the unique properties achieved. Indeed, there is great potential for further advancements via the biomimetic approach to tackle additional challenges in various energy and environmental applications (Fig. 8).

However, there are still some considerable challenges and issues that need to be addressed. Firstly, high-resolution 3D printing is required to replicate micro/nanoscale biomimetic structures, as the resolution of conventional 3D techniques like FDM and SLM is not sufficient [111]. Developing high-resolution 3D printing technologies such as TPP [112], PμSL [113], 3D e-jet printing [114], and 3D nanoprinting [115,116] and even 4D printing [117,118] would be crucial for better mimicking natural nanostructures and achieving the desired functions. For example, the smallest *Xanthosoma sagittifolium* leaf-inspired cylindrical patterns reach

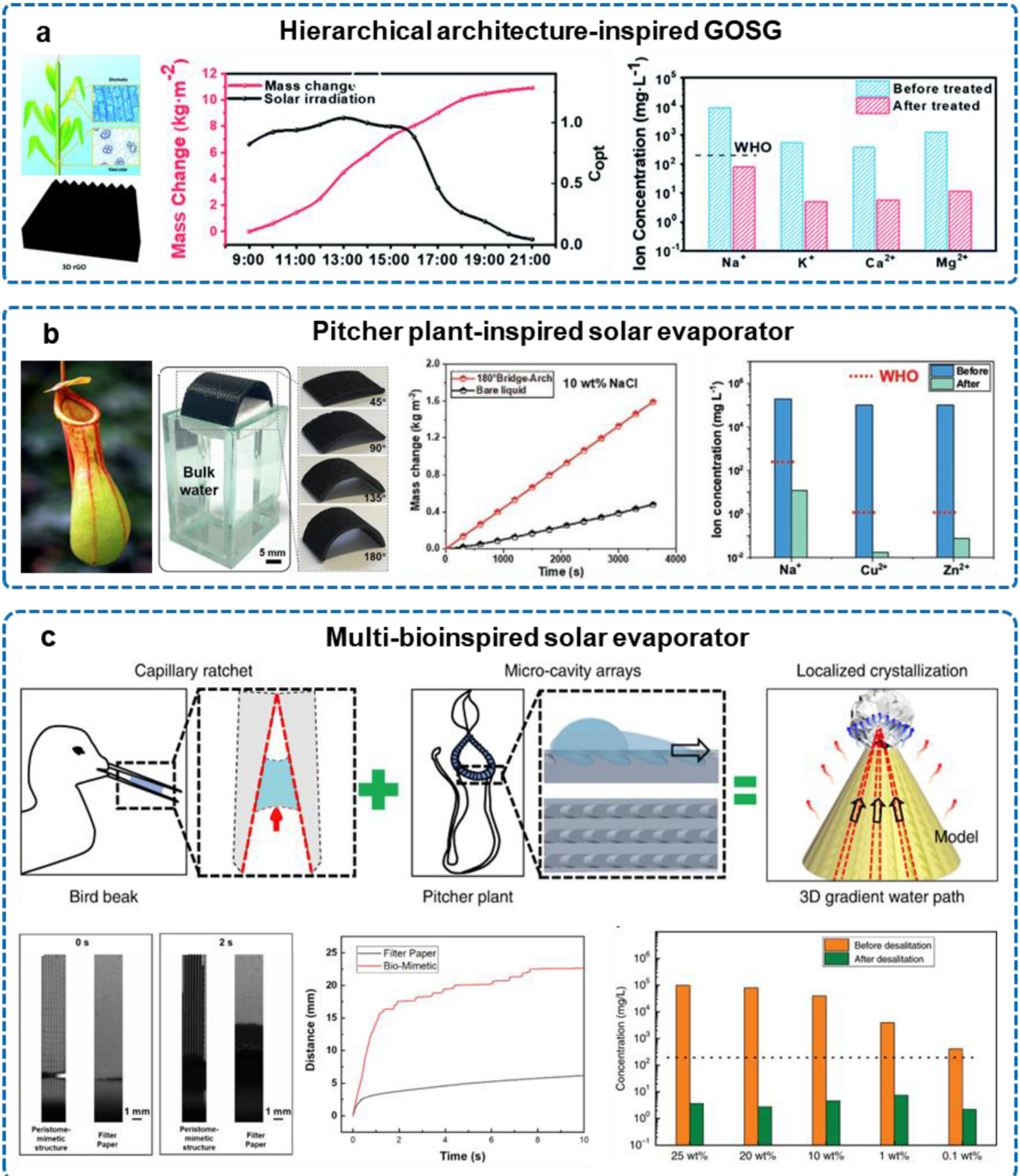

Fig. 7. 3D-printed biomimetic structures for solar evaporators. (a) 3D-printed graphene oxide-based biomimetic solar steam generator (GOSG) inspired by both the natural transpiration phenomenon and artificial origami configuration. Reproduced with permissions from Ref. [82], Copyright 2020, The Royal Society of Chemistry. (b) Biomimetic 3D-printed bridge-arch solar evaporator. Reproduced with permissions from Ref. [85], Copyright 2021, Wiley-VCH. (c) Biomimetic 3D-printed evaporator inspired by the super liquid transportation property of the asymmetric capillary ratchet of the bird beak and the peristome surface of the *pitcher plant*. Reproduced with permissions from Ref. [86], Copyright 2020, Nature Publishing Group.

