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Bio-Inspired Micro/Nanostructures for Functional Applications: A Mini-Review

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Abstract

Three-dimensional (3D) micro/nanostructures based on soft elastomers have received extensive attention in recent years, owing to their potential and advanced applicability. Designing and fabricating 3D micro/nanostructures are crucial for applications in diverse engineering fields, such as sensors, harvesting devices, functional surfaces, and adhesive patches. However, because of their structural complexity, fabricating soft-elastomer-based 3D micro/nanostructures with a low cost and simple process remains a challenge. Bio-inspired designs that mimic natural structures, or replicate their micro/nanostructure surfaces, have greatly benefited in terms of low-cost fabrication, scalability, and easy control of geometrical parameters. This review highlights recent advances in 3D micro/nanostructures inspired by nature for diverse potential and advanced applications, including flexible pressure sensors, energy-harvesting devices based on triboelectricity, superhydrophobic/-philic surfaces, and dry/wet adhesive patches.

Keywords: Bio-inspired micro/nanostructure, Functional applications, Flexible pressure sensor, Triboelectricity, Superhydrophobic/-philic surface, Dry/wet adhesive patch

1. INTRODUCTION

Recently, various studies have been conducted to find the best route for creating novel materials and structures by learning and mimicking things from nature. Especially, bio-inspired structures that mimic the basic structures of natural organisms have attracted significant attention [1].

These bio-inspired and functional materials, which are designed and manufactured from biological perspectives, are proposed as a promising route for next-generation structural designs in many engineering applications. Diverse bio-inspired structures that mimic biological structures, functions, and shapes found in animals [2, 3], plants [4-6], and insects [7, 8] are being developed, and the proposed bio-inspired structures are being used in a number of engineering fields, such as automobiles, buildings, bridges, and aircraft.

Among the various bio-inspired structures, three-dimensional (3D) micro/nanostructures have received significant attention recently, owing to their excellent characteristics, applicability to diverse engineering fields, and the rapid advancement of micro/nano fabrication technologies.

Microstructures can be used to control mechanical properties, such as strength, elastic modulus, and flexibility; thus, they can be applied to impact-absorbing applications to minimize weight [9, 10]. For example, a mechanically reinforced shell, which has a multi-layered structure, efficiently absorbs and disperses external shocks, thereby protecting its structure [11].

Nanostructures also provide unique characteristics, such as superhydrophobicity/-philicity, anti-reflection, adhesion-force control, and structural color [12, 13]. Numerous examples appear in nature, such as lotus leaves, geckos' feet, and insect eyes. Lotus leaves, a representative example of superhydrophobic nanostructures, self-clean their own surfaces and prevent dust adhesion in harsh environments, allowing them to survive in nature. Furthermore, micro/nano-structured surfaces with strong adhesion have been extensively investigated [14], being inspired by geckos' feet, which allow the lizards to easily climb rough or curved surfaces.

The purpose of this review is to provide a comprehensive overview of recent advances in bio-inspired micro/nanostructures, ranging from physical principles to manufacturing methods and potential applications. This review includes ongoing efforts in various fields, including flexible and sensitive pressure sensors, energy-harvesting devices based on triboelectricity, superhydrophobic/-philic surfaces, and adhesion-property control in dry/wet conditions.

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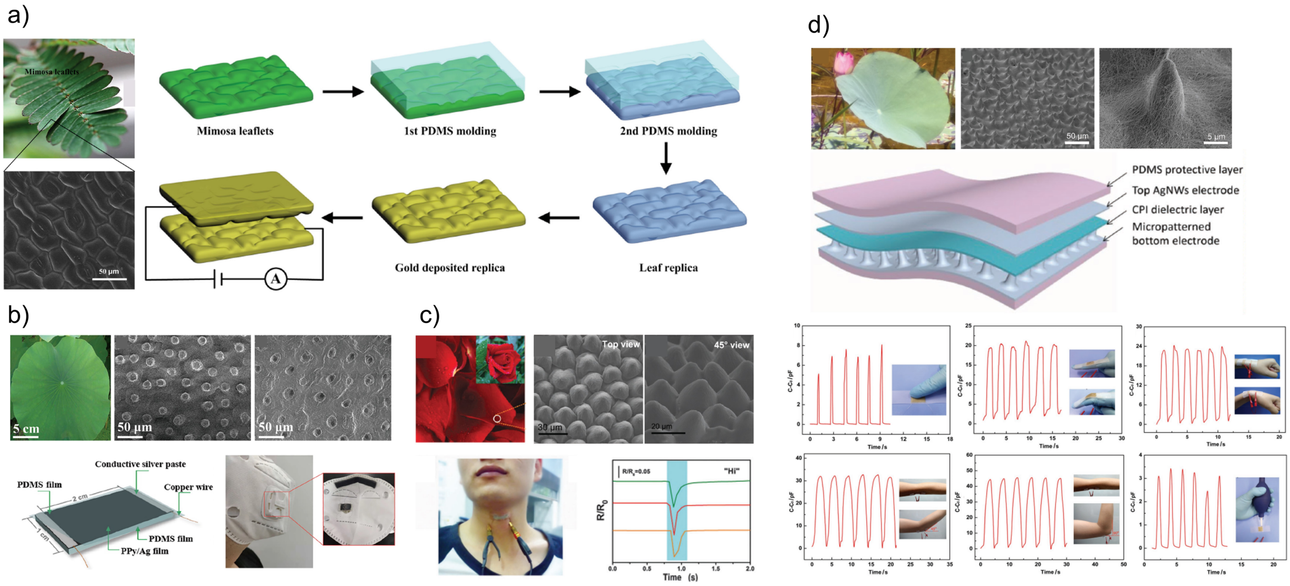

