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Research article

Water harvesting on biomimetic material inspired by bettles

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A R T I C L E I N F O

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A B S T R A C T

Many organisms in nature such as beetles and cacti can survive in arid places by their own surface structures that are still able to collect mist. These surfaces have micro-nano structures that maintain a very low adhesion, allowing them to continuously collect and transport water. Here, we used a light curing three dimensional molding process to create a template for a water harvesting system inspired by the back of a beetle, a hydrogel-like beetle back surface for water transport. By changing the curvature structure of the water evacuation channels and altering the hydrophilic and hydrophobic properties of the surface, the designed large-scale artificial water harvesting study was made possible. The results show that if the surface has a proper curvature structure and hydrophobic density, the water collection on the super-impregnated surface is much higher than that on an ordinary hydrophobic surface. Based on this, a new efficient and environmentally friendly water collection scheme is proposed. The data show that the triangular tip structure imitating beetle-backed hydrogel surface collects the highest amount of water with a water weight of 16 g in 2 h. This study offers interesting prospects for designing a new generation of structural materials with a bionic structure distribution for high-efficiency water harvesting. The results of the study are useful for pushing the improvement of environmental-friendly water collection, transport and separation devices.

Abbreviations: The dorsal shape of the beetle's back is critical for water collection. In this work, while redesigning the shape of the back of the beetle, the method of 3D printing the beetle back template was used to prepare the beetle back made of hydrogel, which greatly improved the water collection performance and has certain engineering application prospects.

- New beetle back shape design greatly improves water collection performance
- The convenience of 3D printing technology and the precision of microstructures

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1. Introduction

One of global concerns is the shortage of freshwater resources. Some arid regions in Africa, Latin America, and Asia have a severe shortage of freshwater resources for daily production and use [1, 2, 3]. Many efforts have been devoted in the last decades to solve this issue of water stress with various technologies, such as purification technologies of wastewater, desalination technologies of seawater and water harvesting technologies [4, 5, 6, 7, 8]. Especially for water harvesting, some plants and animals in desert areas rely on their unique structure, which makes them very good at trapping dew and fog. For example, cacti can effectively trap mist from all directions using spikes and micro-notches on their conical surfaces [9, 10, 11, 12, 13, 14, 15]; Namibian desert beetles can quickly collect water in humid air using striated bumps on their bodies and hydrophilic and hydrophobic regions on their backs [16, 17, 18]; and tiny periodically arranged spindle bodies on spider silk also make them good at trapping mist [19, 20, 21]. These organisms cleverly exploit surface free energy and Laplace pressure differences as the main driving force for water collection [22, 23, 24, 25, 26]. For plants and animals in arid desert regions, mist is a better water resource than precipitation and can also be used as a supplementary water source for humans. Hence, inspired by biological structures water, the biomimic natural fog collection systems has attracted intensive interest and been widely studied to improve the efficiency of fog collection capacity [27, 28, 29] Researchers have designed various fog water collection systems based on differences in surface wettability. Li *et al.* designed a multi-directional artificial spine surface and sputtered hydrophobic coatings on the surface to accelerate water flow and improve water collection efficiency [30]. Li *et al.* based on the bionic structure of multiple curved bodies to trap water and illustrated the mechanism of water trapping in the periplasmic pores of pigweed [31]. Ju *et al.* investigated the relationship between conical spine clusters and trichomes on cactus stems for fog collection [32]. Based on the mechanistic explanation of the above studies, many have used the Laplacian pressure difference induced by shape and wettability gradients to achieve efficient water collection performance [16, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44]. Although these reports have artificially fabricated hybrid wettability surfaces based on beetle backs, most of them have focused on water collection efficiency studies of single arrays, whereas the natural beetle back is a complete arch-shaped collection system with amazingly efficient mist water collection capabilities. Artificially preparing controlled arrays of multi-channel hybrid wettability surface systems is challenging. There are few reports about significant improvement of the efficiency of fog water collection by controllable three-dimensional shapes.

Although much effort has been made by researchers to design hybrid surfaces with high wettability differences by achieving superhydrophilic clustering on a superhydrophobic background, the actual hydrophilic three-dimensional raised structures of fog collecting surfaces on curved beetle-back surfaces have rarely been studied. For example, some flat surfaces with micro-nano structures have been reported previously, which only resemble beetle backs in microstructure, but do not correspond to the actual situation in macroscopic morphology [42]. Therefore, it is necessary to construct three-dimensional concave and convex structures on curved geometrical morphological surfaces and to study the effect of their surfaces on fog water collection.