500 nm in size [119], exceeding the capabilities of common 3D printing technologies that are currently available. Additionally, exploring multi-material 3D printing can lead to the creation of even more complex structures and functional composites with diverse properties, including mechanical, electrical, thermal, and optical characteristics. By combining different materials with distinct properties, researchers shall be able to achieve high-performance hybrids closer to those found in nature [120, 121]. Understanding the roles and relationships of each material is

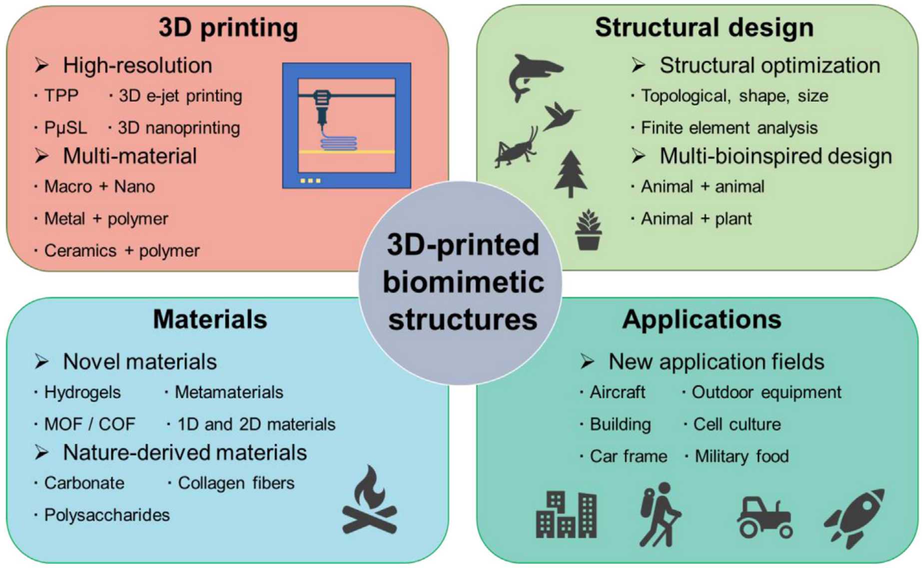

Fig. 8. Remaining challenges and further development directions for biomimetic 3D printing.

therefore essential to produce more practical and better-performing materials with similar or even better functions.

Secondly, optimizing biomimetic structures is also necessary due to the complexity involved. Not all structures can be easily manufactured, and support structures may be required during the printing process, which can be challenging to remove [122]. Nature has achieved some of the most efficient structures through millions of years of evolution, but these may not always be the optimal structures for new and practical applications. Researchers need to analyze and explore the mechanisms behind natural structures, for example through finite element analysis, so that they can proceed with optimization, including shape [123,124], size [124], and topological optimization [125,126]. This could help to simplify complex structures, reduce material and energy waste, and improve design freedom. Additionally, instead of focusing on replicating a single organism or natural structure, there is a need to consider the synergistic effects of multiple biomimetic structures. Combining the advantages of different natural structures can generate new hybrid structures with multifunctional abilities [86,92,127–130]. For example, combining the oil transport capability of fishbone with the anisotropic grooved structure of rice leaves, researchers have created a multi-bioinspired grooved conical spine (BGCS) that exhibits significantly improved transporting velocity and capacity compared to a regular cone [92].

Thirdly, it would be important to explore and utilize advanced and nature-derived materials for 3D printing. Currently, many 3D-printing raw materials used are photocurable resins and common metals. However, there will be a focus on new and advanced materials such as hydrogels [131–135], metal–organic frameworks (MOF) [136–138], covalent organic frameworks (COF) [139–141], metamaterials [142–145], and 1D and 2D materials [146,147], which have been proven effective in various fields. Nature-derived materials like carbonate minerals, polysaccharides and collagen fibers can also be used as raw materials or additives for 3D printing [134,148–151]. By incorporating these materials into multi-material 3D printing, structures can closely resemble the extraordinary structures and functions of nature, with the added benefit of biocompatibility for biomedical applications possibly. In addition, sustainable materials should be developed to reduce material costs and environmental impact.

Lastly, there is still much room to explore new applications for biomimetic 3D printing. While the technology is already used in some sectors of industries, its potential can be further expanded. This includes applications such as new aircraft lightweight design, more durable building structures, high-strength and lightweight vehicle frames, waterproof and anti-fouling outdoor equipment, cell culture, and even 3D printed food, particularly for military purposes where small size, light weight, and high-calorie content are essential.

In conclusion, the field of 3D-printed biomimetic structures has made significant progress, but there are still more challenges to be overcome and also opportunities to explore. By addressing issues related to high-resolution printing, structural optimization, multi-material printing, novel materials, multi-bioinspired structures, and new application fields, researchers can unlock the full potential of biomimetic 3D printing in various industries and domains.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Zhiyang Lyu reports financial support was provided by Southeast University. J. Justin Koh reports financial support was provided by Institute of Materials Research and Engineering (IMRE). John Wang reports financial support was provided by National University of Singapore.

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