DOI: 10.24874/ti.2109.01.26.03

Tribology in Industry

www.tribology.rs

REVIEW

3D Printed Biomimetic Interfaces with Anisotropic Friction and Functional Surface Design

Khan Rajib Hossain[a,b], Jarin Tasnim[c], Md. Rahamatolla[a], M. Abdul Jalil[a,*],
Mohammod Aminuzzaman[a], Md. Abu Saeed[a], Khan Md. Salman Adib Fuad[a]

[a]*Department of Natural Science, BGMEA University of Fashion & Technology, Dhaka 1230, Bangladesh,*
[b]*Materials Engineering, University of Chinese Academy of Sciences, Beijing, 100040, China,*
[c]*Department of Applied Chemistry and Chemical Engineering, University of Rajshahi, Rajshahi 6205, Bangladesh.*

Keywords:

3D printing
Biomimetics
Anisotropic friction
Hydrogels
Functional surfaces

* Corresponding author:

M. Abdul Jalil
E-mail: abduljalil@buft.edu.bd

Received: 11 January 2026
Revised: 24 February 2026
Accepted: 18 March 2026

ABSTRACT

Biomimicry, which involves drawing inspiration from nature to identify solutions to challenges, is a crucial approach to designing adaptive, multifunctional materials, considering that nature's designs have been refined through millions of years of evolution. Anisotropic friction and functional surface engineering are two of these strategies that serve as essential methods for controlling directional motion, enhancing adhesion, reducing drag, and regulating wettability. With the development of state-of-the-art 3D printing techniques, such as micro-stereolithography, direct ink writing, and two-photon polymerization, hierarchical structures inspired by gecko setae, snake scales, lotus leaves, and cat paw pads can now be printed with unprecedented resolution. Additive manufacturing (AM) enables the use of soft-hard composites, stimuli-responsive hydrogels, and micro- and nano-textured surfaces to create synthetic interfaces with controllable adhesion, self-cleaning properties, and improved tribological behavior. Recent studies have shown that structural design and photothermal response enable controllable friction and multifunctional applications. The field is advancing rapidly toward biomimetic materials that are sustainable, responsive, and adaptable, despite challenges in scalability, durability, and cross-disciplinary integration. In this review, we summarize these recent advances, discuss the importance of anisotropic friction for functional interfaces, and provide new perspectives on translating natural inspiration into working technologies.

1. INTRODUCTION

Biomimicry, the study of nature's evolutionary designs for inspiration, has become a potent approach in material science. Nature has provided many examples of highly efficient structures and functions in biological systems (e.g., gecko feet for adhesion, lotus leaves for self-cleaning, and fish scales for drag reduction) that have inspired the design of new materials and interfaces. The development of synthetic systems with artificial behavior, such as adaptability, sustainability, and performance, based on these natural processes, is inspiring [1]. The development of 3D printing has opened up new possibilities for translating natural materials into real-world applications with functional properties. In contrast to conventional subtractive or casting approaches, AM enables the construction of hierarchical structures in a complex manner with accuracy, design freedom, and cost-effectiveness [2]. Biomimetic factors that can be designed, such as anisotropic friction and functional surface design, are two of the most important. In nature, anisotropic friction helps organisms, including snakes, insects, and plants, to orient their grip, locomote, and alter their environment [3]. Functional surface materials, such as hierarchical texturing and soft-hard composites or stimuli-responsive materials, can further enhance the versatility and performance of synthetic interfaces [4]. The promise of biomimetic interfaces produced by AM and advanced surface functionalization is made clear by recent developments. 3D-printed biomimetic structural ceramics with excellent tribological properties present multiscale bioinspired alumina ceramics obtained from direct-ink writing (DIW) 3D printing, combined with femtosecond laser patterning, inspired by the ventral scale structure of the Oriental sand boa. Wang et al. [5] demonstrated that the W3C/polyimide hybrid coating possesses enhanced friction and wear resistance performances under various testing conditions, and MoS_2 films work in collaboration with patterned surfaces to provide synergistic lubrication.

A biomimetic layered hydrogel coating enhances lubrication and load-bearing capacity by producing a gradient (layered) hydrogel on a rigid PEEK substrate, comprising a porous soft layer for water retention (lubrication) and a dense layer for load support. This design features ultra-low coefficients of friction (≈0.01 under a 5N load) and good wear resistance during prolonged reciprocating sliding tests [6]. Haohang et al. [7] investigated PVA hydrogels with a modified layered architecture for load-bearing and lubrication in their study. The hydrophobic and tribological behavior of biomimetic interfaces addresses the changes or effects associated with the wetting of coatings and texturing on lubricant life, such as in boundary lubrication [8]. Amjad et al. [9] covered how superhydrophobic surfaces can be printed using a 3D process and what compromises exist between mechanical strength, durability, and scaling. Maydanshahi et al. [10] provided an analysis of how a layer-by-layer microstructure affects friction and wear in PEEK printed through the material extrusion (ME) process, which is especially relevant for directional mechanical properties in implants.

Herein, we provide a review to overview the recent progress in 3D printed biomimetic interfaces concerning anisotropic friction and functional surface engineering. It focuses on the biological rationale, materials, and microfabrication strategies in these systems, as well as their tribological features and technological applications. This article explores how 3D printed biomimetic surfaces can inspire the development of the next generation of intelligent, flexible, and sustainable materials by integrating biology, materials science, and modern manufacturing techniques.

2. BIOMIMETIC PRINCIPLES AND NATURAL INSPIRATIONS

The Greek word "bio," which means "life," is where the word "bionics" comes from. Biomimicry, also called “biomimetics”, is a science that uses 3.8 billion years of evolutionary knowledge to meet human needs across all areas by copying successful models, systems, and elements of nature [11]. Anisotropic friction, that is, one dependent upon the direction of relative motion, is a common theme in biological systems. Hierarchical setae and spatula arrays in gecko feet adhere reversibly with directional control, even when used for locomotion on vertical and inverted surfaces [12]. Snakes employ oriented scale microstructures to reduce backward slip without affecting forward movement, a design concept now followed by anisotropic tribological surfaces when considering soft robotics and conveyors. Also, the paw pads of cats have soft tissue cushioning augmented with horn IMMs that help in grip on prey and silent walking, and fish scales, as well as wheat awns, are found exhibiting asymmetric micro-barbs guiding motion or aiding in seed dispersal [13].

These anisotropic frictional behaviors are critical for locomotion efficiency, prey capture, and adaptation to varied environments. Inspired by nature, the realization of such directional microstructures has been recently successfully replicated in 3D printing and lithography to make synthetic materials with controllable direction-dependent friction properties [14]. Ji et al. [15] studied that 3D printing is used to generate the structure emulating hook-thorned features of filefish skin surface with specific interface anisotropy (Fig. 1). The anisotropic friction of the 3D printed surface provides actuation directionality, enabling it to move in a specific direction and oscillate when in contact with other surfaces. Ji et al. [16] demonstrated that the dynamic control of anisotropic friction on a bio-inspired surface with structures aligned with respect to the supporting substrate can be achieved by varying the stiffness of the support layer. The biomimetic surface featured hook-shaped spine microstructures embedded in a polymer background, fabricated through 3D printing and transfer replication. A matrix comprises Fe_3O_4 nanoparticles that exhibit outstanding near-infrared (NIR)/infrared (IR) photothermal generation properties, allowing their stiffness to change with light on/off and enabling the realization of continuously tunable, biomimetic surfaces with anisotropic friction properties. The potential of designing an intelligent control device is demonstrated in a proof-of-concept design that enables fastening and unfastening using NIR/IR light (similar to surgical gloves with this property), employing a control mechanism akin to Velcro strips [17,18].

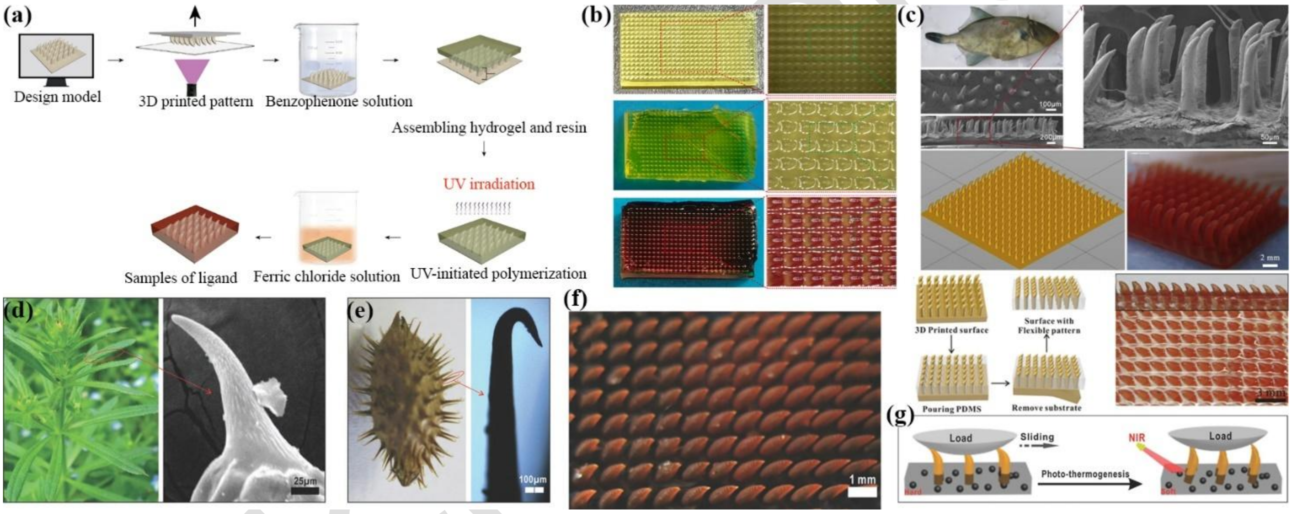

Fig. 1. (a) Schematic of the epoxy resin-hydrogel soft and hard composite surface interface preparation process, [17] (b) 3D printed bionic surface interface topography (top); epoxy resin-hydrogel composite surface interface structure (top middle); Fe3O4/ECH-modified GO as coating layer via iron ion coordination and binding (bottom middle), (c) Image filefish and fish skin surface (top left), scanning electron micrographic images of hooked spines (top right, bottom left); 2-dimensional model for the design of a surface with hook-shaped spines(bottom right), Photographs of electrospinning PLA nanofiber sheets covered with hooked spines, Scheme wire growth in a flexible PDMS layer, [15], (d) a digital photo of Galium aparine and a SEM image of the microstructure in its leaves; (e) A digital photo of the fruit of Xanthium L. and the microstructure of its surface; (f) A digital photo of the biomimetic surface of the PLA@Fe3O4 substrate and the holes in the hook-shaped spines; and (g) A schematic diagram of how the structure changes when rubber is used to change the stiffness of the layer [16].

There are also wide varieties of other surface properties exhibited in nature. Tree frog toe pads and octopus suckers, with both micro/nano structures and soft tissue deformation, exhibit reversible adhesion under moisture conditions [19]. Baik et al. [20] demonstrated a high-drainage and strong adhesive patch inspired by the soft wrinkles of a microscopic 3D octopus sucker, which protects human organs against dry/wet conditions (Fig. 2). A simple model was established to investigate the structural properties of wrinkles, and a general framework based on this was proposed for the enhancement of the capillary interaction of wet wrinkled surfaces. These bioinspired patches offer the potential to enhance the versatility of adhesives in skin- or organ-bonding devices.

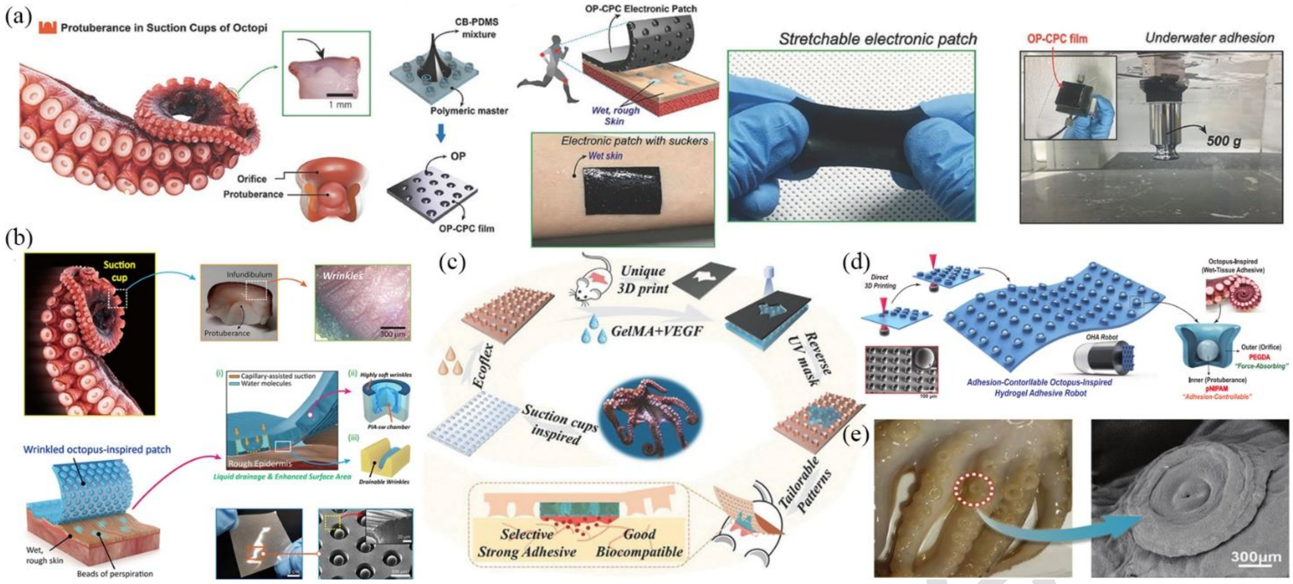

Fig. 2. (a) Octopus-inspired carbon-based CPC electronics phoenixes the suction cups of octopus tentacles, and is a dome-shaped wearable sensor. Reproduced with permission from [21] (b) Soft folds and vertices similar to suction discs of an octopus in an adhesive patch. Photographs or images show that it conforms to sweating skin, [20] (c) Schematic illustration of customizing a wound care dressing bioinspired by the skin-adhesive patch [22], and (d) OHA robots fabricated from direct 3D microprintings with a mimic octopus suckers. PEGDA hydrogel is applied on the outside wall, and an aligned pNIPAM hydrogel is used for inside designs, [23] (e) An octopus picture as well as scanning electron microscope (SEM) images of its offspring [24].