Fig. 1. Flexible and sensitive pressure sensors based on bio-inspired structures. (a) Schematic of a flexible pressure sensor that replicates the randomly arrayed microstructures on the surface of mimosa leaves. Reprinted with permission from Ref. [19]; copyright (2014) John Wiley and Sons. (b) Flexible pressure sensor with bio-inspired regular microcylinder patterns for physiological-signal monitoring. Reprinted with permission from Ref. [20]; copyright (2020) ELSEVIER. (c) Micropapillae surface structure inspired by rose petals, with application results in voice recognition. Reprinted with permission from Ref. [21]; copyright (2015) Royal Society of Chemistry. (d) Lotus leaf with high aspect ratio and low density for sensitive pressure sensors. Reprinted with permission from Ref. [22]; copyright (2018) John Wiley and Sons.

2. BIO-INSPIRED MICRO / NANO STRUCTURES

2.1 Flexible and Sensitive Pressure Sensors and Their Applications

Flexible and sensitive pressure sensors have received tremendous attention, owing to their potential applications in human–machine interfaces, health monitoring, and electronic skin. In recent years, ongoing studies have investigated improving the sensitivity in the low-pressure range (1−10 kPa) [15]. Constructing micro/nanostructures, such as pyramids, wrinkles, and domes, on the active layer's surface is an effective method for manufacturing pressure sensors with excellent sensor characteristics, including sensitivity, response time, limit of detection (LOD), and repeatability, in the low-pressure range [16-18].

When pressure is applied to a sensor with micro/nanostructures, the local stress is concentrated at the tips of the micro/nanostructure. Because of the stress concentration, the local deformation is relatively larger than that in an active layer with a plain surface. Bio-inspired structures, which mimic biological structures and shapes found in plants, are an effective strategy for fabricating flexible and sensitive pressure sensors based on soft elastomers.

Fig. 1(a) presents a schematic of a flexible pressure sensor, based on natural microstructured plant leaves, with low-cost, simple, and environmentally-friendly templates [19]. The bio-inspired microstructure was manufactured using a direct molding from pre-cleaned mimosa leaves and then applied to a flexible pressure sensor by depositing a thin gold layer upon the surfaces. The flexible pressure sensor based on rough microstructures showed excellent sensing performance with a sensitivity as high as 50.17 kPa^{-1} in the range of 0−70 Pa, fast response time within 20 ms, and long-term stability over 10,000 cycles.

Fig. 1(b) depicts a flexible pressure sensor with a bio-inspired microstructure for physiological-signal monitoring [20]. The soft polydimethylsiloxane (PDMS) film with bio-inspired microstructures was manufactured by replicating natural lotus leaves, which possess a periodic microcylinder pattern. The developed pressure sensor exhibited excellent sensing characteristics, such as high sensitivity (0.4 kPa^{-1}, below 100 Pa), good repeatability, and long-term stability during bending and elongation tests.

Furthermore, pressure sensors with bio-inspired microstructures demonstrated applicability in physiological-signal monitoring, such as acoustic vibrations in normal speech, respiration, and human-pulse signals under normal and exercise conditions.

The structure of a rose petal, which is similar to that of the human epidermis or dermis, was used as a template to fabricate a highly sensitive piezoresistive pressure sensor, as shown in Fig. 1(c) [21]. The bio-inspired microstructure, fabricated by replicating the micropapillae on the surface of rose petals and molding the PDMS precursor, is easily deformed by applied pressure, resulting in a significant increase in the contact area between interlocking layers and higher sensitivity.

The fabricated flexible pressure sensor showed high sensitivity (1.35 kPa^{-1}), excellent LOD (2 Pa), short rising and falling times (36 and 30 ms, respectively), and outstanding long-term stability (5,000 loading/unloading cycles with a pressure of 2 kPa). Furthermore, a pressure sensor based on a soft elastomer was used for advanced applications, such as voice recognition in response to different spoken words and wrist-pulse monitoring.

Wan *et al.* proposed a sensitive capacitive pressure sensor, based on bio-inspired microstructures that replicated the sparse and high aspect-ratio structures of lotus leaves (Fig. 1(d)) [22]. The unique microstructures of the lotus-leaf surface have a high aspect ratio and low density, making them ideal candidates for sensitive pressure sensors. Especially, the low density of the microstructures leads to a highly compressible sensor structure, resulting in high sensitivity. The proposed flexible pressure sensor shows a high sensitivity of 1.194 kPa^{-1}, short response time within 36 ms, and excellent long-term stability for at least 100,000 cycles. Based on the high sensing characteristics, the flexible pressure sensor was applied to finger touching, finger/wrist/elbow bending, and air-flow detection.

2.2 Energy-Harvesting Devices Based on Triboelectric Generators

In recent years, with the growing public concern about climate-change issues, many studies have investigated sustainable and renewable energy harvesting. Among various energy-harvesting mechanisms, the triboelectric generator (TEG) is a promising mechanism, owing to its high efficiency at low frequencies [23]. A TEG harvests renewable energy by converting wasted mechanical energy into electrical energy.