Light cured three dimensional molding technology (briefly called as 3D printing) is one of the effective methods for rapid fabrication of complex multi-curvature parts, which has been widely applied in industry, scientific research, and daily life in recent years [43]. The application of 3D printing technology in bionic material fabrication is a novel direction [44, 45, 46, 47, 48]. Here, we designed a water collection surface imitating the back of a desert beetle and changed the wettability of the surface to improve the water collection efficiency. The curvature structures of the imitation beetle back surfaces were investigated and optimized based on aerodynamic theory. The triangular tip structure hydrogel surface of the imitation beetle back shows excellent water collection performance. As an environment-friendly water collection system, the optimized 3D-printed surface of the bionic beetle back shows latent capacity in applications of high-efficiency water collection, transportation of water and separation of oil-water.

2. Experimental section

2.1. 3D printed beetle back and template

The raw material for the photosensitive resin is epoxy acrylic resin. Different beetle back structures were designed by solidworks2018 software and converted into STL format for importing into 3D printer (EnvisionTec P4 LED Mini) for secondary data processing. A 405 nm LED light source (intensity 20 mW/cm^2) was used to adjust the XY pixel resolution to 20 microns, with an exposure time of 2 s per layer, and finally cured with a medium-pressure mercury lamp (intensity 30 mW/cm^2). The detail parameters for all structures are shown in Figure S3. The each units is 2 mm apart. The height or depth is different for each structures as shown in the following Figure S3.

2.2. Preparation of imitation beetle back hydrogel

By replicating the surface morphology of the 3D printing template, an artificial hydrophilic polyvinyl alcohol (PVA) hydrogel replica was prepared. The 3D printing template was first treated by Plasma (the water collections on 3D printing templates are also tested as shown in Figure S2). The PVA powder is dispersed in a liquid mixed with deionized water (DI water) and dimethyl sulfoxide (DMSO) at room temperature for 0.5 h to swell. The mass ratio of PVA: DI water: DMSO is 4:9:27. The dispersion was then heated in a water bath at a temperature of 90 °C and stirred at a speed of 600 rpm for 4 h to completely dissolve PVA powder. Pour the PVA solution onto the printed resin template and store it in a refrigerator at −10 °C for 10 h to prepare a PVA hydrogel replica. The surfaces of PVA hydrogel replica were investigated by ultra-depth three-dimensional microscope (VHX-6000, Keyence, Japan). The images of the surface roughness of these hydrogel surfaces are shown in Figure S4.

Figure 1. Inspired by the Namib beetle and biomimetic preparation of the beetle's back. (A) Natural beetle using its back to collect water [13]. (B) Physical view of the 3D printed beetle back. (C) Schematic diagram of the printed beetle back simulating a water collection device in a high humidity environment.