Drag reduction through sharkskin riblets lowers flow resistance and hydrodynamic drag, leading to potential applications in coatings for ships and aircraft [25]. Wettability and Self-Cleaning Lotus leaves display superhydrophobicity through a combination of hierarchical papillae covered with waxy nanostructures that lead to the “lotus effect” applied in anti-fouling and self-cleaning [26]. Nature often integrates micro- and nano-scale structures, as seen in the gecko setae, where nanoscale spatulae are supported by microscale hair, which is attached to a macroscale toe pad. Biological surfaces can change their properties in response to stimuli (e.g., chameleons changing the color of their skin, lotus leaves exhibiting hydrophobicity upon humidity). Smart polymers and hydrogels with anisotropic responses to light, temperature, or humidity are now part of inspired synthetic surfaces. The aim is to create artificial materials with these properties for use in technology and industry where varying friction levels are needed. It is also essential to design surfaces that can be controlled by friction, with their frictional properties changing in response to external forces [27]. For devices with anisotropy, it is necessary to develop micropatterned crystal materials with ordered pores. Crystalline, porous metal-organic frameworks (MOFs) are attractive because they exhibit extraordinary chemical and structural diversity, allowing for the fine-tuning of functional properties for applications in microelectronics and photonics. Hernández et al. [28] also prepared a MOF film patterned with a photomask and oriented using X-rays (Fig. 3). The Mo-MOF is utilized as a resistor and, at the same time, a functional porous material. The high quality of the extended MOF micro patterns was evidenced by their capability as diffraction gratings under laser illumination. In addition, fluorescent dyes were functionalized to the oriented MOF patterns, enhancing their optical properties and enabling applications in sensors and imaging technologies. By controlling the functionality of light response, this MOF paging method could potentially be implemented in the microfabrication of optical elements used in photonics. Bruzewicz et al. [29] propose a way to organize things in three dimensions based on nature. They show how an electric light detector works. This method is based on how biological macromolecules bend into a sphere. The strips were patterned to accommodate liquid solder metallic features, and as part of a string of 3D ripples, which were bonded to flat polymer strips to form linear three-dimensional (3D) structures. Many soft, hydrogel-like materials found in nature have ordered structures composed of tiny parts. Nature produces many soft, hydrogel-like materials with ordered structures engineered at the micro- and nanoscale. Because they are so complicated and different, these materials work very well. Synthetic analogs of anisotropic hydrogels have recently garnered significant interest for not only possessing properties reminiscent of their natural counterparts but also exhibiting exceptional and novel functionalities that isotropic gels are unable to offer. Such materials contain high water content, and as a result, it is challenging to control polymer interactions and the resulting microstructure. Mredha et al. [30] proposed the fabricated isotropic and anisotropic biomimetic hydrogel prototypes, which are shown to be scalable along with state-of-the-art processing methodologies and governing design parameters for superior performance (Fig. 3b,c). The remarkable performance of anisotropic hydrogels makes them excellent candidates in diverse fields.

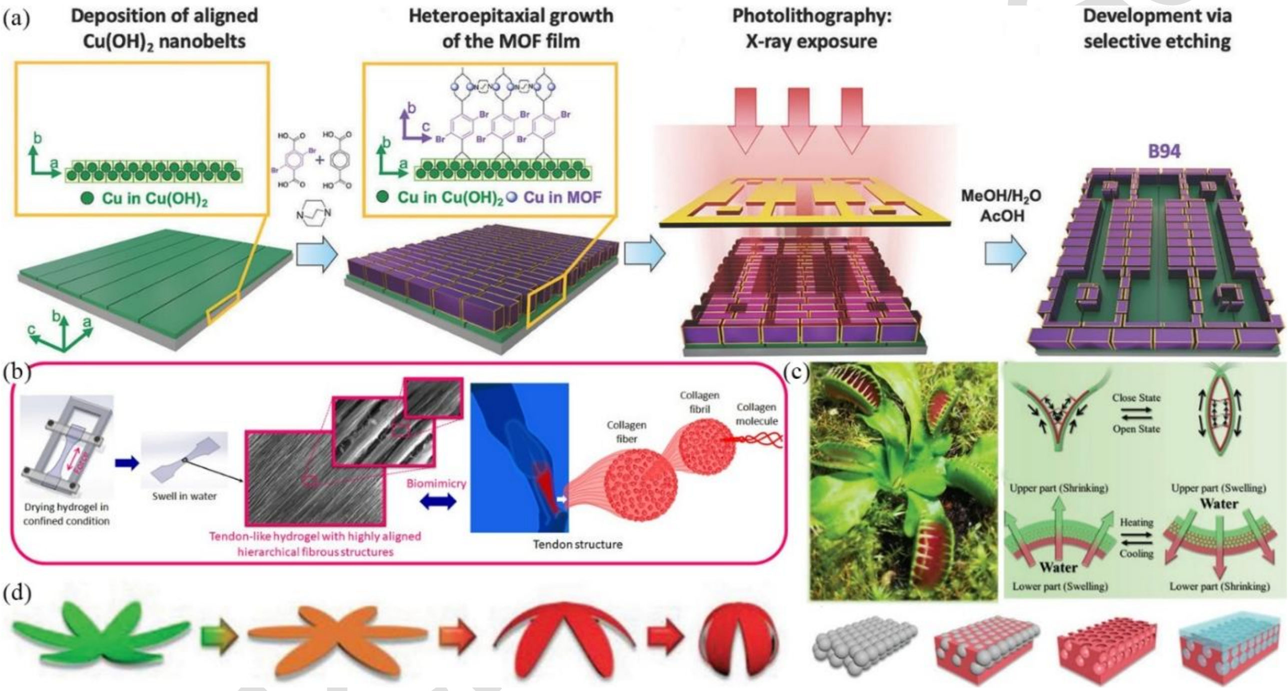

Fig. 3. (a) Schematic illustrating the fabrication procedures at different stages and the resist-free patterning of oriented MOF films. A film of aligned Cu(OH)2 nanobelts is deposited on a silicon (Si) wafer, [28] (b) A schematic of a typical anisotropic hydrogel for bio-mimicry, which presents hierarchically fibrous structures approaching a perfectly aligned tendon, (c) an image of the Venus flytrap and its schematic diagram showing that water infiltrates in between two layers to trigger the snap closure movement; introducing inverse opal structure interface into the crosslinked results in a bicoloremulti layer hydrogel, and (d) The diagrams are images for flower-shaped bilayer flower like hydrogel [30].

Several natural biological systems (snake skin, filefish scales, and insect cuticle) combine soft and stiff domains for flexibility along with toughness. Composite hydrogels and soft-hard hybrids manufactured via AM could replicate these architectures successfully. Soft polymer materials, similar to human tissues, have come into focus in interdisciplinary research in recent times. 3D printing is preferable to traditional processing because 3D printing enables rapid prototyping and mass customization, which are particularly suitable means for working with soft polymer materials. On the other hand, several limitations related to 3D printing based on soft polymer materials need to be addressed for advanced 3D printing in this field at an early stage, including the limited availability of printout materials, unsatisfactory resolution, print speed, and functionality [31].

Li et al. [32] focused on recent advances in research on the wet friction modification of soft elastomers through deformation. The authors discussed how characteristic textures could be used to modulate and control the wet sliding behavior of soft surfaces, from traditional dimple patterns to biomimetic architecture. Their role in determining interface friction could be either constructive or destructive. Huang et al. [33] reviewed the development of surface texturing and solid lubricants. First, in the design strategy (Fig. 4), it is studied that the design and treatment of surface texture, as well as the use of solid lubricants, are introduced, along with the preparation method of texture-attached lubricants. Finally, the influence of surface texture and solid lubricants on tribological performance, particularly in terms of friction reduction, wear resistance, and other advantages, is presented. Then, the synergistic behavior of surface texture and solid lubricants was introduced, emphasizing the interface between the textured surface/interface of the lubricating coating and the lubrication effect of texture on solid-lubricant materials.

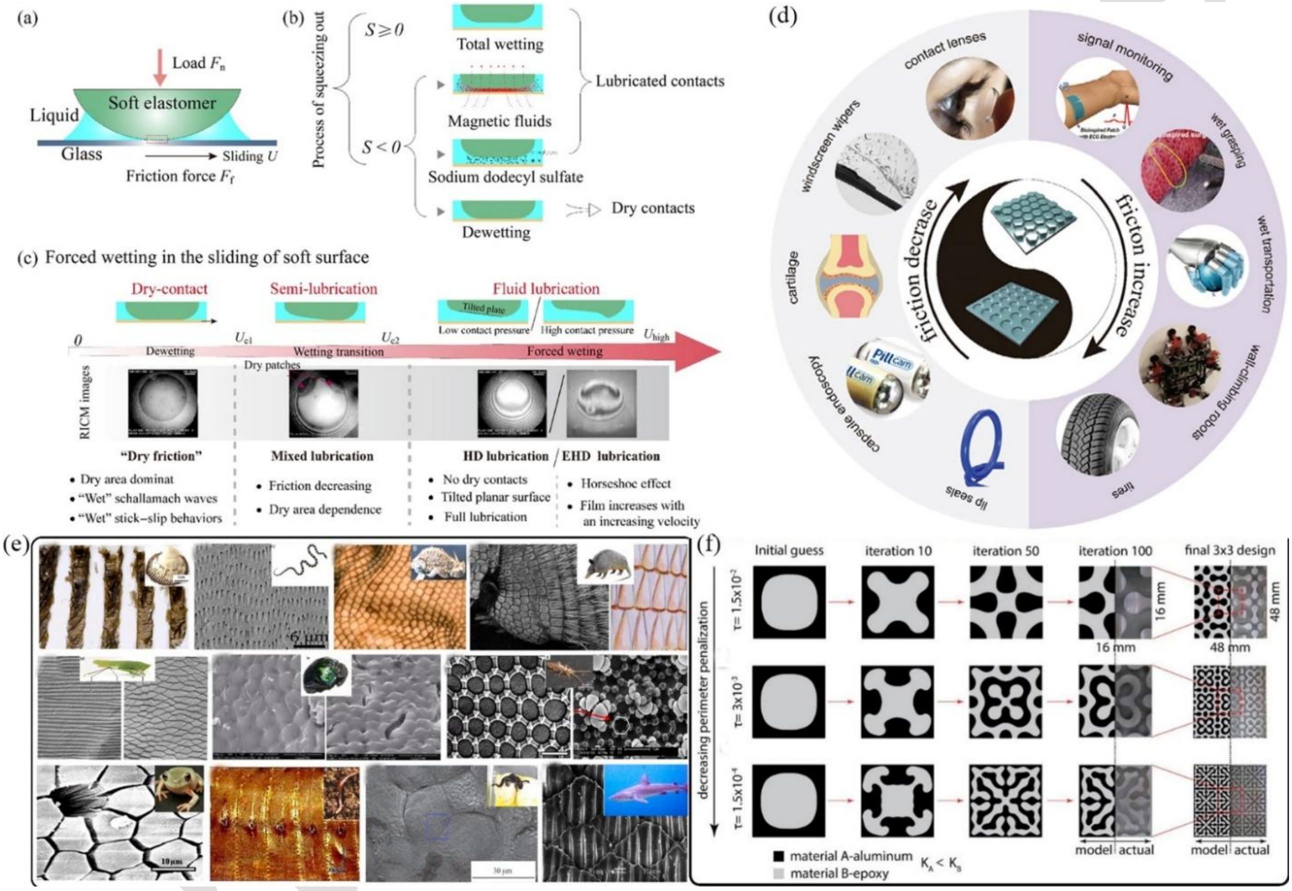

Fig. 4. (a) Schematic of soft elastomer sliding on a glass substrate in the presence of liquid, (b) The film is extruded between the elastomer and the substrate. (c) Wetting transition as a function of the flexible contact and sliding speed, [32] (d) Possible applications of texturing in soft material surface, (e) Structural and functional bionics, which are some examples for typical biological textures, and (f) Examples of topology optimization applied to texture: average temperature on the metal surface after topological topology optimization; topological optimized model using initial solid fraction estimate with final shapes generated 10 times, 50 times and 100 times [33].

These approaches show that biomimicry is more than just copying; it is also about applying evolutionary solutions to new situations. Advancements in 3D printing, micro-stereolithography, and responsive polymers now enable the precise application of these principles in next-generation biomimetic materials.

3. DESIGNS FOR BIOMIMETIC INTERFACES

The design of biomimetic materials has evolved over the past few years due to micro-stereolithography, a 3D printing technology that allows for very precise and detailed manufacturing at the micrometric scale [34]. Polygon-based 3D modeling would improve the design and development of materials with specific microstructures to mimic biological structures [35]. The unique feature of cat paws for favorable surfaces is not to lose sensitivity; therefore, they also make an ideal assistive footwear for better-grounded tactility. Compared to traditional printing samples, 3D polymer composite functional devices have a more complex and accurate structure, lighter weight, richer design freedom, and higher integration. With the maturity and development of computer-aided enabling technologies, many engineering disciplines (such as medicine, biology, chemistry, physics, and food science) are far more advanced than ever before, thus attracting numerous research initiatives and competencies. For them, bionics is a very promising and attractive study. The most critical work in the field of bionics is figuring out and modeling the shapes of natural systems. A 3D model is of the utmost importance for geometric characterization and representation, particularly in computer graphics visualization [36]. Engineering of bio-inspired microstructured surfaces has drawn much interest, in particular, toward their attractive features such as optical responsiveness, wettability, and sliding behaviors. Suzuki et al. [37] developed new methods for creating relief patterns with biomimetic hemispherical shapes (Fig. 5). It takes advantage of the fact that two materials have different refractive indices. When light enters from one side where the refractive index is higher than from the other, it forms a cone of light with a slight solid angle surrounding the critical angle. PμSL is a high-resolution (resolution up to 0.6 μM) 3D printing process based on a real projection-based photopolymerization technique. It can be used to create complex 3D structures over several scales and could utilize many different types of materials. Ge et al. [38] discussed how three-dimensional printing technology has advanced in recent years and some of the ways it can be used. It concludes some common applications of PsLS, such as mechanical metamaterials, optical devices, 4D printing, and biomimetic materials, as well as biology (Fig. 5c-e), and suggests future development directions of the pμSL in 3D SL printing technology.