The basic TEG mechanism is based on the conjunction of triboelectrification and electrostatic induction through the physical contact and separation of two dielectric films. When the two oppositely charged dielectric films are brought into contact, free electrons are transferred from one electrode to another to balance the potential drop generated by the triboelectric charges. As the two dielectric films are separated, the charge separation is maintained, resulting in a voltage difference between the two dielectric films. This voltage difference can be employed to drive an electrical current through a resistor connected to the TEG.

The TEG's key advantages include a simple working principle, easy fabrication process, ability to use a variety of materials, and excellent output characteristics. These allow them to harvest ambient environmental energy from a variety of mechanical motions, such as ocean waves, vibrations, wind, and human motions [24]. Especially, well-designed micro/nanostructures significantly enhance the performance, such as efficient energy harvesting and better mechanical stability under an applied force for sustainable energy harvesting.

Among various design and optimization efforts to improve TEG performance, bio-inspired structures from nature have proven to dramatically enhance the performance of TEGs. Fig. 2(a) depicts highly ordered hexagonal microbead arrays, inspired by the friction pads of treefrogs, to improve the electrification performance and reliability of TEGs [25].

A TEG based on bio-inspired microstructures demonstrated excellent harvesting performance, including a power density of 23.9 W/m^2, output voltage of 490 V, and current density of 24.4 $\mu A/cm^2$ under an applied force of ~38 N at a frequency of 5 Hz. This resulted in a seven-times-higher power-density enhancement than that of a bare (flat) PDMS-based TEG. Four-hundred LEDs were successfully powered by two symmetrically assembled bio-inspired microstructures using a fabricated device from simple hand pressing.

Yao *et al.* reported the fabrication of bio-inspired TEGs through a simple replication of the array of cone-like microstructures on the Calathea zebrine leaf surface (Fig. 2(b)) [26]. The combination of two surfaces with bio-inspired interlocking microstructures from the zebrine leaf surface significantly enhanced the harvesting performance in contact–separation mode, leading to a 14-times-higher power density than that of a flat surface under the same pressure. They verified that TEGs based on bio-inspired microstructures could be easily attached to a robotic hand for human–robot interaction like handshaking, as well as recognizing objects and gestures.

Fig. 2(c) shows a superhydrophobic TEG based on a micro/nanostructure inspired by the lotus leaf, which is one of the most common natural objects with randomly distributed micro-scale humps and a nano-scale rough surface [27]. The bio-inspired micro/nanostructure, which was manufactured through lithography and an elastomer-molding process, showed a high