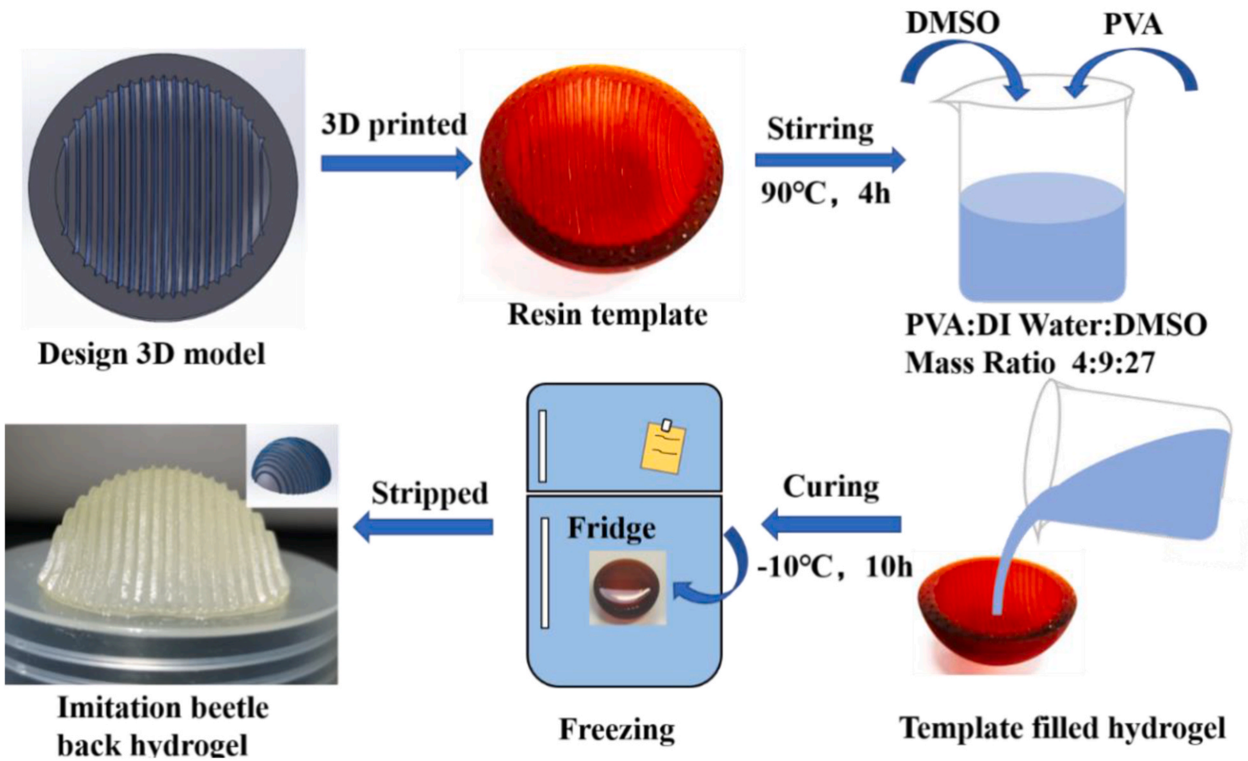

Figure 2. Schematic diagram of the preparation process of hydrogel-like beetle back structure.

2.3. *Water collection testing and measurement*

The mist was controlled by a humidifier (MH-400, MELING) with a mist flow rate of about 15 cm/s, allowing the bionic beetles back to collect mist at a humidity of about 90%. The distance between the humidifier nozzle and the sample was kept at about 5 cm. The collected liquid mass was recorded in real time by an electronic balance (JJ224BC) every 30 min for a total of 4 times.

3. Results and discussion

A typical beetle dorsal surface adhering to water droplets is shown in Figure 1A. There are many tiny raised structures on the dorsal surface of the beetle, which are capable of retaining water from the air on the dorsal surface and conducting directional transport to obtain water resources that can sustain life [17]. Inspired by the water collection principle of beetle dorsum, we exploit light-curing 3D printing technology to prepare bionic beetle dorsal water collection devices and obtained a set of beetle dorsal structures with different curvature structures (as shown in Figure 1B). The water collection ability of 3D printed beetle backs was investigated in saturated humid air with 90% relative humidity at room temperature. Figure 1C shows the laboratory homemade fog water collection device, including humidifier, iron holder and glass dish. When the 3D printed beetle back was put in a high humidity environment, water droplets were able to adhere to and gradually cover the entire surface on the curvature structure of the surface, and drip down into the