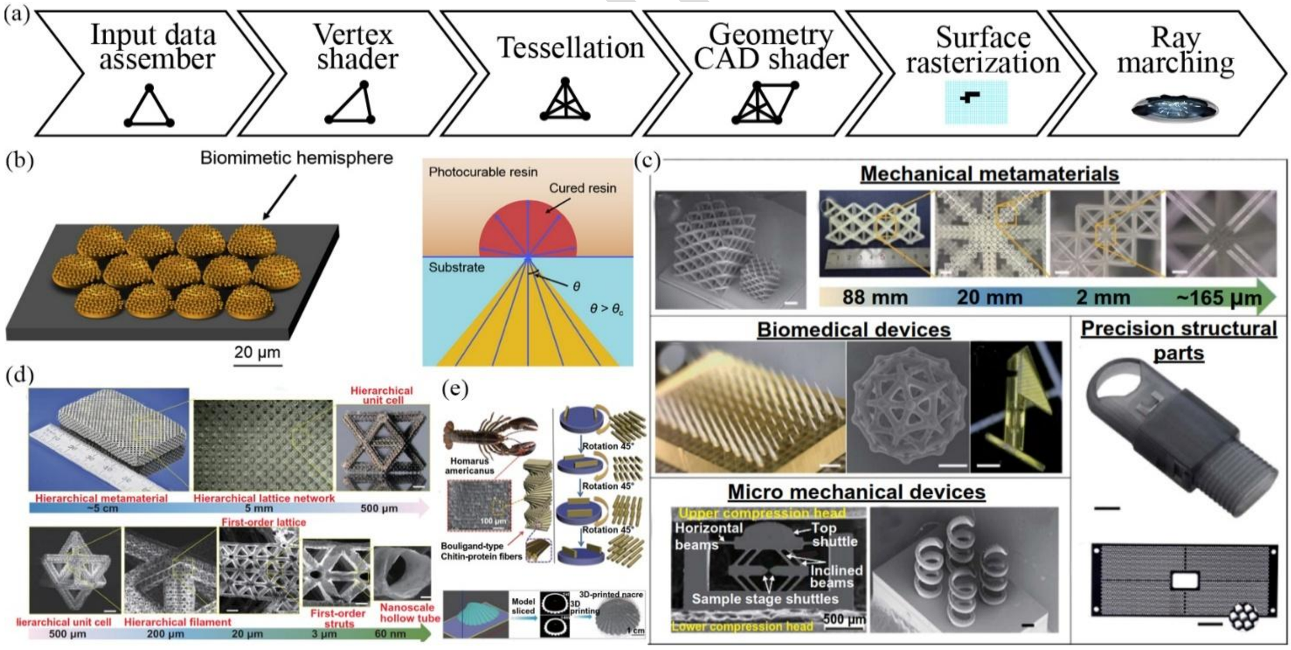

Fig. 5. (a) 3D Biomimetic modeling of a living system, (b) Schematic illustration of an enlarged mosquito eye. There are relief structures on them (a hemisphere manufacturing idea). The critical angle is θc while the incident angle is θ, [37] (c) application of mechanical waving metamaterials and bio-in-nature devices: The mechanical waving metamaterial in hierarchical manner and octet truss form, MMD for precision structural parts, microfiber connectors, Micro sockets and In-situ tensile testing about micro/nanowires (d) Multiscale metallic metamaterials; (e) 3D printing on with a hybrid bifractal x-z-t axis electrical assisting/3D printed-electrode to mimic biomimetic architecture of Bouligand type MWCNT-S: a nacre-inspired structures using graphene nanoplatelets(GNs) [38].

Most synthetic materials have invariable frictional behavior and can only be used wherever dynamics are not relevant. Friction is not necessarily isotropic, or the same in all directions. Typically, the magnitude and sign of the friction depend on your direction of motion. The contact surface of an object has "grooves", so the friction is not equal in all directions. The imitation of the anisotropic friction behavior of a snake's scales would enable the construction of robot actuators and conveyor belts or shoes that change their surfaces as a function of orientation [39]. Another significant challenge is to produce surfaces that can dynamically adapt their properties in response to external stimuli. The skin of a chameleon or a lotus leaf can change its texture, color, etc. in response to environmental change [40]. While the prospect of synthetic materials that can mimic this responsiveness is very exciting, engineering such materials will be a complex task [41]. Surface texture is a property of the material surface, defined by three factors: lay (topography), surface roughness, and waviness. Surface roughness plays a crucial role in friction, providing insight into how the layers slide relative to each other. Surface textures that can be processed are both isotropic and anisotropic. Many soft biological materials in nature have anisotropic and superior mechanical properties, which provide them with directionality-dependent properties and functions [42]. In contrast to the anisotropic, complex hierarchical structures and high mechanical performance of natural organisms, traditional hydrogels generally exhibit isotropic structure and weak properties. The surface interface of the nature-oriented structure exhibits a friction anisotropic phenomenon, and principles and inspiration are derived from this. In this regard, various fabrication techniques have been proposed for fabricating anisotropic structured hydrogels (Fig. 6). These preparation methods are primarily based on prefabrication or mechanical training [43], directional freeze casting [44], structural biology templates [45], and shear-induced 3D printing, among others.

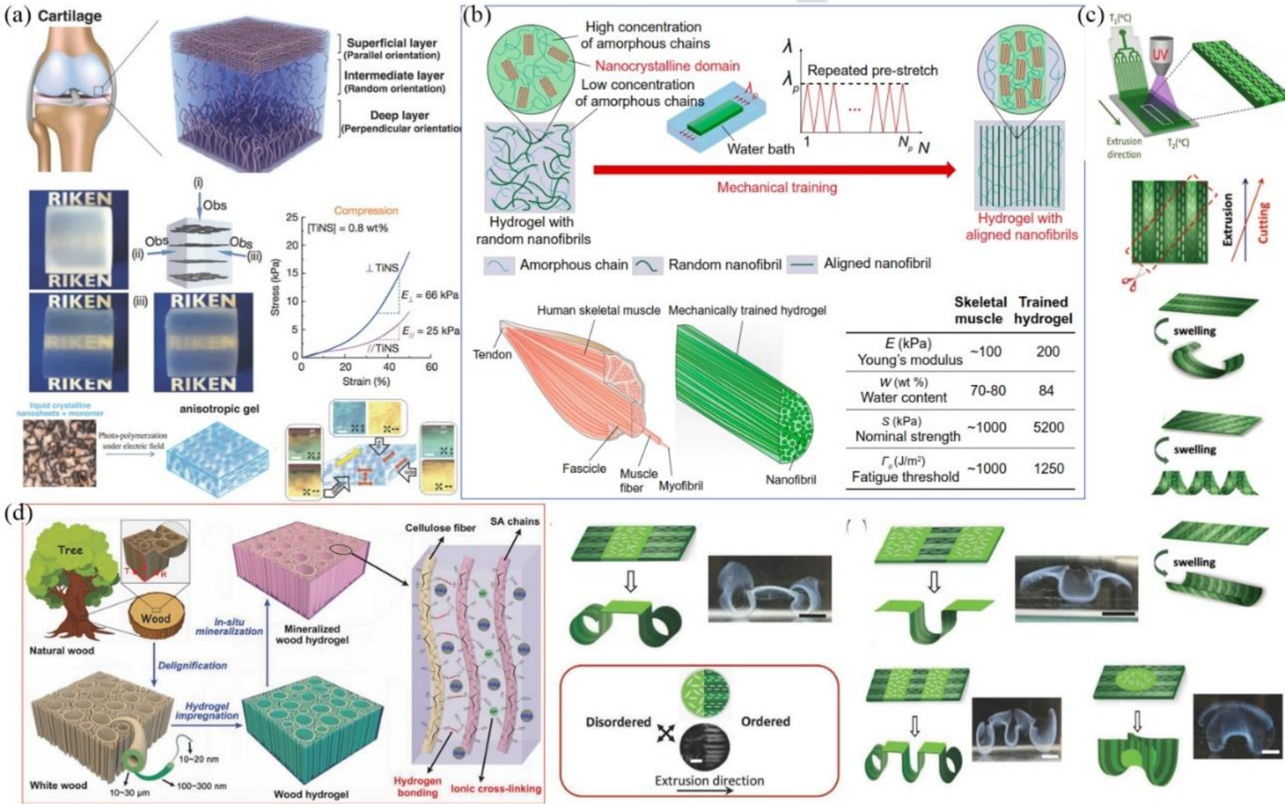

Fig. 6. (a) Schematic of the organ-like organized soft tissue structures within the human body, such as cartilage; Hydrogels with cofacially aligned TINSs display mechanical anisotropy, [42] (b) Fabrication of hydrogels with muscle-like texture. (d) A representative case of microstructure (PVA hydrogel with randomly distributed nanofibrils), mechanically trained MTHs, human skeletal muscle, and human skeletal muscle over the range considered for each combination, [43] (c) Schematic setup of a shear-mediated extrusion method implemented in a microfluidic printer to photopattern CNC/GelMA hydrogel sheet, ordered and disordered regions were actuated by swelling. Top: schematic representation of the interface between hydrogel regions (that is, left and right-hand side (ordered and disordered) hydrogel), [46] and (d) Schematic of mineralized wood hydrogels structure and fabrication [45].

Switchable hierarchy surfaces develop a surface with self-adapted frictional properties, stimulated by external forces, such as elastic forces, which is a key component of this grant. Fabrication of biomimicking surfaces has not only practical utility but also showcases the usefulness of biomimetic materials. The horizontal surface of a resin 3D-printed part is usually assumed to be very smooth, but it is significantly influenced by the microscopic interaction between the light source of a printer and photopolymerized resins. Imprinting of micropatterns of luminescent quantum dots using 3D-printed stamps exemplifies the utilizable relevance to control horizontal surface conditions [47]. Yan Lu et al. [48] presented a new method for fabricating biomimetically engineered surfaces/layers in a lotus leaf-like hierarchical microstructure (Fig. 7a). The structure-related surface hydrophobicity was investigated using contact angle measurements. Air lubrication leads to hydrophobicity and minimizes liquid/solid contact. The tribological test revealed that the biomimetic layered surface demonstrated significantly improved lubrication performance. The simulation results show that as hydrophobicity increases, friction resistance can decrease sharply because there is a higher proportion. Silicone products are quickly manufacturable, particularly for low-volume production, especially for customized medical devices. To enhance the elasticity of 3D-printed silicones, dynamic non-covalent interchain interactions between polymer chains were enhanced by introducing thiourea groups. Moreover, a molecular design principle was established by using "oligomeric" and "polymeric" PDMS units to control the proportion of thiourea segments. The resulting cured silicone elastomer shows a maximum elongation of up to 1000% during tensile testing and outstanding cyclic compression resistance. Silicon thiourea resin could potentially be applied to medical equipment, wearable devices, and soft robots [49]. In vivo, Liu et al. [50] demonstrated that, rather than deforming the predefined shape into a physical barrier, the aligned biomimetic periosteum can actively promote local angiogenesis and early osteogenesis. The desirable biomimetic periosteum is envisioned to envelop diverse bone interfaces and establish a superior microenvironment for bone regeneration, including local vascularisation, osteoblast recruitment, and mineralized extracellular matrix (ECM) formation (Fig. 7c). To recapitulate the function of natural periosteum in bone regrowth, 4D printing technology was used for the first time to incorporate aligned cell sheets into a deformable hydrogel, which presented biophysical cues and spatially controllable mechanics. The biomimetic periosteum can digitally organize its 3D geometry to conform to a specific macroscopic bone shape and retain the bone-healing microenvironment, thanks to an outer hydrogel layer. The hMSCs layer inside also facilitates the (co-)cultured cells to move and form tubes, and shows very good osteogenic induction ability.

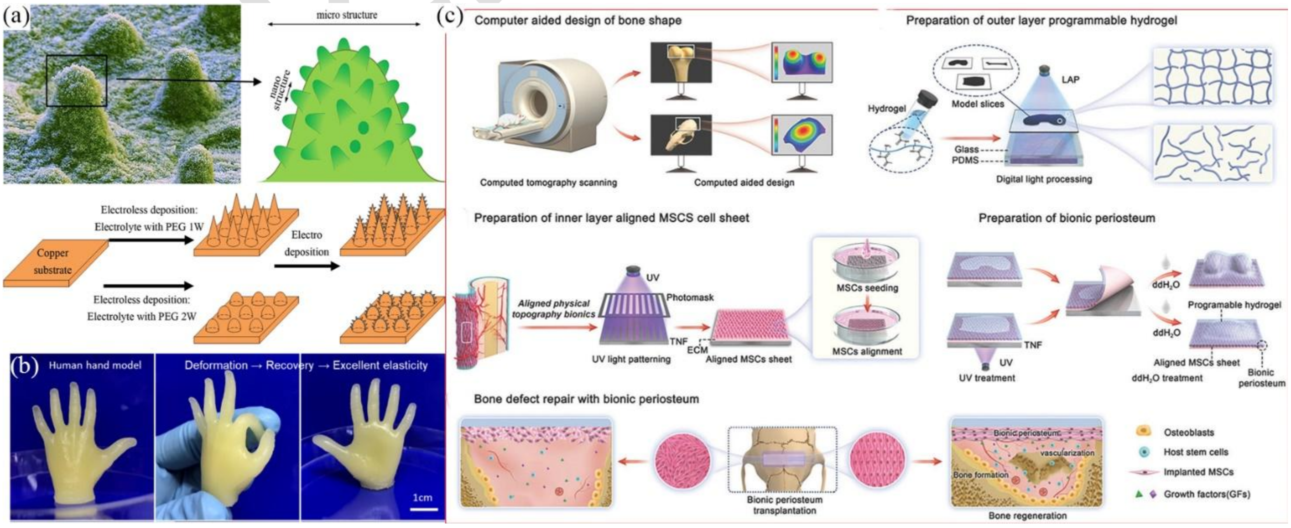

Fig. 7. (a) Lotus leaf layered dual scale micro-nano structure bionic surface; the fabrication scheme of a layered structured surface, [48] (b) 3D printed soft elastic materials with adjustable mechanical parts and extreme flexibility human hand model, [49] and (c) A schematic representation of the biomimetic periosteum for bone regeneration. Scan and pattern bone outlines before defect modeling, hydrogel programming, and seeding of hMSCs; UV delamination; cranial restoration [50].

4. 3D PRINTING AND MICROFABRICATION APPROACHES

3D printing (3DP) is a transformative industrial production technology that enables the creation of stronger and lighter parts directly from digital files. A conventional manufacturing process, which removes material from a piece of raw material (subtractive), 3DP adds material to form an object (additive). This has led to the industrial revolution in aerospace, automotive, healthcare, and manufacturing sectors [51]. 3DP can be traced back to the 1980s. The seeds of modern AM were sown in 1981 when Dr Hideo Kodama developed a rapid prototyping method based on light-sensitive photopolymers. The father of 3D printing, Chuck Hull, patented stereolithography (SLA) in 1986 and formed the company 3D Systems Corporation [52]. Carl Deckard and Joe Beaman invented the selective laser sintering (SLS) process, with Scott Crump of Stratasys having developed fused deposition modeling (FDM) [53]. The new developments broadened the spectrum of materials and areas of application. In the 2000s, AM was opened up to a broader audience, thanks to the prominence of Adrian Bowyer's RepRap project (2005), which highlighted the availability of self-replicating printers [54]. The 2010s brought a wave of consumer printers, fueled by companies like MakerBot, and industrial systems that grew in size, precision, and diversity of materials [55]. The evolution of manufacturing can be classified into three periods: subtractive processing (carving, cutting), identical material processing (cast molding), and additive processing, which includes CAD, CNC, molding, and the like [56]. Under the guidance of "four modernizations", that is, innovation, automation operations, digitization, and intelligence, AM breaks through traditional technique approaches in terms of precision and flexibility [57]. Stereolithography (SLA) is one of the key AM technologies, which is recognized for its high accuracy and excellent surface quality, rendering it indispensable in dentistry, jewelry, and medical modeling. SLA is also slower and more expensive than other methods, such as FDM, which might not be suitable for making many things [58]. Nevertheless, SLA remains important for highly detailed prototypes and complex structures [59]. Personalized SLA also applies a UV laser, allowing for high-detail structures, but requires supporting structures to be highly [60]. Another technique, called Digital Light Processing (DLP) (Fig. 8), utilizes a projector to cure layers of material simultaneously, allowing for a higher build rate by using smaller build sizes [61].