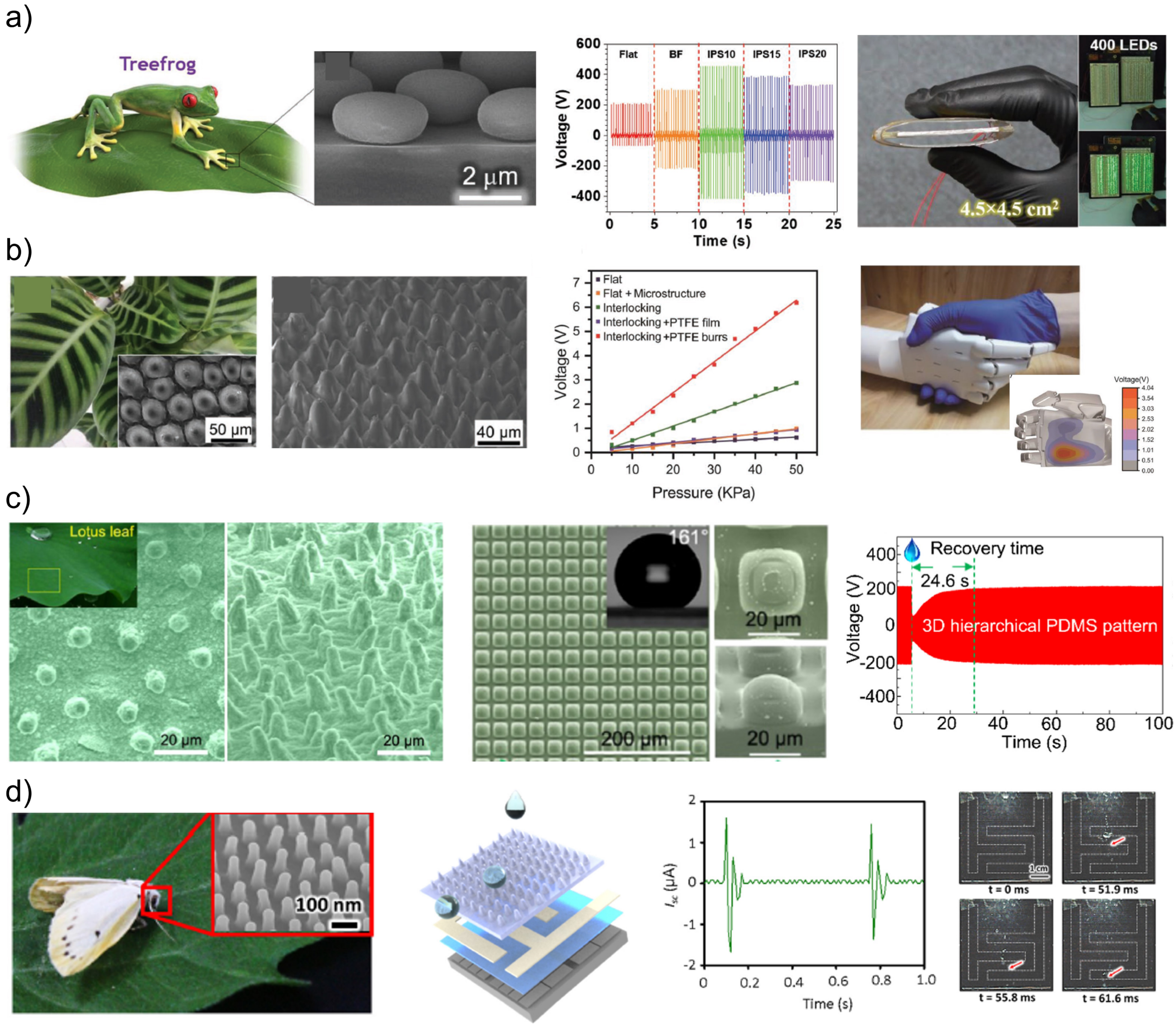

Fig. 2. Triboelectric generators (TEGs) based on bio-inspired micro/nanostructures. (a) TEG based on microbead arrays, inspired by the friction pads of treefrogs. Reprinted with permission from Ref. [25]; copyright (2019) John Wiley and Sons. (b) TEG with a bio-inspired cone-like array of microstructures from the Calathea zebrine leaf surface for human–robot interaction. Reprinted with permission from Ref. [26]; copyright (2020) John Wiley and Sons. (c) Superhydrophobic TEG based on a micro/nanostructure inspired by the lotus leaf. Reprinted with permission from Ref. [27]; copyright (2019) ELSEVIER. (d) Hybrid energy harvester integrating a TEG and a solar cell inspired by a moth's eye. Reprinted with permission from Ref. [28]; copyright (2019) ELSEVIER.

static water-contact angle of 161°, leading to the high humidity resistance of TEGs. The suggested TEG not only retained up to 86% of its initial performance at a relative humidity of 80%, but also recovered faster than a TEG with a flat surface under the same wet conditions.

Yoo *et al.* suggested a new type of hybrid energy harvester integrating a TEG and a solar cell (Fig. 2(d)). It was inspired by a moth's eye, which exhibits excellent light transmittance, resulting from the anti-reflective properties of the tapered and uniform nanopillar structures [28]. The hybrid energy-harvesting system is composed of a TEG, based on nanopillar structures, located on top and a conventional solar cell at the bottom.

They verified that the suggested moth's eye–mimicking TEG showed excellent harvesting performance, owing to the liquid–solid contact electrification. In addition, they demonstrated that the proposed nanopillar structures with prominent high transmittance played an important role in the durable operation of the solar cell, as a protective layer for self-cleaning from falling water droplets.

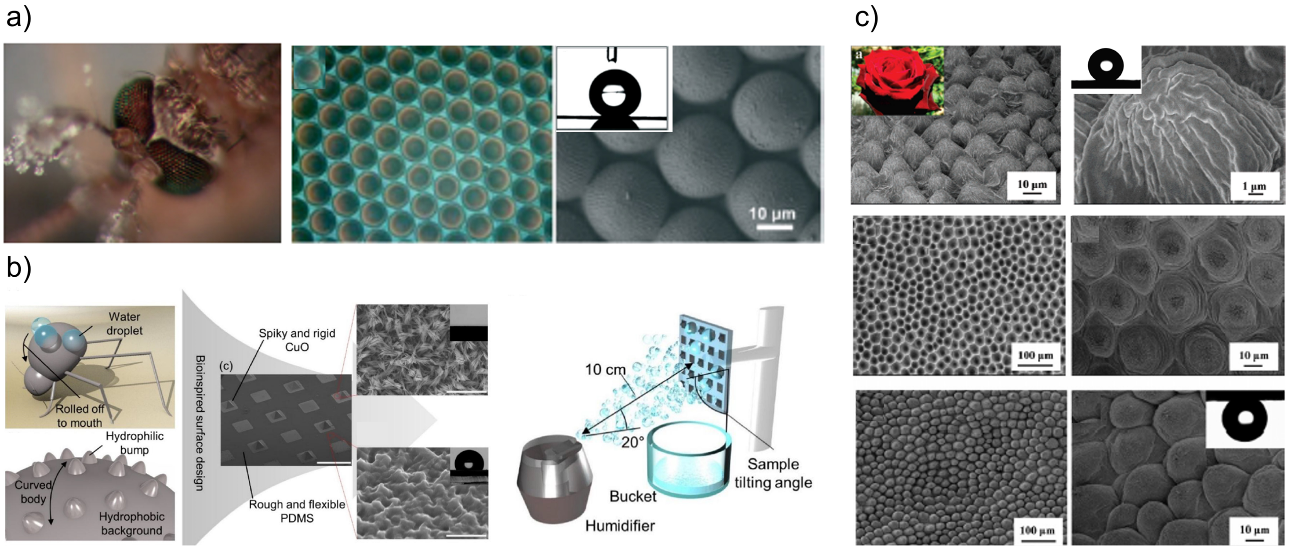

Fig. 3. Bio-inspired structures for superhydrophobic/-philic surfaces. (a) Superhydrophobic compound-eye microstructures covered with nanospheres inspired by the mosquito's compound eye. Reprinted with permission from Ref. [30]; copyright (2007) John Wiley and Sons. (b) Bio-inspired hydrophobic/-philic hybrid surface for fog harvesting by mimicking the Namib Desert beetles. Reprinted with permission from Ref. [31]; copyright (2019) Multidisciplinary Digital Publishing Institute. (c) Micropapillae and nanofolds inspired by the surfaces of red rose petals. Reprinted with permission from Ref. [32]; copyright (2008) American Chemical Society.