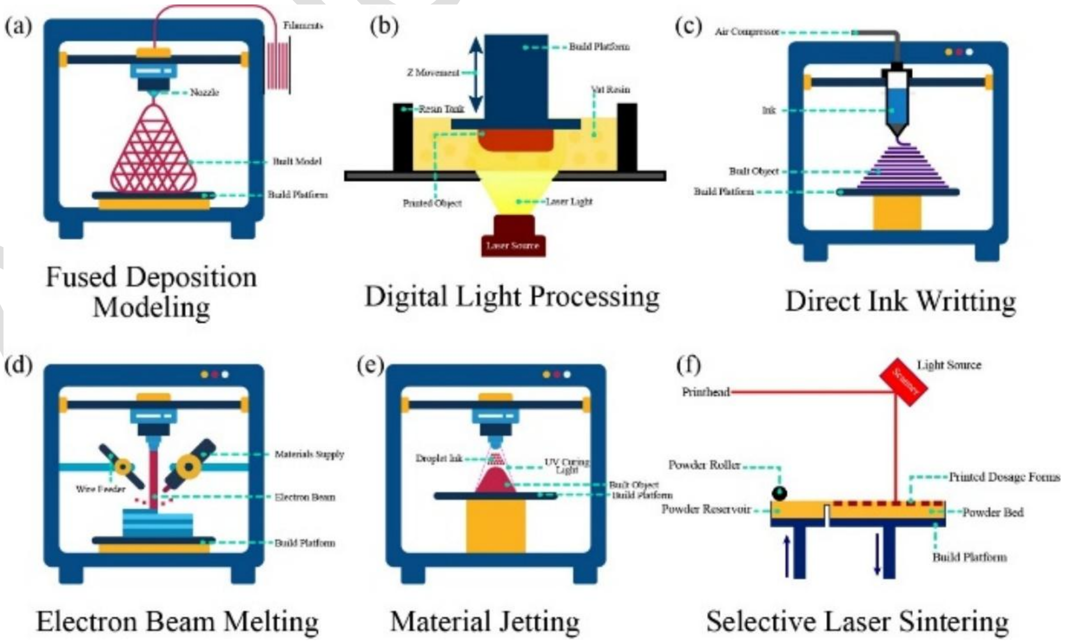

Fig. 8. The Schematic illustrations representing a few major categories of Additive Manufacturing with nanomaterials: (a) Fused Deposition Modeling (FDM), (b) Digital Light Processing, (c) Direct Ink Writing, (d) Electron Beam Melting, (e) Material Jetting, and (f) Selective Laser Sintering [71].

The CLIP (Continuous Liquid Interface Production) gives very high speed and good mechanical properties, but requires proprietary resins, which are expensive [62]. Micro SLA (MSLA) utilizes an LCD-based system for layer exposure, compromising between speed and resolution; however, the weakness of the LCD film aging can be a problem [63]. Laser-scanning SLA (LSLA) with multibeam lasers enables large builds but is overwhelmingly industrial [64]. Nanoimprint lithography (NIL) is a prompt, efficient, and cost-effective method for replicating nanoscale patterns [65]. In addition to SLA, other resin-based and powder-bed processes extend 3D printing: high-strength nylon parts printed using Selective Laser Sintering (SLS) [66], multi-material prints from PolyJet/Multi-Jet Printing (MJP) [67], lightweight titanium implants via Electron Beam Melting (EBM) [68], and precise metal components printed by Direct Metal Laser Sintering (DMLS) [69]. As development continues, SLA and other similar technologies are catalysts for progress in dentistry, jewelry, automotive, aerospace, and medical, among others [70].

5. ANISOTROPIC FRICTION IN BIOMIMETIC INTERFACES

DLP stereolithography as a prospective 3D printing method. The printing process itself is frequently multilayer, introducing an aliasing artifact in the surface. Luongo et al. [72] embed laws to achieve controlled anisotropic surface appearances. Stereolithography sub-voxel growth control for 3D printing with a controllable surface appearance. With two-photon polymerization (TPP) microfabrication techniques, it is possible to fabricate micro-nano structures of various shapes and dimensions with very high precision (Fig. 9a). The developed NM can be broadly employed in microfluidics, tissue engineering, drug injection, and micro-nano photonics. Along with the extensive use of 3D microstructures in the biomedical area, attention has been more focused on the physicochemical properties of respective materials, including biocompatibility, biodegradability, responsiveness to stimuli, and immunogenicity. Table 1 provides a qualitative comparison of anisotropy levels and frictional behavior across common bioinspired surface motifs. In this sense, bio-microstructures using biocompatible synthetic polymers, polysaccharides, proteins, and their complexes have been widely studied. Wang et al. [73] briefly describe the TPP process as well as the photoinitiators used in TPP microfabrication, biomaterial-based photoresist, and their respective resulting microstructures as described herein, along with subsequent biomedical applications. Yanagawa et al. [74] described these hydrogel microfabrication techniques for such in vitro reconstruction and culture. Biologically relevant three-dimensional (3D) tissue constructs are crucial for the development of alternatives to organ transplantation in regenerative medicine and drug screening applications. The advancements in hydrogel microfabrication technology, including micromolding, 3D bioprinting, photolithography, and stereolithography techniques, have also resulted in the fabrication of 3D tissue constructs possessing specific 3D microstructured biological functions (Fig. 9c). Microfluidic technology has made it possible to create 3D tissue cultures with vascular networks, thereby enabling perfused cultures. The design and construction of some organisms, including the lobster claw, honeycomb structures, nacre, balsa wood, and others (Figs. 9d-e) [75,76].

Table 1. Qualitative comparison of anisotropy in bioinspired surface motifs.

Surface motif	Typical anisotropy level	Mechanism	Load sensitivity	Wet sensitivity
Tilted pillars	Medium-High	Directional bending	Moderate	Moderate
Scale-like ridges	Medium	Asymmetric geometry	High	Low–Moderate
Microhooks	High	Mechanical interlocking	High	Low
Suction-cup arrays	Direction-dependent adhesion	Capillary + vacuum	Moderate	High
Hierarchical textures	Medium-High	Multi-scale contact	Moderate	Moderate

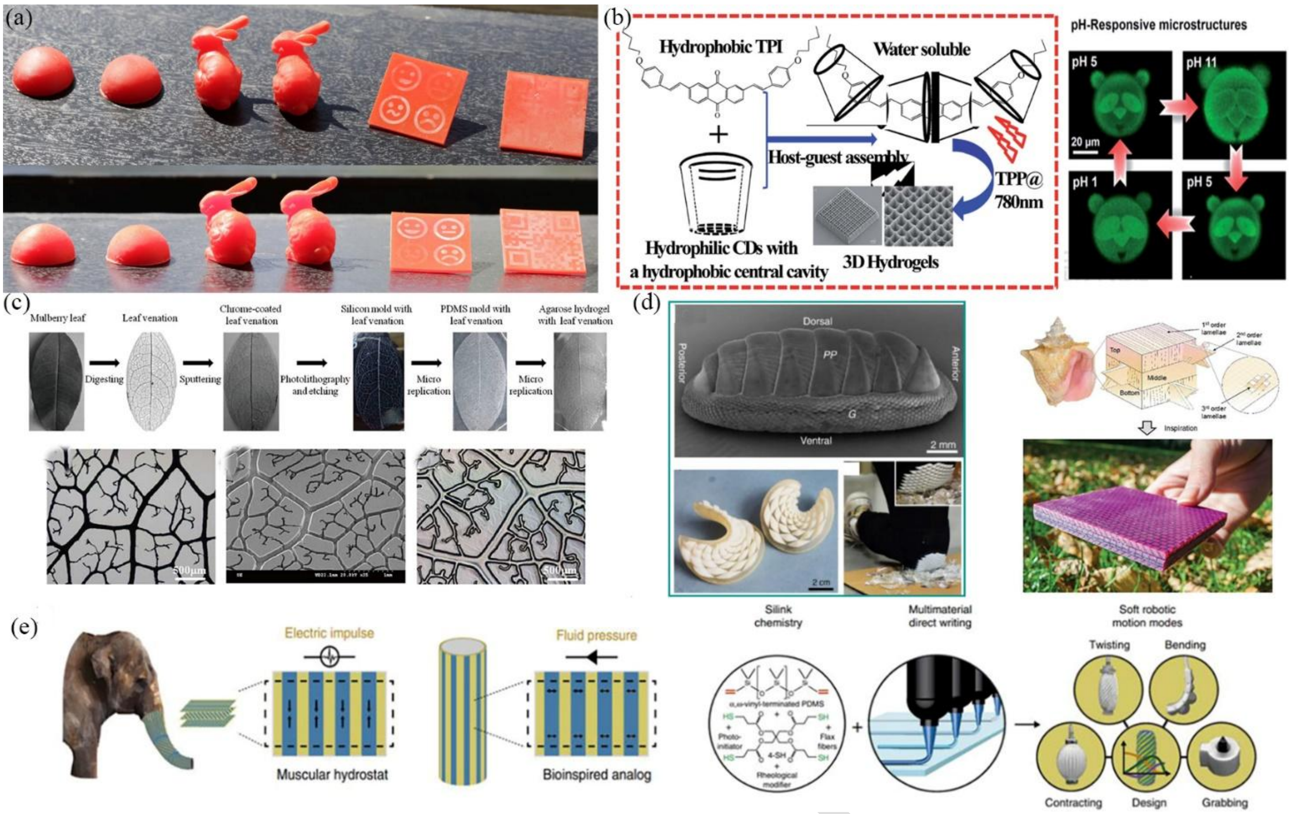

Fig. 9. (a) Control of microstructure in DLP printing. Flat samples with spatially varying anisotropic reflectance (hemispheres and bunnies) with flat sea (turtles), rough swan face, printability scale samples, (b) Hydrophobic TPI/ hydrophilic CDs interactions to18 result in the water-soluble TPI phase and to enable pH responsive panda face micropatterns 3D hydrogel constructs [46], (c) control over howells-daisy morphology pixel having contact angle characters onto a spinner for control on morphology feature scales Hz-azimuthal rotation stage of an agarose gel micro-mold using leaves, [74] (d) Bioinspired reinforced structures, in both printing and as flexible armor out of stiff polymers that are chiton scale inspired, A 3-tiered calcium carbonate structure utilizing cross-lamellae, inspired by the conch shell, has been fabricated through 3D printing, alongside soft actuators modeled after the elephant trunk, employing biomimicry techniques [75].

6. FUNCTIONAL SURFACE DESIGN STRATEGIES

Multifunctional interfaces with adjustable friction, wettability, and adhesion are made possible by combining bioinspired surface engineering with additive manufacturing. Engineers and designers have utilized 3D printing to create biomimetic surfaces and interfaces, which have great potential for replicating the sustainability and efficiency found in nature [77]. In aerospace, biomimetic surfaces that mimic the aerodynamics of bird wings minimize drag and save fuel. Biomimetic interfaces enhance the comfort and functionality of medical systems, including implants and prostheses [78,79]. 3D printing of biomimetic surfaces and interfaces is a good example of how human ingenuity can indeed live in harmony with the wisdom of nature [80]. This new space has the opportunity to fundamentally change industries by introducing ideas and materials that harness nature's millennia-old ingenuity, along with greater efficiency. Such a hierarchy of the gecko's adhesive system is shown in Fig. 10a, an eye view to the ventral side of a gecko, mesoscale sensors with setae, a cryo-SEM picture for one single seta of the gecko's footpad, and a microscale array of setae, and even on the nanoscale, orders and outstates where hundreds of spatulae contact [81]. A tree frog, Rhacophorus dennysi, and a polypedates climb up a wet, smooth glass surface to reach the top pad, which has hexagonal micropillar epithelial cells. Cross-sections of the toe pad and the hierarchical concave pillar surface are shown in Fig. 10b. Nanopillars are densely packed into each micropillar [82]. Development of miniature biocompatible octopus-like hydrogel adhesive (OHA) robot with controllable wet adhesion; fabrication of the OHA robot; simulation of the adhesion process in sucker structure with/without inner protuberance structure; enhanced-adhesive OHA that can adhere under an attached state at a low temperature; repeated bonding for inner pNIPAM and outer PEGDA octopus samples [83]. The constituents of hydrogel ink, as well as the process for DLP 3D printing, images and models showing the 3D printed programmable array suckers, and an evaluation of adhesion performance of three types of hydrogel suckers (Figs. 10c-d) [84].

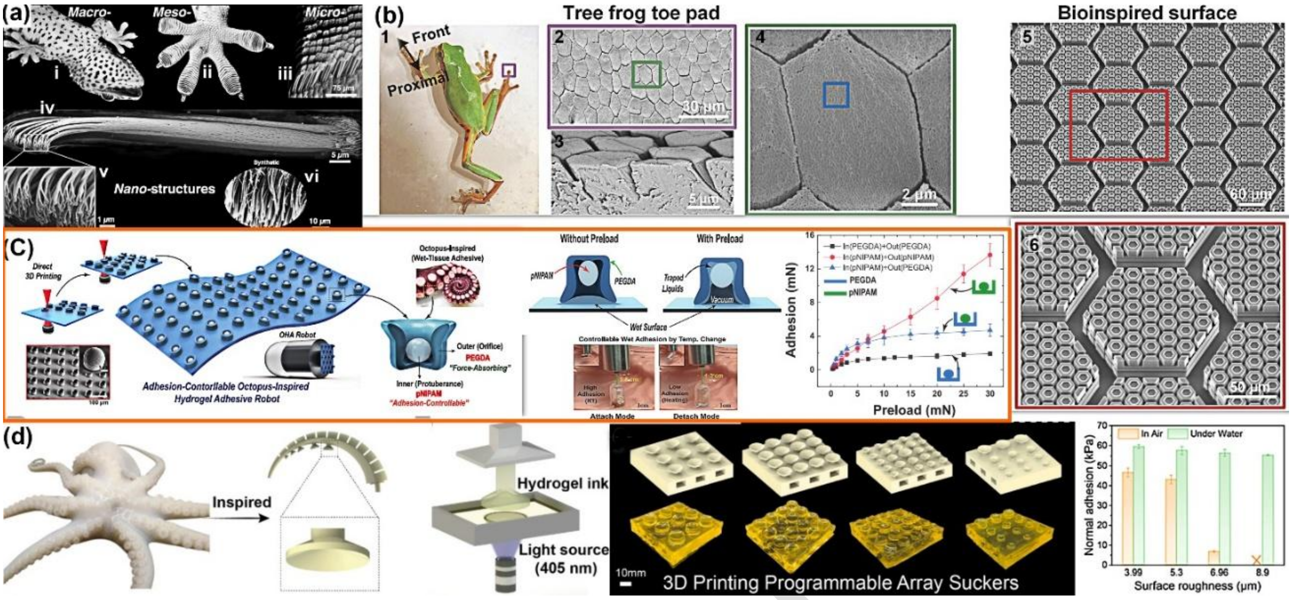

Fig. 10. (a) The hierarchical distribution mechanism of the gecko-inspired adhesive system [81], for example, (a) Seta-bearing sensors and microscale setae arrays on which nano molded polyimide spatulas are mounted; (b) tree frog climbing on glass, hexagonal micropillar epithelial cell, bioinspired concave pillar skin, and dense nanopillar array; (c) Small-scale octopus-inspired OHA robot with controlling tissue adhesion with schematic representation, [83] (d) Illustration and schematic hydrogel octopus suckers and grippers in use, composition of the hydrogel ink, DLP 3D printing of printed suckers [84].

Anisotropic friction is a long-standing problem in engineering and design. It occurs when the resistance to movement changes with direction. Recent improvements in three-dimensional (3D) printing technology, on the other hand, allow for the design and AM of surfaces with custom anisotropic friction properties. This could change many industries. It has been hard and limited to make surfaces with only anisotropic friction properties in the past [85]. Regardless of the direction, objects often exhibit constant friction properties (Fig. 11). Surfaces with anisotropic friction could exhibit different friction coefficients in moving directions. This characteristic emulates the behavior of natural surfaces in interaction with their environment, for example, the hair coat of animals and the leaves of plants [86].

Three-dimensionally printed anisotropic surfaces possess applications in robotics. Surfaces can be applied to robot grippers and feet, effectively increasing traction in specific directions and helping them move more precisely and deliberately. This is particularly useful for working with delicate objects or when walking over rough terrain. Applications of 3D printed anisotropic surfaces include biomechanical/sports equipment, such as footwear, which provides stability and grip [89]. Mishra et al. [90] demonstrate that these 3D-printed anisotropic surfaces can be applied to aircraft and automotive components. Surfaces can be used to increase tire traction in a variety of road conditions or to enhance an aircraft's control and stability in flight, thereby increasing its efficiency and safety. 3D printed anisotropic friction surfaces are an impressive feat of engineering. The tailored friction properties of these surfaces could enable this extraordinary surface to impact several industries, ranging from manufacturing to wearable technology and robotics. Biomimetic syntheses offer a potential framework for the synthesis of biological nanomaterials by emulating their natural structure, properties, and functions. The marine antifouling and antibacterial application of the bionic antifouling interface can be further extended. These techniques and approaches alter the morphology and chemical composition of BM interfaces to enhance wettability, adsorption, and drag reduction, among other properties [91].

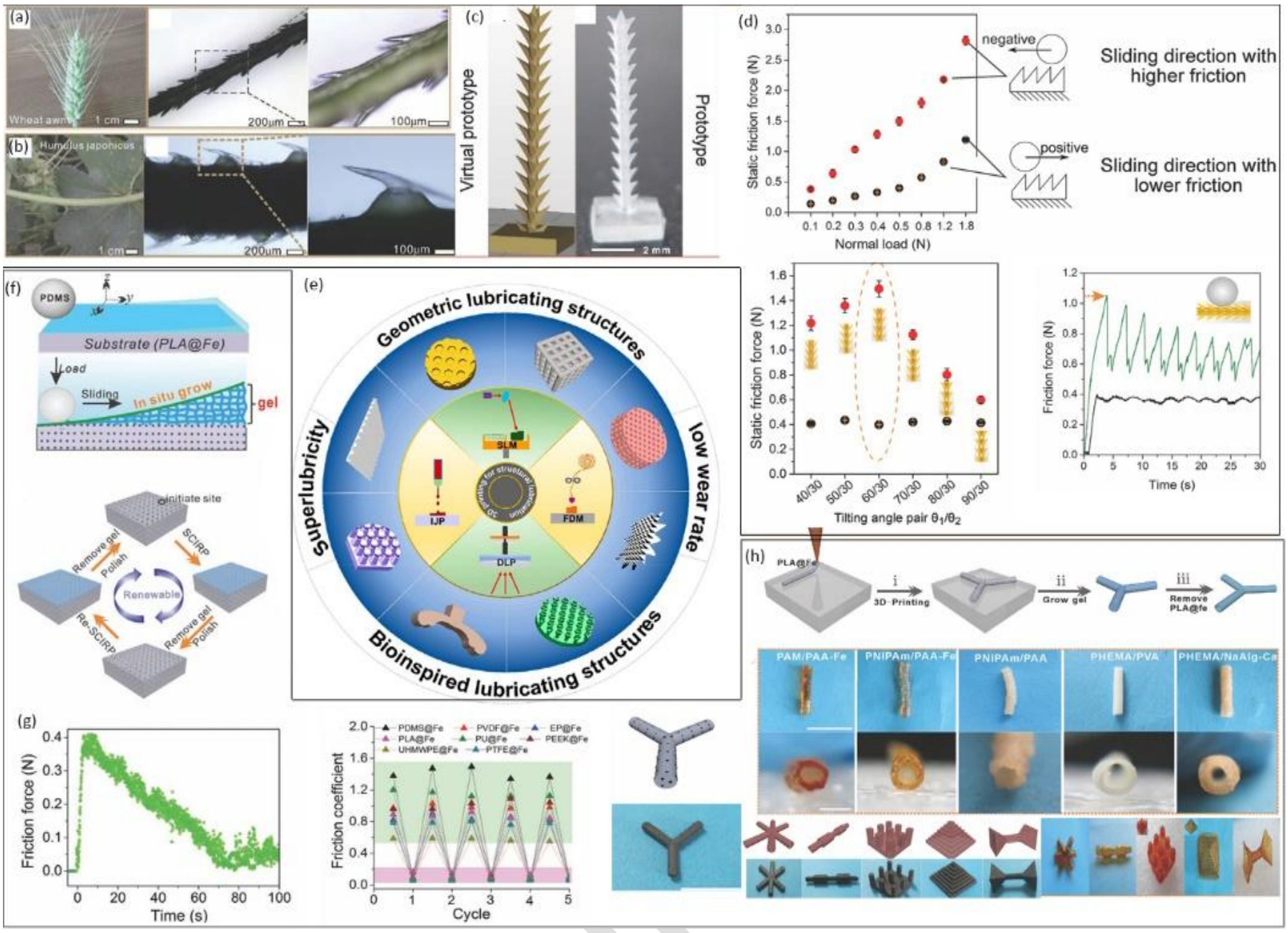

Fig. 11. SEM image of the (a) illustration wheat awn, (b) Humulus japonicus stem, (c) shows features a bioinspired surface virtual prototype and ProPhoto, and (d) analyses frictional properties of biomimetic printed anisotropic surfaces [85], (e) Diagram to different 3D printing methods for geometric and bioinspired lubrication structures [86], (f) Schematic diagrams show real-time friction experiments on the renewable surface polymerization process of versatile substrates [87], and (g-h)) Friction coefficient on iron-based surfaces switches reversibly between low and high friction upon alternating hydrogel pulp removal [88].

Mimetic mushrooms, or refoldable micro-mushroom structures, have generated considerable interest among researchers due to their exceptional water-repellent properties. Liu et al. [92] developed a 3D-printed biomimetic superhydrophobic surface featuring petal-like microstructures, inspired by the droplet-pinning phenomenon observed in pitcher plant lips (Fig. 12). The values of petal number, petal proportion, and spacing were further investigated and optimized to enhance the water resistance as well as droplet carrying capacity. The number of petals is 4, the spacing is equal to 100 µm, the petal ratio is 50%, and in such a case, the microtexture exhibits maximum droplet-carrying ability. In contrast with the common mushroom-shaped microstructure, the optimal petal-type microstructure can increase maximum bearing capacity by 58.3%. The corresponding mechanism analysis indicates that this super-repellent performance is due to the cameo effect and the arching curve effect. Furthermore, its hydrophobicity makes the surface applicable in water droplet manipulation, oil/water separation, and air admittance for drag reduction. Friction between the tongue surface and the oral contact wall is fundamental in the orchestration of food transport [93]. Andablo-Reyes et al. [94] created a realistic 3D biomimetic soft surface with topography and wettability similar to those of the human tongue. The papillary distribution (random) is represented by 3D-printed fabrication according to the Poisson point method, and then the soft silicone surface with wettability variations is micro-molded. They demonstrate the superior capability of these surfaces to mimic analytically defined and simulated nipple impact probabilities and closely replicate the tribological effect of human masks. These from-scratch biomimetic surfaces enable a detailed study of the mechanics of interaction within the oral mucosa. 3D printing evolves into 4D printing, allowing objects to take a particular form, then 'remember' themselves for transformation. The authors investigate the regulation of magnetic fields and the application of magnetically active soft materials (MASM) for 3D-printed soft sensors and actuators using magnets. Using 3D MP, two anisotropic composite materials (ACMs) are made. These materials include reinforcements with magnets.

Resolution manipulation and scalability have remained challenging in the production of structural color materials. Bi et al. [95] developed a simple method of printing cholesteric liquid crystal elastomers (CLCE) in complex structural color patterns with tunable resolution and superior scalability. The synthesized CLC oligomers were added to volatile solvents to alter their rheological properties so that DIW of the inks was performed under ambient conditions. The multi-responsive bionic butterflies and flowers with bionic prints in the image, movement, and color. This design greatly reduces the processing difficulty of accurate full-color printing and broadens the cooperation space of structural color materials with other systems. With the continued exploration of functional surfaces with biomimetic properties and their microstructure, the macroscopic function study of more biomimic interfaces will be investigated.

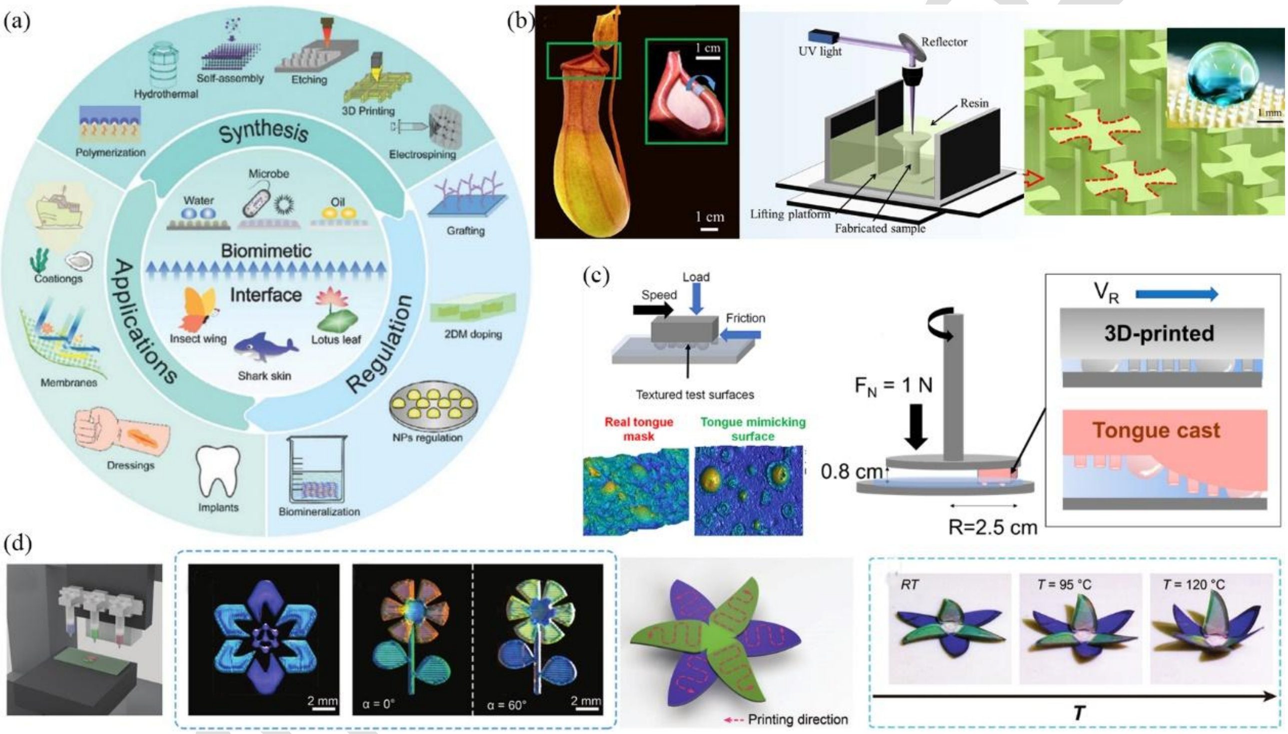

Fig. 12. (a) An illustration of the biomimetic interface preparation and modulation for the development of marine antifouling coatings, antifouling films, and biomedical antifouling materials, [91] (b) Petal-shaped biomimetic microstructures using 3D printing. Photograph of Nepenthes exhibiting lip-directed water diffusion behavior, schematic diagram of the PμSL 3D printing system, petal-shaped model with sharp curved edges in microstructure form [92], (c) 3d bionic tongue simulation surface for tribology application; an illustration of the setup including a polymer surface printed tongue using a rotational rheometer and a hydrophobic silicone lubricated by allowing it to slide along spiked model, [94] and (d) Schematic representation of multi-ink printing mode. Two-color logo and three-color flowers printed at various angles of incidence, and a schematic illustration of the printing trajectory for bionic flowers [95].

7. APPLICATIONS OF 3D PRINTED BIOMIMETIC INTERFACES

3D printing enables the creation of custom interfaces for biomedical devices and prosthetics that match the unique properties of human tissue, making them more comfortable and functional. Biomimetic surfaces make wearable electronics and devices that attach to the skin more flexible and adaptable. Furthermore, in assistive devices and safety surfaces (such as anti-slip structures resembling cat paws), 3D-printed biomimetic interfaces enhance grip and user safety [96].

7.1 Robotics and soft actuators

3D-printed biomimetic interfaces use micro- and nanoscale structures to create directional anisotropic friction and controllable adhesion. Wang et al. [97] examined columns and scaly surfaces inspired by straw, snake scales, or lizard toes that produce high friction in one direction while markedly reducing friction in the opposite direction, facilitating passive or active locomotion, including crawling, propulsion, and grasping. In the field of soft robotics, 3D multi-material printing combined with functional materials (such as liquid crystal elastomers, magnetically responsive materials, or shape memory polymers) enables the direct integration of biomimetic surface structures into pneumatic or solid-state actuators, generating programmable walking, grasping, and deformation behaviors [98]. Liu et al. [99] discussed how biomimetic interfaces with adjustable friction and adhesion have been used to make robotic grippers more stable, create reversible adhesion-based wall-climbing systems, and enable micromanipulation and transport devices to move in one direction and propel themselves.