2.3 Bio-inspired Structures for Superhydrophobic/-philic Surfaces

Superhydrophobic/-philic surfaces are the most representative examples of surfaces observed in nature. When water is dropped onto a solid surface, it tends to spread to a lower energy state. Different water-contact angles can reflect a solid surface's wettability. Superhydrophobic/-philic surfaces are defined with a water-contact angle higher than 150° or lower than 10°, respectively. The surface's wettability is primarily determined by its surface roughness and surface energy [29]. Bio-inspired superhydrophobic/-philic surfaces can be widely applied in many fields, including self-cleaning, water repellence, and drag reduction.

Fig. 3(a) shows superhydrophobic compound-eye microstructures covered with nanospheres inspired by the mosquito's compound eye [30]. The compound-eye micro/nanostructures were fabricated using typical soft-lithography and transfer techniques. The uniformly and densely arrayed micro/nanostructures greatly enhanced the water-resistance property of a surface, leading to a high water-contact angle of 155°.

Fig. 3(b) presents a schematic of a bio-inspired hydrophobic/-philic hybrid surface for fog harvesting by mimicking Namib Desert beetles [31]. They live in one of the driest areas on the earth, and can effectively gather water in foggy environments, owing to their wax-coated hydrophobic dorsal surface and few-hundred-microns-tall hydrophilic bumps. The authors fabricated a hydrophobic/-philic hybrid surface using copper oxidation and a PDMS casting process. The proposed hydrophobic/-philic hybrid surface was applied to water-harvesting devices in foggy environments and exhibited better performance than any other samples.

Fig. 3(c) depicts micropapillae and nanofolds inspired by the surfaces of red rose petals [32]. Micro/nanostructured surfaces were fabricated using the petal as a replication template and a solvent-evaporation-driven nanoimprint pattern-transfer process. These micro/nanostructures exhibited sufficient roughness for a superhydrophobic property with a contact angle of about 152.4°.

2.4 Bio-inspired Structures for Adhesives in Dry/Wet Environments

Over the last two decades, researchers have been actively investigating bio-inspired adhesives that mimic the unique dry and wet adhesion mechanisms of living systems. Robust and strong adhesion adjusted to harsh environments has played an important role in survival because it enables efficient activities, such as climbing. Extensive research over the last two decades has suggested various micro/nanostructures inspired by natural species.