7.2 Biomedical devices and prosthetics

Biomimetic designs are being made based on natural human cartilage, which has an ordered orientation, a multi-layered gradient, and a structure that combines cartilage and bone. Inspired by the structure of natural human cartilage, the team employed magnetic induction, freeze-thaw, and annealing techniques to construct an anisotropic hydrogel biomimetic cartilage material that combines high strength with low friction. The hydrogel bionic cartilage material shows an anisotropic microstructure and exhibits excellent mechanical properties, with a tensile strength of 10.65 MPa, a toughness of 52.2 MJ/m3, and a compressive strength of 4.86 MPa, which are higher than those of other isotropic hydrogels and most reported hydrogel materials [100]. Based on the hierarchical structure of natural human articular cartilage and the integrated structure of natural articular cartilage/bone, multilayer bionic cartilage materials were prepared using PVA/HA composite hydrogel and PVA/HA/PAA composite hydrogel. This bionic soft/hard integrated material exhibits a hierarchical structure and excellent properties of high strength and low friction, successfully simulating the hierarchical structure and providing new ideas for the bionic design and manufacture of soft/hard integrated artificial joints [101]. Using antimicrobial chitosan (CS) and gelatin (GT) as bio-inks, they used 3D printing technology to create a CS-GT hydrogel coating with a porous reticular structure on a titanium alloy substrate. The 3D-printed CS-GT antimicrobial hydrogel coating possesses a dual-scale porous network structure, excellent hydrophilicity, and biocompatibility, providing an ideal microenvironment for cell adhesion and bone growth, promoting rapid fixation between the bone interface and the artificial joint prosthesis [102].

7.3 Wearable electronics and skin-adhesive patches

3D-printed biomimetic interfaces achieve anisotropic friction through the use of controllable micro/nanostructures, offering a new design path for wearable electronics and skin-adhesive patches. The fracture friction can be significantly varied in different sliding directions, thereby achieving a two-state contact characteristic of "easy attachment/easy release". ensuring stability during movement and quick removal when needed [103]. In wearable electronics, 3D printing can integrate flexible conductive materials with biomimetic microstructures to create a skin-electronics interface that is both conductive and mechanically interlocked. This allows sensors, soft actuators, and energy harvesting units to maintain good contact and signal transmission under complex bending strains. Hybrid 3D-printed microsuction cup/micropillar structures are used in breathable wearable patches [104]. From a production standpoint, multi-material 3D printing allows for the fine control of geometry, stiffness gradients, and electrode alignment by integrating conductive inks, elastomeric substrates, and bioinspired microtextures in a single fabrication step. These mechanistic factors establish a clear connection between microstructural design and user comfort, durability, and sensor accuracy [105].

7.4 Renewable energy sector

Biomimetic surface architectures affect energy harvesting system performance through contact electrification, wettability modification, and interfacial charge transfer. Biomimetic interfaces produced via AM are handy for businesses in the renewable energy sector. Self-cleaning solar panels can perform much better at converting sunlight into electricity and cost less to maintain if they have AM wettability-controlled surfaces. Biomimetic interfaces produced by AM can be used in seawater desalination and wastewater treatment to produce cleaner water and recover more of it. AM biomimetic electrode materials can help make solar photovoltaic power generation more cost-effective by improving battery performance in converting solar energy into electricity. AM technology can precisely control the composition and microstructure of battery electrode materials. Biomimetic catalysts produced via AM can make reactions more selective and efficient while reducing costs in chemical synthesis and environmental protection. A micro-nano-sized hydrophobic structure, which can be used for self-cleaning, is a superhydrophobic surface that can adsorb water droplets. The structure has multiple unique eggbeater-shaped microstructures. The tip of the eggbeater has a hydrophilic structure, and its surface is covered with nano-shaped superhydrophobic structures. In this way, the air can remain inside the eggbeater shape for a long time, so that the surface of the leaf can be isolated from the water, and the droplets maintain a stable spherical state on the leaf surface [106].

7.5 Others

Friction, wear, fatigue, and energy dissipation are key issues in aerospace, automotive, and energy equipment. Wang et al. [107] reported that 3D-printed biomimetic structural ceramics were used to prepare multi-scale biomimetic Al_2O_3 ceramics. Combined with a MoS_2 solid lubricant film, the friction coefficient and wear scar depth were significantly reduced under both dry and lubricated conditions (the friction coefficient decreased by approximately 20-45% under dry conditions). Xiao et al. [108] designed a 3D-printed sole inspired by cat paw pads and a triply periodic minimal surface (TPMS) structure. This sole, filled with a shear-thickening fluid (STF), targets impact attenuation and can reduce the maximum vertical ground reaction force by approximately 15.5% in a parachuting landing simulation. Friction at biomimetic anisotropic interfaces is typically generated by a combination of mechanisms, including adhesion, deformation/plowing, mechanical interlocking, capillary/adsorption, and electrostatic or triboelectric effects in some devices. The dominant mechanisms differ across application scenarios. To facilitate understanding of their functional origins, Table 2 summarizes the main frictional contribution mechanisms.

Table 2. Common friction contribution mechanisms and their physical sources in biomimetic interfaces.

Friction contribution type	**Physical essence**	**Mechanism of action**	**Applications**	**Influencing Parameters**
Adhesive action [20]	van der Waals forces and interfacial chemical bonding	Increase the actual contact area and enhance the interfacial bonding force	Skin-adhesive sensors, dry flexible interfaces	Surface energy, material modulus, contact area
Deformation/Plowing action [32]	Microstructure elastic or plastic deformation	Energy dissipation and increased interfacial resistance	Soft elastomer texture, buffer structure	Elastic modulus, load, structural height
Mechanical interlock [105]	Geometric directional structural interlocking	Directional drag and anisotropic friction	Inclined micropillars, microhook structures, biomimetic scales	Structural angles, spacing, and load direction
Capillary/Adsorption [91]	Hydraulic bridge force or local negative pressure	Enhanced wet adhesion	Octopus sucker-like structure, wet skin interface	Humidity, liquid viscosity, cavity geometry
Electrostatic/triboelectric effect [106]	Contact electrification and charge separation	Charge generation and potential difference formation	Triboelectric nanogenerators, energy harvesting devices	Dielectric constant, contact area, separation rate

8. CHALLENGES AND FUTURE PERSPECTIVES

The task for materials science of the present time is to fabricate materials that are robust, durable, while at the same time flexible and environmentally friendly. A grand challenge in science and engineering is the synthesis of such complex biological systems with synthetic materials, which will depend on our understanding of structures in biology and our ability to mimic these structures at micro- and nanometer scales [109]. Despite recent improvements, methods such as micro-stereolithography are still far from imitating the complex microstructures and geometries of many biological materials [110]. There is a significant challenge of taking biomimetic materials out of the lab and using them in practical contexts. While such materials might be probed theoretically and in the lab to extract potentially attractive behavior, one should keep potential applications (such as the design of cat-paw-inspired assistive surfaces) in mind and considerations on costs, production scale, and durability [111]. Shin et al. [112] created a stretchable wearable electronic patch that adheres to the CPC film and features micropatterns resembling octopus suction cups. Inspired by the attachment mechanism of octopus suckers, a great deal of attention has been focused on designing skin/organ adhesive patches that offer reversible high adhesion forces to dry and wet surfaces. Hierarchical nano to microstructures occur in many natural systems that can function extremely well. It is challenging to fabricate soft hydrogels that can mimic biological tissues, even mechanical robustness and long-term stability against water/ physiological conditions are always a concern. The solution to such material constraints is essential for the design of biomimetic surfaces with global performance comparable to that of their biological counterparts [113]. Another problem is with scaling and cost. High-resolution techniques such as micro-stereolithography or TPP are still time- and energy-consuming, limiting their widespread application. Industrial translation must also be combined with scalable manufacturing techniques, such as roll-to-roll nanoimprinting or hybrid 3D printing-laser processing [114]. Durability and environmental compatibility also pose serious challenges. While high-resolution AM technologies (such as micro-stereolithography and two-photon polymerization) demonstrate superior precision in constructing biomimetic microstructures, limitations in build volume, low manufacturing rates, high energy consumption, and a finite range of materials restrict large-scale production and industrialization. Extrusion and DLP are highly efficient but have limited precision; wearable devices require stability and moisture resistance, energy devices require dielectrics and energy storage, and bio-devices require compatibility and sterilization. Therefore, future research needs to strike a balance between resolution, material diversity, manufacturing efficiency, and device reliability and explore hybrid manufacturing and continuous processes to promote the sustainable industrial deployment of biomimetic interface technologies [115]. Fabricating bioinspired composites with soft-hard domains could be a solution to enhance long-term reliability [116]. 4D printing, in which materials change shape on demand in response to stimuli, provides a path to programmable biomimetic systems [117]. Responsive and stimuli-induced surfaces can now switch adhesion, wettability, or friction by leveraging, e.g., nanocomposites and stimuli-responsive polymeric materials [118]. In addition, incorporating sustainability into biomimetic materials via biodegradable polymers and low-energy fabrication routes aligns it with global ecological challenges [119].

9. CONCLUSION

Biology-inspired principles investigated through advanced manufacturing have created revolutionary opportunities for materials science and engineering. However, the latest developments in 3D-printed biomimetic interfaces suggest that, rather than mere geometric imitation, AM is already a mature platform for replicating the functionalities, hierarchical organization, and adaptive features of natural systems. Techniques such as micro-stereolithography, projection micro-lithography, and direct ink writing enable the fabrication of intricate micro- and nano-architectures that mimic the adhesion structures of gecko setae, snake scales, lotus leaves, or cat paw pads. These biomimetic structures exhibit superior mechanical, tribological, and adaptive properties, including adjustable adhesion and drag reduction for switchable self-cleaning, and a common thread in these new developments has been the importance of anisotropic friction and design/surface engineering. Such a directional phenomenon in friction, as already demonstrated for gecko adhesion, snake locomotion, and fish-scale hydrodynamics, was then successfully extended to engineered materials. Enabling anisotropic friction in artificial materials facilitates controlled motion, energy conservation, and adaptable grasping in robotic, healthcare, and wearable technologies. Simultaneously, functional surface engineering with hierarchical structuring, soft–complex integration, and stimulus responsiveness has enabled multifunctionality in artificial interfaces. These findings indicate that beneficial biomimetic design involves not only structural mimicry but also dynamic and environment-responsive functionality. The promising biomimetic materials and technologies align biological inspiration with industry use. Light-responsive hydrogels, light-tunable anisotropic surfaces, and soft–complex hybrid composites will take intelligent interfaces to the next level in soft robotics, prosthetics, biomedical patches, energy harvesting, and aerospace. When paired with the accuracy and flexibility of 3D printing, these nature-inspired systems are expected to provide very sustainable, adaptable, and multifunctional materials that are just as efficient, if not more so, than those developed over millions of years of evolution. Biomimetic interfaces are an example of how nature's strategies can directly inspire engineering solutions, influencing future tribology and surface science research, as well as innovation in robotics, medicine, and next-generation adaptive systems.

Acknowledgement

This research was supported by relevant institutions and projects, and we would like to express our sincere gratitude.

REFERENCES

[1] X. Le, W. Lu, J. Zhang, and T. Chen, "Recent progress in biomimetic anisotropic hydrogel actuators," Advanced Science, vol. 6, no. 5, p. 1801584, Mar. 2019. doi:10.1002/advs.201801584.

[2] Y. A. Meier, K. Zhang, N. D. Spencer, and R. Simic, "Linking friction and surface properties of hydrogels molded against materials of different surface energies," Langmuir, vol. 35, no. 48, pp. 15805-15812, Dec. 2019. doi:10.1021/acs.langmuir.9b01636.

[3] S. Ma et al., "Bioinspired 3D printed locomotion devices based on anisotropic friction," Small, vol. 15, no. 1, p. 1802931, Jan. 2019. doi:10.1002/smll.201802931.

[4] H. He, P. Zhang, and J. Ji, "Globular Proteins as Functional-Mechanical Materials: A Multiscale Perspective on Design, Processing, and Application," Materials Horizons, 2025. doi:10.1039/D5MH01107H.

[5] Z. Wang, Y. Liu, B. Jiang, Z. Xin, and Z. Jiao, "Three-Dimensional-Printed Biomimetic Structural Ceramics with Excellent Tribological Properties," Materials, vol. 18, no. 6, p. 1376, Mar. 2025. doi:10.3390/ma18061376.

[6] X. Hu, Y. Zhao, S. Cheng, J. Zhen, Z. Jia, and R. Zhang, "Biomimetic Layered Hydrogel Coating for Enhanced Lubrication and Load-Bearing Capacity," Coatings, vol. 14, no. 9, Sep. 2024. doi:10.3390/coatings14091229.

[7] Y. Haohang et al., "Design, Preparation and Tribological Performance Study of Bionic Layered Polyvinyl Alcohol Hydrogel Lubricating Materials," Tribology, vol. 44, no. 11, pp. 1592-1601, 2024. http://dx.doi.org/10.16078/j.tribology.2024215.

[8] K. Yang et al., "Hydrophobic and tribological properties of biomimetic interfaces," Coatings, vol. 14, no. 5, p. 529, May 2024. doi:10.3390/coatings14050529.

[9] M. Amjad, M. Nguir, X. Ma, and D. Wen, "Superhydrophobic 3D-printed microstructures: applications, challenges, and prospects," Progress in Additive Manufacturing, pp. 1-28, 2025. doi:10.1007/s40964-025-01155-9.

[10] M. R. Maydanshahi, M. R. Najari, T. Slatter, and M. Mohammadpour, "The anisotropic mechanical and tribological behaviors of additively manufactured (material extrusion) implant-grade polyether ether ketone (PEEK)," Lubricants, vol. 12, no. 10, p. 347, Oct. 2024. doi:10.3390/lubricants12100347.

[11] M. Bijari, A. Aflaki, and M. Esfandiari, "Plants Inspired Biomimetics Architecture in Modern Buildings: A Review of Form, Function and Energy," Biomimetics, vol. 10, no. 2, p. 124, Feb. 2025. doi:10.3390/biomimetics10020124.

[12] A. V. Srinivasan, G. K. Haritos, and F. L. Hedberg, "Biomimetics: advancing man-made materials through guidance from nature," 1991. doi:10.1115/1.3119489.

[13] C. Wang Z. Zhao, X. Sun., "Mechanical and tribological properties of FDM-printed polyamide," Tribology International, vol. 191, p. 109198, Mar. 2024. doi:10.1016/j.triboint.2023.109198.

[14] C. Greiner and M. Schäfer, "Bio-inspired scale-like surface textures and their tribological properties," Bioinspiration & Biomimetics, vol. 10, no. 4, p. 044001, Aug. 2015. doi:10.1088/1748-3190/10/4/044001.

[15] Z. Ji et al., "3D printing of bioinspired topographically oriented surfaces with frictional anisotropy for directional driving," Tribology International, vol. 132, pp. 99-107, Apr. 2019. doi:10.1016/j.triboint.2018.12.010.

[16] Z. Ji et al., "Biomimetic surface with tunable frictional anisotropy enabled by photothermogenesis-induced supporting layer rigidity variation," Advanced Materials Interfaces, vol. 6, no. 2, p. 1801460, Jan. 2019. doi:10.1002/admi.201801460.

[17] X. Jian et al., "Anisotropic Friction of Epoxy-Bydrogel Based Surfaces with Soft-Hard Combination," Tribology, vol. 44, no. 3, pp. 335-344, 2023. doi:10.16078/j.tribology.2023015.

[18] J. Tirado, A. Parvaresh, B. Seyidoğlu, D. A. Bedford, J. Jørgensen, and A. Rafsanjani, "Multimodal Limbless Crawling Soft Robot with a Kirigami Skin," Cyborg and Bionic Systems, vol. 6, p. 0301, 2025. doi:10.34133/cbsystems.0301.

[19] S. Baik, D. W. Kim, Y. Park, T. J. Lee, S. Ho Bhang, and C. Pang, "A wet-tolerant adhesive patch inspired by protuberances in suction cups of octopi," Nature, vol. 546, no. 7658, pp. 396-400, Jun. 2017. doi:10.1038/nature22382.

[20] S. Baik, H. J. Lee, D. W. Kim, H. Min, and C. Pang, "Capillarity-enhanced organ-attachable adhesive with highly drainable wrinkled octopus-inspired architectures," ACS Applied Materials & Interfaces, vol. 11, no. 29, pp. 25674-25681, Jul. 2019. doi:10.1021/acsami.9b05511.

[21] S. Chun, D. W. Kim, S. Baik, H. J. Lee, J. H. Lee, S. H. Bhang, and C. Pang, "Conductive and stretchable adhesive electronics with miniaturized octopus-like suckers against dry/wet skin for biosignal monitoring," Advanced Functional Materials, vol. 28, no. 52, p. 1805224, Dec. 2018. doi:10.1002/adfm.201805224.

[22] R. Huang, X. Zhang, W. Li, L. Shang, H. Wang, and Y. Zhao, "Suction cups-inspired adhesive patch with tailorable patterns for versatile wound healing," Advanced Science, vol. 8, no. 17, p. 2100201, Sep. 2021. doi:10.1002/advs.202100201.

[23] Y. W. Lee, S. Chun, D. Son, X. Hu, M. Schneider, and M. Sitti, "A tissue adhesion-controllable and biocompatible small-scale hydrogel adhesive robot," Advanced Materials, vol. 34, no. 13, p. 2109325, Apr. 2022. doi:10.1002/adma.202109325.

[24] C. Xiang et al., "A bioinspired smart adhesion actuator with fast-driving and self-sensing capability," Advanced Materials Technologies, vol. 8, no. 8, p. 2201715, Apr. 2023. doi:10.1002/admt.202201715.

[25] B. Dean and B. Bhushan, "Shark-skin surfaces for fluid-drag reduction in turbulent flow: a review," Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, vol. 368, no. 1929, pp. 4775-4806, Oct. 2010. doi:10.1098/rsta.2010.0201.

[26] W. Barthlott and C. Neinhuis, "Purity of the sacred lotus, or escape from contamination in biological surfaces," Planta, vol. 202, no. 1, pp. 1-8, Apr. 1997. doi:10.1007/s004250050096.

[27] D. Chowdhury, A. Batham, U. Sehgal, C. Ghosh, B. Bhattacharya, and S. Datta, "Analysing the frictional properties of micro dimpled surface created by milling machine under lubricated condition," Tribology International, vol. 146, p. 106260, Jun. 2020. doi:10.1016/j.triboint.2020.106260.

[28] M. D. J. Velásquez-Hernández et al., "Fabrication of 3D oriented MOF micropatterns with anisotropic fluorescent properties," Advanced Materials, vol. 35, no. 25, p. 2211478, Jun. 2023. doi:10.1002/adma.202211478.

[29] D. A. Bruzewicz, M. Boncheva, A. Winkleman, J. M. St. Clair, G. S. Engel, and G. M. Whitesides, "Biomimetic fabrication of 3D structures by spontaneous folding of tapes," Journal of the American Chemical Society, vol. 128, no. 29, pp. 9314-9315, Jul. 2006. doi:10.1021/ja062973q.

[30] M. T. I. Mredha and I. Jeon, "Biomimetic anisotropic hydrogels: Advanced fabrication strategies, extraordinary functionalities, and broad applications," Progress in Materials Science, vol. 124, p. 100870, Feb. 2022. doi:10.1016/j.pmatsci.2021.100870.

[31] L. Zhou, Y. Fu, T. Yin, and Z. Luo, "Synergetic effect of epoxy resin and carboxylated nitrile rubber on tribological and mechanical properties of soft paper-based friction materials," Tribology International, vol. 129, pp. 314-322, Jan. 2019. doi:10.1016/j.triboint.2018.08.020.

[32] M. Li, W. Shi, J. Shi, T. Wang, L. Shi, and X. Wang, "Regulation and control of wet friction of soft materials using surface texturing: A review,"

Friction, vol. 11, no. 3, pp. 333-353, Mar. 2023. doi:10.1007/s40544-022-0617-6.

[33] Q. Huang, X. Shi, Y. Xue, K. Zhang, and C. Wu, "Recent progress on surface texturing and solid lubricants in tribology: Designs, properties, and mechanisms," Materials Today Communications, vol. 35, p. 105854, Jun. 2023. doi:10.1016/j.mtcomm.2023.105854.

[34] Q. Ge et al., "Projection micro stereolithography based 3D printing and its applications," International Journal of Extreme Manufacturing, vol. 2, no. 2, p. 022004, Jun. 2020. doi:10.1088/2631-7990/ab8d9a.

[35] J. S. Chen, Q. Smithwick, and D. Chu, "Implementation of shading effect for reconstruction of smooth layer-based 3D holographic images," in Stereoscopic Displays and Applications XXIV, vol. 8648, pp. 218-226, SPIE, Mar. 2013. doi:10.1117/12.2004704.

[36] S. Zhang, K. Hapeshi, and A. K. Bhattacharya, "3D modelling of biological systems for biomimetics," Journal of Bionic Engineering, vol. 1, no. 1, pp. 20-40, Mar. 2004. doi:10.1007/BF03399451.

[37] Y. Suzuki, K. Suzuki, M. Michihata, K. Takamasu, and S. Takahashi, "One-shot stereolithography for biomimetic micro hemisphere covered with relief structure," Precision Engineering, vol. 54, pp. 353-360, Oct. 2018. doi:10.1016/j.precisioneng.2018.07.004.

[38] Q. Ge et al., "Projection micro stereolithography based 3D printing and its applications," International Journal of Extreme Manufacturing, vol. 2, no. 2, p. 022004, Jun. 2020. doi:10.1088/2631-7990/ab8d9a.

[39] M. J. Benz, A. E. Kovalev, and S. N. Gorb, "Anisotropic frictional properties in snakes," in Bioinspiration, Biomimetics, and Bioreplication 2012, vol. 8339, pp. 256-261, SPIE, 2012. doi:10.1117/12.916972.

[40] M. S. Hossain, M. M. Hossain, M. K. Khatun, and K. R. Hossain, "Hydrogel-based superadsorbents for efficient removal of heavy metals in industrial wastewater treatment and environmental conservation," Environmental Functional Materials, vol. 2, no. 2, pp. 142-158, 2023. doi:10.1016/j.efmat.2024.01.001.

[41] A. Malshe, K. Rajurkar, A. Samant, H. N. Hansen, S. Bapat, and W. Jiang, "Bio-inspired functional surfaces for advanced applications," CIRP Annals, vol. 62, no. 2, pp. 607-628, 2013. doi:10.1016/j.cirp.2013.05.008.

[42] Z. Zhao, R. Fang, Q. Rong, and M. Liu, "Bioinspired nanocomposite hydrogels with highly ordered structures," Advanced Materials, vol. 29, no. 45, p. 1703045, Dec. 2017. doi:10.1002/adma.201703045.

[43] S. Lin, J. Liu, X. Liu, and X. Zhao, "Muscle-like fatigue-resistant hydrogels by mechanical training," Proceedings of the National Academy of Sciences, vol. 116, no. 21, pp. 10244-10249, May 2019. doi:10.1073/pnas.1903019116.

[44] X. Liang, S., Zhang, J., Wang., "Anisotropically fatigue-resistant hydrogels," Advanced Materials, vol. 33, no. 30, p. 2102011, Jul. 2021. doi:10.1002/adma.202102011.

[45] X. Wang Zhu, W., Zhong., "Bioinspired highly anisotropic, ultrastrong and stiff, and osteoconductive mineralized wood hydrogel composites for bone repair," Advanced Functional Materials, vol. 31, no. 20, p. 2010068, May 2021. doi:10.1002/adfm.202010068.

[46] A. Gevorkian, M., Kheiri, S., Khuu, "Actuation of three-dimensional-printed nanocolloidal hydrogel with structural anisotropy," Advanced Functional Materials, vol. 31, no. 17, p. 2010743, Apr. 2021. doi:10.1002/adfm.202010743.

[47] R. Bail, S. B. Lee, and D. H. Lee, "3D printing of micropatterned stamps with tunable horizontal surface properties," Surface and Interface Analysis, vol. 55, no. 4, pp. 217-225, Apr. 2023. doi:10.1002/sia.7180.

[48] Y. Lu, "Superior lubrication properties of biomimetic surfaces with hierarchical structure," Tribology International, vol. 119, pp. 131-142, Mar. 2018. doi:10.1016/j.triboint.2017.10.021.

[49] K. Du, J. Basuki, V. Glattauer, C. Mesnard, A. T. Nguyen, D. L. Alexander, and T. C. Hughes, "Digital light processing 3D printing of PDMS-based soft and elastic materials with tunable mechanical properties," ACS Applied Polymer Materials, vol. 3, no. 6, pp. 3049-3059, Jun. 2021. doi:10.1021/acsapm.1c00260.

[50] C. Liu, Z., Ma, H., Sun., "4D Printing of Personalized-Tunable Biomimetic Periosteum with Anisotropic Microstructure for Accelerated Vascularization and Bone Healing," Advanced Healthcare Materials, vol. 12, no. 22, p. 2370130, Sep. 2023. doi:10.1002/adhm.202370130.

[51] Z. Ji, P. Jiang, R. Guo, K. R. Hossain, and X. Wang, "4D-printed light-responsive structures," in Smart Materials in Additive Manufacturing, pp. 55-105, Elsevier, 2022. doi:10.1016/B978-0-12-824082-3.00017-9.

[52] C. A. G. Lengua, "History of rapid prototyping," in Rapid Prototyping in Cardiac Disease: 3D Printing the Heart, pp. 3-7, Cham: Springer International Publishing, 2017. doi:10.1007/978-3-319-53523-4_1.

[53] J. Peels, "Additive Manufacturing Pioneers: David K. Leigh," 3D Printing and Additive Manufacturing, vol. 1, no. 4, pp. 178-180, Dec. 2014. doi:10.1089/3dp.2014.0020.

[54] A. Bowyer, "3D printing and humanity's first imperfect replicator," 3D Printing and Additive Manufacturing, vol. 1, no. 1, pp. 4-5, Mar. 2014. doi:10.1089/3dp.2013.0003.

[55] G. A. Nowlan, "Developing and implementing 3D printing services in an academic library," Library Hi Tech, vol. 33, no. 4, pp. 472-479, Nov. 2015. doi:10.1108/LHT-05-2015-0049.

[56] M. H. Rahman, N. Y. Liza, K. R. Hossain, D. R. Kalambhe, M. A. Shyeed, and D. H. Noor, "Additive manufacturing in nano drug delivery systems," Pharmaceutical Science Advances, vol. 2, p. 100036, Dec. 2024. doi:10.1016/j.pscia.2024.100036.

[57] A. Jandyal, I. Chaturvedi, I. Wazir, A. Raina, and M. I. U. Haq, "3D printing–A review of processes, materials and applications in industry 4.0," Sustainable Operations and Computers, vol. 3, pp. 33-42, 2022. doi:10.1016/j.susoc.2021.09.004.

[58] A. K. Kushwaha H., Hart, D., Hughes., "Fundamentals of stereolithography: techniques, properties, and applications," in Tribology of Additively Manufactured Materials, pp. 87-106, Elsevier, 2022. doi:10.1016/B978-0-12-821328-5.00003-2.

[59] T. Finnes, "High definition 3d printing–comparing sla and fdm printing technologies," The Journal of Undergraduate Research, vol. 13, no. 1, p. 3, 2015. https://openprairie.sdstate.edu/jur/vol13/iss1/3.

[60] M. Ntousia and I. Fudos, "3D printing technologies & applications: an overview," in Proceedings of the CAD 2020 Conference, Singapore, pp. 243-248, 2019. doi:10.14733/cadconfP.2019.243-248.

[61] G. Katal, N. Tyagi, and A. Joshi, "Digital light processing and its future applications," International Journal of Scientific and Research Publications, vol. 3, no. 4, pp. 2250-3153, Apr. 2013.

[62] D. Martin and H. Johansen, "Development of a Multi-physics Model to Optimize Continuous Liquid Interface Production (CLIP) for Additive Manufacturing (Carbon3D HPC4Mfg Final Report)," Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States), 2021. doi:10.2172/1833999.

[63] I. Ahmed, K. Sullivan, and A. Priye, "Multi-resin masked stereolithography (MSLA) 3D printing for rapid and inexpensive prototyping of microfluidic chips with integrated functional components," Biosensors, vol. 12, no. 8, p. 652, Aug. 2022. doi:10.3390/bios12080652.

[64] S. Kirihara, "Laser Scanning Stereolithography," in Laser Micro-Nano-Manufacturing and 3D Microprinting, pp. 305-312, Cham: Springer International Publishing, 2020. doi:10.1007/978-3-030-59313-1_10.

[65] S. Y. Chou, P. R. Krauss, and P. J. Renstrom, "Nanoimprint lithography," Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures Processing, Measurement, and Phenomena, vol. 14, no. 6, pp. 4129-4133, Nov. 1996. doi:10.1116/1.588605.

[66] M. B. Kumar, P. Sathiya, and M. Varatharajulu, "Selective laser sintering," in Advances in Additive Manufacturing Processes, pp. 28-47, Bentham Science Publishers, 2021. doi:10.2174/9789815036336121010l.

[67] R. D. Sochol et al., "3D printed microfluidic circuitry via multijet-based additive manufacturing," Lab on a Chip, vol. 16, no. 4, pp. 668-678, Feb. 2016. doi:10.1039/C5LC01389E.

[68] M. Galati, "Electron beam melting process: A general overview," in Additive Manufacturing, pp. 277-301, 2021. doi:10.1016/B978-0-12-818411-0.00014-8.

[69] K. V. Venkatesh and V. V. Nandini, "Direct metal laser sintering: a digitised metal casting technology," The Journal of Indian Prosthodontic Society, vol. 13, no. 4, pp. 389-392, Dec. 2013. doi:10.1007/s13191-013-0256-8.

[70] X. Xu, P. Robles-Martinez, C. M. Madla, F. Joubert, A. Goyanes, A. W. Basit, and S. Gaisford, "Stereolithography (SLA) 3D printing of an antihypertensive polyprintlet: Case study of an unexpected photopolymer-drug reaction," Additive Manufacturing, vol. 33, p. 101071, May 2020. doi:10.1016/j.addma.2020.101071.