Among the various creatures, gecko lizards, octopi, and beetles

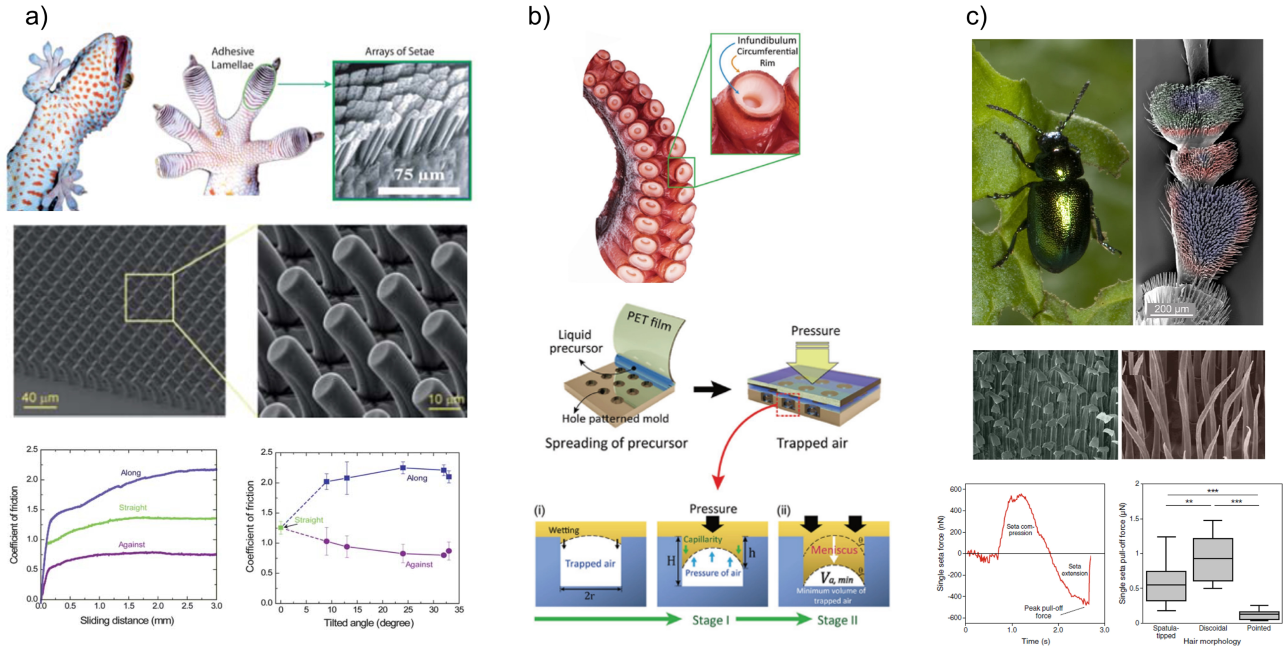

Fig. 4. Bio-inspired structures for adhesives in dry/wet environments. (a) Tilted Janus micropillars on an elastomeric polymer surface inspired by geckos' feet. Reprinted with permission from Ref. [34]; copyright (2010) Royal Society of Chemistry. (b) Dry/wet adhesion system inspired by protuberances in the suction cups of octopi. Reprinted with permission from Ref. [35]; copyright (2018) John Wiley and Sons. (c) Adhesives inspired by leaf beetles. Reprinted with permission from Ref. [36]; copyright (2016) Springer Nature.

have attracted significant attention, owing to their strong adhesion properties for climbing rough or curved surfaces, reusability, and applicability in dry/wet environments [33].

Fig. 4(a) depicts the tilted Janus micropillars on an elastomeric polymer surface inspired by geckos' feet [34]. A gecko's feet are covered with hundreds of thousands of micro-scale hair-like structures, which are responsible for the exceptional adhesion abilities. Tilted micropillars inspired by gecko lizards' footpads were fabricated by molding a photopatterned template with a soft elastomer, followed by an ion-beam exposure at a tilted angle (~30°). It was demonstrated that the friction force along the tilting direction was approximately three times higher than that against the tilting direction, owing to the difference in the contact area during the sliding of a glass ball.

Baik *et al.* demonstrated a dry/wet adhesion system inspired by protuberances in the suction cups of octopi (Fig. 4(b)) [35]. The adhesives inspired by an octopus use the mechanism of the pressure difference through a suction cup. An inner space, called the sucker, exists within the suction cup. The pressure drops in the suction cup with a volumetric change under an applied preload, where the dome-like structure inside the cavity maximizes the pressure difference between the inside and outside.

Artificial, reversible, and highly reproducible dry/wet adhesives are fabricated using a replicating polymeric master by partially filling a precursor composed of polyurethane-acrylate-based polymer into the micron-scale holes of a silicon mold, leaving small dimple structures at the bottom. Baik *et al.* also demonstrated an adhesive patch inspired by octopi that exhibited a rapid increase in its adhesion characteristics under dry/wet conditions.

Finally, James *et al.* suggested a new type of adhesive device inspired by leaf beetles (Fig. 4(c)) [36]. The beetles can climb rough and textured surfaces using arrays of micron-sized adhesive hairs with varying morphology. The authors measured the pull-off forces of three types of hair for comparison. Discoidal hairs exhibited the highest mean force (919 ± 104 nN), exceeding those of spatulate (582 ± 59 nN) and pointed (127 ± 19 nN) hairs.

Measuring adhesion characteristics at the level of individual hairs allowed researchers to not only understand how adhesion occurs in natural adhesive systems, but also to explain the functional implications of the various morphologies inspired by natural species.

3. CONCLUSIONS

This review highlighted recent research related to 3D micro/nanostructures inspired by nature, such as animals, insects, and plants. We summarized the fabrication process of well-designed 3D micro/nanostructures through transferring, replicating, and molding processes.

In addition, this review introduced recent advances in bio-inspired 3D micro/nanostructures for numerous advanced applications, such as pressure-sensing devices, triboelectric generators for sustainable energy harvesting, superhydrophobic/-philic surfaces, and adhesives in dry/wet environments.

Finding effective routes to fabricate and mimic these 3D micro/nanostructures is still a critical task to extend their applicability. It is expected that these developments will not merely prove their potential in engineering fields, but also suggest new approaches that are essential for adopting diverse practical applications in the future.

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REFERENCES

[1] B. Zhang, Q. Han, J. Zhang, Z. Han, S. Niu, and L. Ren, “Advanced bio-inspired structural materials: Local properties determine overall performance”, *Mater. Today*, Vol. 41, pp. 177-199, 2020.

[2] Y. Liu, H. Gu, Y. Jia, J. Liu, H. Zhang, R. Wang, B. Zhang, H. Zhang, and Q. Zhang, “Design and preparation of biomimetic polydimethylsiloxane (PDMS) films with superhydrophobic, self-healing and drag reduction properties via replication of shark skin and SI-ATRP”, *Chem. Eng. J.*, Vol. 356, pp. 318-328, 2019.

[3] I. H. Chen, J. H. Kiang, V. Correa, M. I. Lopez, P. Y. Chen, J. McKittrick, and M. A. Meyers, “Armadillo armor: Mechanical testing and micro-structural evaluation”, *J. Mech. Behav. Biomed. Mater.,* Vol. 4, No. 5, pp. 713-722, 2011.

[4] P. Zhang, L. Lin, D. Zang, X. Guo, and M. Liu, “Designing Bioinspired Anti-Biofouling Surfaces based on a Superwettability Strategy”, *Small.*, Vol. 13, No. 4, p. 1503334, 2019.

[5] Y. Zhao, C. Yu, H. Lan, M. Cao, and L. Jiang, “Improved Interfacial Floatability of Superhydrophobic/Superhydrophilic Janus Sheet Inspired by Lotus Leaf”, *Adv. Funct. Mater.,* Vol. 27, No. 27, p. 1701466, 2017.

[6] R. M. Erb, J. S. Sander, R. Grisch, and A. R. Studart, “Self-shaping composites with programmable bioinspired microstructures”, *Nat. Commun.,* Vol. 4, No. 1, pp. 1712(1)-1712(8), 2013.

[7] H. Zhu, R. Duan, X. Wang, J. Yang, J. Wang, Y. Huang, and F. Xia, “Prewetting dichloromethane induced aqueous solution adhered on Cassie superhydrophobic substrates to fabricate efficient fog-harvesting materials inspired by Namib Desert beetles and mussels”, *Nanoscale,* Vol. 10, No. 27, pp. 13045-13054, 2018.

[8] S. Zhang, J. Huang, Z. Chen, and Y. Lai, “Bioinspired Special Wettability Surfaces: From Fundamental Research to Water Harvesting Applications”, *Small*, Vol. 13, No. 3, p. 1602992, 2017.

[9] Y. Jung, J. Ahn, J. S. Kim, J. H. Ha, J. Shim, H. Cho, Y. S. Oh, Y. J. Yoon, Y. Nam, I. K. Oh, J. H. Jeong, and I. Park, “Spherical Micro/Nano Hierarchical Structures for Energy and Water Harvesting Devices”, *Small Methods,* Vol. 6, No. 7, pp. 2200248(1)-2200248(11), 2022.

[10] A. M. Brzozowska, S. Maassen, R. Goh Zhi Rong, P. I. Benke, C. S. Lim, E. M. Marzinelli, D. Jańczewski, S. L. M. Teo, and G. J. Vancso, “Effect of Variations in Micropatterns and Surface Modulus on Marine Fouling of Engineering Polymers”, *ACS Appl. Mater. Interfaces,* Vol. 9, No. 20, pp. 17508-17516, 2017.

[11] Z. Wang, Y. Sun, H. Wu, and C. Zhang, “Low velocity impact resistance of bio-inspired building ceramic composites with nacre-like structure”, *Constr. Build. Mater.,* Vol. 169, pp. 851-858, 2018.

[12] J. Ahn, Z. J. Zhao, J. Choi, Y. Jeong, S. Hwang, J. Ko, J. Gu, S. Jeon, J. Park, M. Kang, D. V. Del Orbe, I. Cho, H. Kang, M. Bok, J. H. Jeong, and I. Park, “Morphology-controllable wrinkled hierarchical structure and its application to superhydrophobic triboelectric nanogenerator”, *Nano Energy,* Vol. 85, p. 105978, 2021.

[13] X. Yan, F. Chen, S. Sett, S. Chavan, H. Li, L. Feng, L. Li, F. Zhao, C. Zhao, Z. Huang, and N. Miljkovic, “Hierarchical Condensation”, *ACS Nano,* Vol. 13, No. 7, pp. 8169-8184, 2019.

[14] Y. Zhang, S. Ma, B. Li, B. Yu, H. Lee, M. Cai, S. N. Gorb, F. Zhou, and W. Liu, “Gecko’s Feet-Inspired Self-Peeling Switchable Dry/Wet Adhesive”, *Chem. Mater.,* Vol. 33, No. 8, pp. 2785-2795, 2021.

[15] Y. Zang, F. Zhang, C. A. Di, and D. Zhu, “Advances of flexible pressure sensors toward artificial intelligence and health care applications”, *Mater. Horizons,* Vol. 2, No. 2, pp. 140-156, 2015.

[16] Y. Jung, K. K. Jung, D. H. Kim, D. H. Kwak, S. Ahn, J. S. Han, and J. S. Ko, “Flexible and highly sensitive three-axis pressure sensors based on carbon nanotube/polydimethylsiloxane composite pyramid arrays”, *Sensors Actuators A Phys.,* Vol. 331, p. 113034, 2021.

[17] L. Miao, J. Wan, Y. Song, H. Guo, H. Chen, X. Cheng, and H. Zhang, “Skin-Inspired Humidity and Pressure Sensor with a Wrinkle-on-Sponge Structure”, *ACS Appl. Mater. Interfaces,* Vol. 11, No. 42, pp. 39219-39227, 2019.

[18] Y. Jung, J. Choi, W. Lee, J. S. Ko, I. Park, and H. Cho, “Irregular Microdome Structure-Based Sensitive Pressure Sensor Using Internal Popping of Microspheres”, *Adv.*

Funct. Mater., Vol. 32, No. 27, pp. 2201147(1)-2201147 (12), 2022.

[19] B. Su, S. Gong, Z. Ma, L. W. Yap, and W. Cheng., "Mimosa?Inspired Design of a Flexible Pressure Sensor with Touch Sensitivity", *Small.,* Vol. 11, No. 16, pp. 1866-1891, 2015.

[20] D. Wang, X. Zhou, R. Song, C. Fang, Z. Wang, C. Wang, and Y. Huang, "Freestanding silver/polypyrrole composite film for multifunctional sensor with biomimetic micropattern for physiological signals monitoring", *Chem. Eng. J.,* Vol. 404, p. 126940, 2021.