[71] K. R. Hossain, S., Rahman, M. S., Rahman., "Nanomaterials function in additive manufacturing," Journal of Kufa-Physics, vol. 15, no. 2, pp. 23-39, 2023, doi: 10.31257/2018/JKP/2023/v15.i02.13538.

[72] A. Luongo, V. Falster, M. B. Doest, M. M. Ribo, E. R. Eiríksson, D. B. Pedersen, and J. R. Frisvad, "Microstructure control in 3D printing with digital light processing," in Computer Graphics Forum, vol. 39, no. 1, pp. 347-359, Feb. 2020. doi:10.1111/cgf.13807.

[73] X. Wang, Z. Wei, C. Z. Baysah, M. Zheng, and J. Xing, “Biomaterial-based microstructures fabricated by two-photon polymerization microfabrication technology,” RSC Advances, vol. 9, no. 59, pp. 34472-34480, 2019. doi:10.1039/C9RA05645A.

[74] F. Yanagawa, S. Sugiura, and T. Kanamori, “Hydrogel microfabrication technology toward three dimensional tissue engineering,” Regenerative Therapy, vol. 3, pp. 45-57, Mar. 2016. doi:10.1016/j.reth.2016.02.007.

[75] X. Yan, S., Lin, S., Tran., “Recent advancements in biomimetic 3D printing materials with enhanced mechanical properties,” Frontiers in Materials, vol. 8, p. 518886, Apr. 2021. doi:10.3389/fmats.2021.518886.

[76] C. Dautremont and E. Gobbo, “Mapping of Circular Construction Ecosystems' Characteristics: Interconnections, Relationships, and Synchronization of Stakeholders at the Micro, Meso, and Macro Scales,” Sustainability, vol. 17, no. 2, Jan. 2025. doi:10.3390/su17020541.

[77] A. Du Plessis, A. J. Babafemi, S. C. Paul, B. Panda, J. P. Tran, and C. Broeckhoven, “Biomimicry for 3D concrete printing: A review and perspective,” Additive Manufacturing, vol. 38, p. 101823, Feb. 2021. doi:10.1016/j.addma.2020.101823.

[78] W. Xiang and B. Honarvar Shakibaei Asli, “Advances in Gecko-Inspired Climbing Robots: From Biology to Robotics—A Review,” Electronics, vol. 14, no. 14, p. 2810, Jul. 2025. doi:10.3390/electronics14142810.

[79] A. Kuru, P. Oldfield, S. Bonser, and F. Fiorito, “Biomimetic adaptive building skins: Energy and environmental regulation in buildings,” Energy and Buildings, vol. 205, p. 109544, Dec. 2019. doi:10.1016/j.enbuild.2019.109544.

[80] B. Barraza, F. Olate-Moya, G. Montecinos, J. H. Ortega, A. Rosenkranz, A. Tamburrino, and H. Palza, “Superhydrophobic SLA 3D printed materials modified with nanoparticles biomimicking the hierarchical structure of a rice leaf,” Science and Technology of Advanced Materials, vol. 23, no. 1, pp. 300-321, Dec. 2022. doi:10.1080/14686996.2022.2063035.

[81] K. Autumn, “Gecko adhesion: structure, function, and applications,” MRS Bulletin, vol. 32, no. 6, pp. 473-478, Jun. 2007. doi:10.1557/mrs2007.80.

[82] L. Zhang et al., “Micro–nano hierarchical structure enhanced strong wet friction surface inspired by tree frogs,” Advanced Science, vol. 7, no. 20, p. 2001125, Oct. 2020. doi:10.1002/advs.202001125.

[83] Y. W. Lee, S. Chun, D. Son, X. Hu, M. Schneider, and M. Sitti, “A tissue adhesion-controllable and biocompatible small-scale hydrogel adhesive robot,” Advanced Materials, vol. 34, no. 13, p. 2109325, Apr. 2022. doi:10.1002/adma.202109325.

[84] Y. Wang, J., Xu, X., Yang, “3D printing of octopi-inspired hydrogel suckers with underwater adaptation for reversible adhesion,” Chemical Engineering Journal, vol. 457, p. 141268, Feb. 2023. doi:10.1016/j.cej.2022.141268.

[85] S. Ma, M. Scaraggi, C. Yan, X. Wang, S. N. Gorb, D. Dini, and F. Zhou, “Bioinspired 3D printed locomotion devices based on anisotropic friction,” Small, vol. 15, no. 1, p. 1802931, Jan. 2019. doi:10.1002/smll.201802931.

[86] Y. Zhao, H. Mei, P. Chang, C. Chen, L. Cheng, and K. G. Dassios, “Infinite approaching superlubricity by three-dimensional printed structures,” ACS Nano, vol. 15, no. 1, pp. 240-257, Jan. 2021. doi:10.1021/acsnano.0c08713.

[87] R. Aziz, M. I. U. Haq, and A. Raina, “Effect of surface texturing on friction behaviour of 3D printed polylactic acid (PLA),” Polymer Testing, vol. 85, p. 106434, May 2020. doi:10.1016/j.polymertesting.2020.106434.

[88] S. Ma, C. Yan, M. Cai, J. Yang, X. Wang, F. Zhou, and W. Liu, “Continuous surface polymerization via Fe (II)-mediated redox reaction for thick hydrogel coatings on versatile substrates,” Advanced Materials, vol. 30, no. 50, p. 1803371, Dec. 2018. doi:10.1002/adma.201803371.

[89] M. R. Binelli, R., Nagel, Y., Kim., “Digital manufacturing of personalised footwear with embedded sensors,” Scientific Reports, vol. 13, no. 1, p. 1962, Feb. 2023. doi:10.1038/s41598-023-29261-0.

[90] P. K. Mishra and T. Jagadesh, “Applications and challenges of 3D printed polymer composites in the emerging domain of automotive and aerospace: a converged review,” Journal of The Institution of Engineers (India): Series D, vol. 104, no. 2, pp. 849-866, Dec. 2023. doi:10.1007/s40033-022-00426-x.

[91] Y. Xu, X. Luan, P. He, D. Zhu, R. Mu, Y. Wang, and G. Wei, “Fabrication and functional regulation of biomimetic interfaces and their antifouling and antibacterial applications: a review,” Small, vol. 20, no. 21, p. 2308091, May 2024. doi:10.1002/smll.202308091.

[92] Y. Liu, H. Zhang, P. Wang, Z. He, and G. Dong, “3D-printed bionic superhydrophobic surface with petal-like microstructures for droplet manipulation, oil-water separation, and drag reduction,” Materials & Design, vol. 219, p.

110765, Jul. 2022. doi:10.1016/j.matdes.2022.110765.

[93] D. Liu, X. Wang, Q. Zhou, Y. Zhu, Z. Chen, J. Hu, and P. Zhou, "Investigating the role of water in rheological and friction properties of pureed foods: A deep dive into avocado puree," Journal of Food Engineering, vol. 385, p. 112268, Jan. 2025. doi:10.1016/j.jfoodeng.2024.112268.

[94] E. Andablo-Reyes, M. Bryant, A. Neville, P. Hyde, R. Sarkar, M. Francis, and A. Sarkar, "3D biomimetic tongue-emulating surfaces for tribological applications," ACS Applied Materials & Interfaces, vol. 12, no. 44, pp. 49371-49385, Nov. 2020. doi:10.1021/acsami.0c12925.

[95] R. Bi, X. Huang, J. Huang., "3D-Printed Biomimetic Structural Colors," Small, vol. 20, no. 5, p. 2306646, Feb. 2024. doi:10.1002/smll.202306646.

[96] K. R. Hossain, Y. Zheng, X. Yao, H. Hu, Z. Ji, and X. Wang, "Biomimetic surface texturing with tunable stimulus-responsive friction anisotropy," Journal of Bionic Engineering, vol. 21, no. 6, pp. 2942-2954, Nov. 2024. doi:10.1007/s42235-024-00595-3.

[97] D. Wang, D. Chen, and Z. Chen, "Recent progress in 3D printing of bioinspired structures," Frontiers in Materials, vol. 7, p. 286, Sep. 2020. doi:10.3389/fmats.2020.00286.

[98] X. Song, W. Zhang, H. Liu, L. Zhao, Q. Chen, and H. Tian, "3D printing of liquid crystal elastomers-based actuator for an inchworm-inspired crawling soft robot," Frontiers in Robotics and AI, vol. 9, p. 889848, May 2022. doi:10.3389/frobt.2022.889848.

[99] Y. Liu, H. Wang, J. Li, P. Li, and S. Li, "Gecko-inspired controllable adhesive: Structure, fabrication, and application," Biomimetics, vol. 9, no. 3, p. 149, Mar. 2024. doi:10.3390/biomimetics9030149.

[100] Q. Chen, X. Zhang, K. Chen, X. Wu, T. Zong, C. Feng, and D. Zhang, "Anisotropic hydrogels with enhanced mechanical and tribological performance by magnetically oriented nanohybrids," Chemical Engineering Journal, vol. 430, p. 133036, Feb. 2022. doi:10.1016/j.cej.2021.133036.

[101] X. Zhang, X. Chen, Q. Chen., "Fabrication and characterization of a multilayer hydrogel as a candidate for artificial cartilage," ACS Applied Polymer Materials, vol. 3, pp. 5039-5050, 2021. doi:10.1021/acsapm.1c00807.

[102] X. Wu, S. Liu, K. Chen, F. Wang, C. Feng, L. Xu, and D. Zhang, "3D printed chitosan-gelatine hydrogel coating on titanium alloy surface as biological fixation interface of artificial joint prosthesis," International Journal of Biological Macromolecules, vol. 182, pp. 669-679, Jul. 2021. doi:10.1016/j.ijbiomac.2021.04.046.

[103] Z. Ji, X. Jia, X. Wang, "Biomimetic surface with tunable frictional anisotropy enabled by photothermogenesis-induced supporting layer rigidity variation," Advanced Materials Interfaces, vol. 6, no. 2, p. 1801460, Jan. 2019. doi:10.1002/admi.201801460.

[104] A. A. Alsharif, A. M. Syed, X. Li, N. A. Alsharif, G. Lubineau, and N. El-Atab, "Hybrid 3D Printing of a Nature-Inspired Flexible Self-Adhesive Biopatch for Multi-Biosignal Sensing," Advanced Functional Materials, vol. 34, no. 44, p. 2406341, Oct. 2024. doi:10.1002/adfm.202406341.

[105] W. Shi, X. Cheng, and K. Cheng, "Gecko-inspired adhesives with asymmetrically tilting-oriented micropillars," Langmuir, vol. 38, no. 29, pp. 8890-8898, Jul. 2022. doi:10.1021/acs.langmuir.2c01002.

[106] Y. Yang, X. Li, X. Zheng, Z. Chen, Q. Zhou, and Y. Chen, "3D-printed biomimetic super-hydrophobic structure for microdroplet manipulation and oil/water separation," Advanced Materials, vol. 30, no. 9, p. 1704912, Mar. 2018. doi:10.1002/adma.201704912.

[107] Z. Wang, Y. Liu, B. Jiang, Z. Xin, and Z. Jiao, "Three-Dimensional-Printed Biomimetic Structural Ceramics with Excellent Tribological Properties," Materials, vol. 18, no. 6, p. 1376, Mar. 2025. doi:10.3390/ma18061376.

[108] Y. Xiao, D. Hu, Z. Zhang, B. Pei, X. Wu, and P. Lin, "A 3D-printed sole design bioinspired by cat paw pad and triply periodic minimal surface for improving paratrooper landing protection," Polymers, vol. 14, no. 16, p. 3270, Aug. 2022. doi:10.3390/polym14163270.

[109] S. Das, N. Cadirov, S. Chary, Y. Kaufman, J. Hogan, K. L. Turner, and J. N. Israelachvili, "Stick–slip friction of gecko-mimetic flaps on smooth and rough surfaces," Journal of The Royal Society Interface, vol. 12, no. 104, p. 20141346, Mar. 2015. doi:10.1098/rsif.2014.1346.

[110] S. Tawfick, M., Copic, D., Park., "Engineering of micro-and nanostructured surfaces with anisotropic geometries and properties," Advanced Materials, vol. 24, no. 13, pp. 1628-1674, Apr. 2012. doi:10.1002/adma.201103796.

[111] R. Kruiper, J. F. Vincent, E. Abraham, R. C. Soar, I. Konstas, J. Chen-Burger, and M. P. Desmulliez, "Towards a design process for computer-aided

biomimetics," Biomimetics, vol. 3, no. 3, p. 14, Jul. 2018. doi:10.3390/biomimetics3030014.

[112] Y. Shin, H. S. Lee, J. U. Kim, Y. H. An, Y. S. Kim, N. S. Hwang, and D. H. Kim, "Functional-hydrogel-based electronic-skin patch for accelerated healing and monitoring of skin wounds," Biomaterials, vol. 314, p. 122802, Mar. 2025. doi:10.1016/j.biomaterials.2024.122802.

[113] I. Boudene and Y. Bougdid, "Two-photon polymerization-assisted 3D laser nanoprinting: from fundamentals to modern applications," Journal of Materials Chemistry C, vol. 13, no. 36, pp. 18597-18630, 2025. doi:10.1039/D5TC02037A.

[114] A. S. Kulkarni, S. Khandelwal, Y. Thakre, J. Rangole, M. B. Kulkarni, and M. Bhaiyya, "A Review on 3D-Printed Miniaturized Devices for Point-of-Care-Testing Applications," Biosensors, vol. 15, no. 6, p. 340, Jun. 2025. doi:10.3390/bios15060340.

[115] Y. Haohang, O., Weiyi, ., "Design, Preparation and Tribological Performance Study of Bionic Layered Polyvinyl Alcohol Hydrogel Lubricating Materials," Tribology, vol. 44, no. 11, pp. 1592-1601, 2024.

[116] T. Aguilar-Planet, A. Picardo, J. F. Fernández-Rodríguez, A. Martín-Mariscal, and E. Peralta, "Biomimicry: Engineering Inspired by Nature," International Journal of Design Management & Professional Practice, vol. 19, no. 1, pp. 155-175, 2025. doi:10.18848/2325-162X/CGP/v19i01/155-175.

[117] A. Ding, F. Tang, and E. Alsberg, "4D printing: A comprehensive review of technologies, materials, stimuli, design, and emerging applications," Chemical Reviews, vol. 125, no. 7, pp. 3663-3771, Apr. 2025. doi:10.1021/acs.chemrev.4c00070.

[118] W. Chen, Z. Huang, T. Xiao, L. Jiang, X. Tan, and Y. Lei, "Advancing superhydrophobic surfaces: From mechanism insights and design strategies to intelligent applications," APL Materials, vol. 13, no. 6, Jun. 2025. doi:10.1063/5.0271653.

[119] D. Cheng, M. Wang, D. Xiao, and D. Ma, "Cu/Mo2CTx interface drives CO2 hydrogenation to methanol," Matter, vol. 5, no. 8, pp. 2469-2471, Aug. 2022. doi:10.1016/j.matt.2022.06.019.