[21] Y. Wei, S. Chen, Y. Lin, Z. Yang, and L. Liu "Cu–Ag core–shell nanowires for electronic skin with petal molded microstructure", *J. Mater. Chem. C.,* Vol. 3, No. 37, pp. 9594-9602, 2015.

[22] Y. Wan, Z. Qiu, Y. Hong, Y. Wang, J. Zhang, Q. Liu, Z. Wu, and C. F. Guo, "A Highly Sensitive Flexible Capacitive Tactile Sensor with Sparse and High-Aspect-Ratio Microstructures", *Adv. Electron. Mater.,* Vol. 4, No. 4, pp. 1700586(1)-1700586 (8), 2018.

[23] R. Lei, Y. Shi, Y. Ding, J. Nie, S. Li, F. Wang, H. Zhai, X. Chen, and Z. L. Wang, "Sustainable high-voltage source based on triboelectric nanogenerator with a charge accumulation strategy", *Energy Environ. Sci.,* Vol. 13, No. 7, pp. 2178-2190, 2020.

[24] C. Rodrigues, D. Nunes, D. Clemente, N. Mathias, J. M. Correia, P. Rosa-Santos, F. Taveira-Pinto, T. Morais, A. Pereira, and J. Ventura, "Emerging triboelectric nanogenerators for ocean wave energy harvesting: State of the art and future perspectives", *Energy Environ. Sci.,* Vol. 13, No. 9, pp. 2657-2683, 2020.

[25] V. T. Bui, Q. Zhou, J. N. Kim, J. H. Oh, K. W. Han, H. S. Choi, S. W. Kim, and I. K. Oh, "Treefrog Toe Pad-Inspired Micropatterning for High-Power Triboelectric Nanogenerator", *Adv. Funct. Mater.,* Vol. 29, No. 28, pp. 1901638(1)-1901638(10), 2019.

[26] G. Yao, L. Xu, X. Cheng, Y. Li, X. Huang, W. Guo, S. Liu, Z. L. Wang, and H. Wu, "Bioinspired Triboelectric Nanogenerators as Self-Powered Electronic Skin for Robotic Tactile Sensing", *Adv. Funct. Mater.,* Vol. 30, No. 6, pp. 1907312(1)- 1907312 (9), 2020.

[27] Q. Zhou, K. Lee, K. N. Kim, J. G. Park, J. Pan, J. Bae, J. M. Baik, and T. Kim, "High humidity- and contamination-resistant triboelectric nanogenerator with superhydrophobic interface", *Nano Energy,* Vol. 57, pp. 903-910, 2019.

[28] D. Yoo, S. C. Park, S. Lee, J. Y. Sim, I. Song, D. Choi, H. Lim, and D. S. Kim, "Biomimetic anti-reflective triboelectric nanogenerator for concurrent harvesting of solar and raindrop energies," *Nano Energy,* Vol. 57, pp. 424-431, 2019.

[29] Y. Si, Z. Dong, and L. Jiang, "Bioinspired Designs of Superhydrophobic and Superhydrophilic Materials", *ACS Cent. Sci.,* Vol. 4, No. 9, pp. 1102-1112, 2018.

[30] X. Gao, X. Yan, X. Yao, L. Xu, K. Zhang, J. Zhang, B. Yang, and L. Jiang, "The dry-style antifogging properties of mosquito compound eyes and artificial analogues prepared by soft lithography", *Adv. Mater.,* Vol. 19, No. 17, pp. 2213-2217, 2007.

[31] J. K. Park and S. Kim, "Three-dimensionally structured flexible fog harvesting surfaces inspired by Namib desert beetles", *Micromachines,* Vol. 10, No. 3, pp. 201(1)-201(10), 2019.

[32] L. Feng, Y. Zhang, J. Xi, Y. Zhu, N. Wang, F. Xia, and L. Jiang, "Petal effect: A superhydrophobic state with high adhesive force", *Langmuir,* Vol. 24, No. 8, pp. 4114-4119, 2008.

[33] M. Kang, K. Sun, M. Seong, I. Hwang, H. Jang, S. Park, G. Choi, S. H. Lee, J. Kim, and H. E. Jeong, "Applications of Bioinspired Reversible Dry and Wet Adhesives: A Review", *Front. Mech. Eng.*, Vol. 7, pp. 668262(1)-668262(14), 2021.

[34] M. W. Moon, T. G. Cha, K. R. Lee, A. Vaziri, and H. Y. Kim, "Tilted Janus polymer pillars", *Soft Matter,* Vol. 6, No. 16, pp. 3924-3929, 2010.

[35] S. Baik, J. Kim, H. J. Lee, T. H. Lee, and C. Pang, "Highly Adaptable and Biocompatible Octopus-Like Adhesive Patches with Meniscus-Controlled Unfoldable 3D Microtips for Underwater Surface and Hairy Skin", *Adv. Sci.,* Vol. 5, No. 8, pp. 1800100(1)-1800100(7), 2018.

[36] J. M. R. Bullock and W. Federle, "Beetle adhesive hairs differ in stiffness and stickiness: In vivo adhesion measurements on individual setae", *Naturwissenschaften,* Vol. 98, pp. 381-387, 2011.