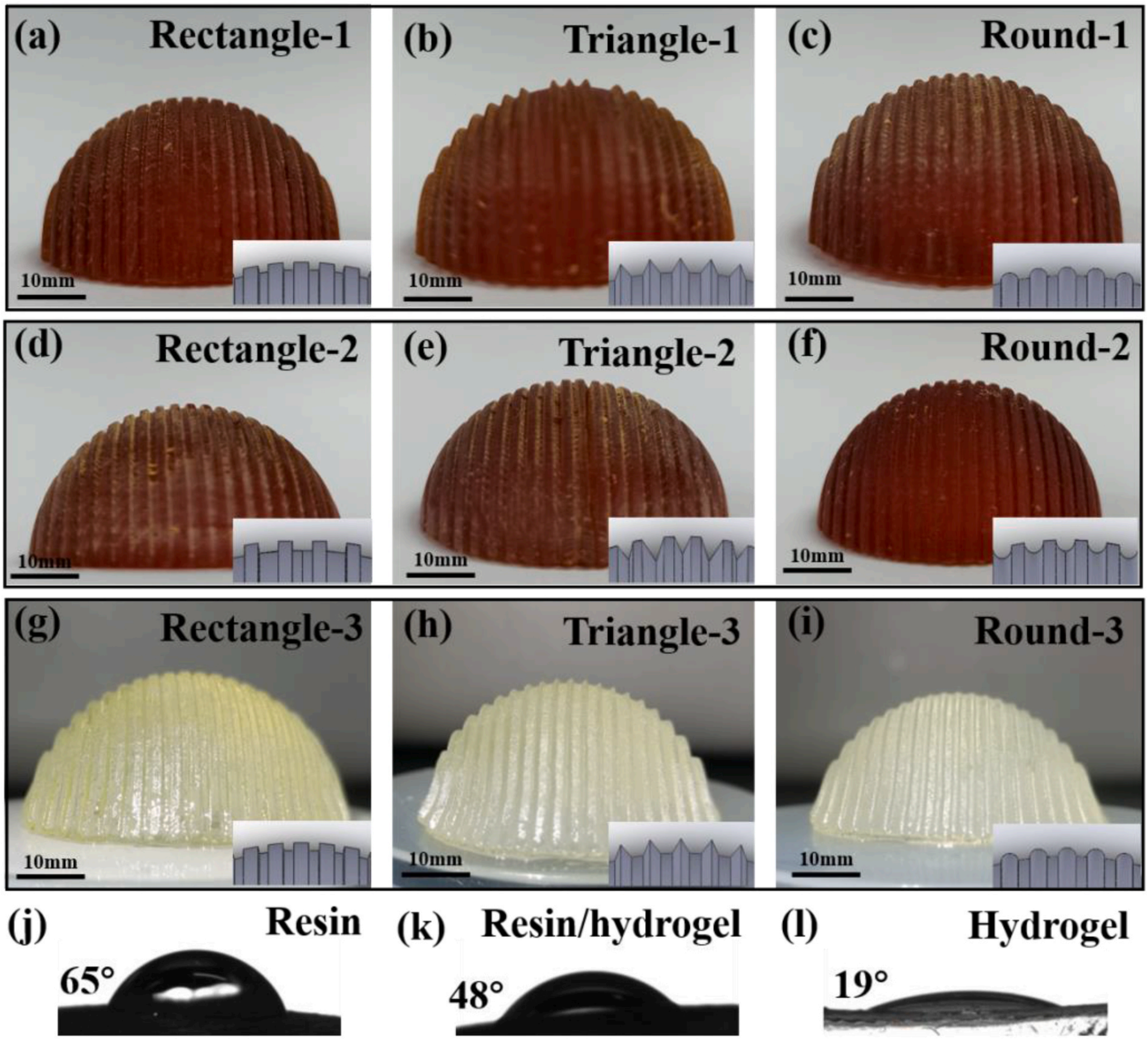

Figure 3. 3D printed beetle back model. (A–C) 3D printed beetle backs with different structures on convex surfaces; (D–F) 3D printed beetle backs with different structures on concave surfaces; (G–I) Hydrogel beetle backs with different structures; (J–L) Contact angles of the printed resin material, resin coated hydrogel and PVA hydrogel material surfaces. The inset corresponds to a partial enlargement of the beetle back model.

glass dish under the effect of gravity.

Figure 2 shows the preparation process of imitation beetle-back hydrogel. The beetle back template was printed using 3D printing technology, and then PVA and DMSO were dissolved in deionized water by heating at a certain mass ratio to obtain PVA hydrogel. The hydrogels were poured into the templates and frozen at −10 °C for 10 h to prepare hydrogel beetle backs with different curvature structures.

The ability of the beetle back to trap mist is related to the surface structure and the adhesion of the surface to the droplets, while the Laplace pressure of the surface structure affects the droplet transport rate. As shown in Figure 3, three surface shapes with different curvatures, rectangular, triangular and circular structures, were designed, and the three structures were compared with convex and concave surfaces (as shown in Figure 3A, B, C, D, E, F). It is well known that the chemical surface modification and the surface roughness will affect the surface tension and adhesion of water, and hydrophilic surfaces are more favorable for water collection [8, 36]. Therefore, we coated the surface of 3D printed structures with a hydrophilic PVA hydrogel to change the hydrophilicity of the original resin surface. As can be seen from Figure 3J, K, L, the water contact angle of the resin surface used directly for 3D printing was 65°, while the contact angle was reduced to 48° after coating the resin surface with a layer of PVA hydrogel, and the contact angle of the PVA hydrogel surface was only 19°, and the contact angle was approximately equal to 0° after 3s. We have also tested the sliding angle of these hydrophilic surfaces. The results are shown in Figure S5 in the supporting information.

As shown in Figure 4A, the curves of water collection with time from the fog trapping experiments show that the water collection of beetle dorsal for triangular structures on the convex surface is better than that of rectangles similar to that of circles, and the water collection of triangular structures for 2 h is higher than that of rectangles by about 0.5 g. Because the curvature change of triangles and circles is greater than that of rectangles, the fog is more easily collected and transmitted on the surface of the structures. While the water collection of different structures of beetle back on the concave surface is similar to that on the convex surface (as shown in Figure 4B), the water collection of triangular and circular structures is about 1 g higher than that of rectangles, and the water collection of rectangular structures on the concave surface is 0.37 g lower than that of the convex surface. Because the rectangular structures on

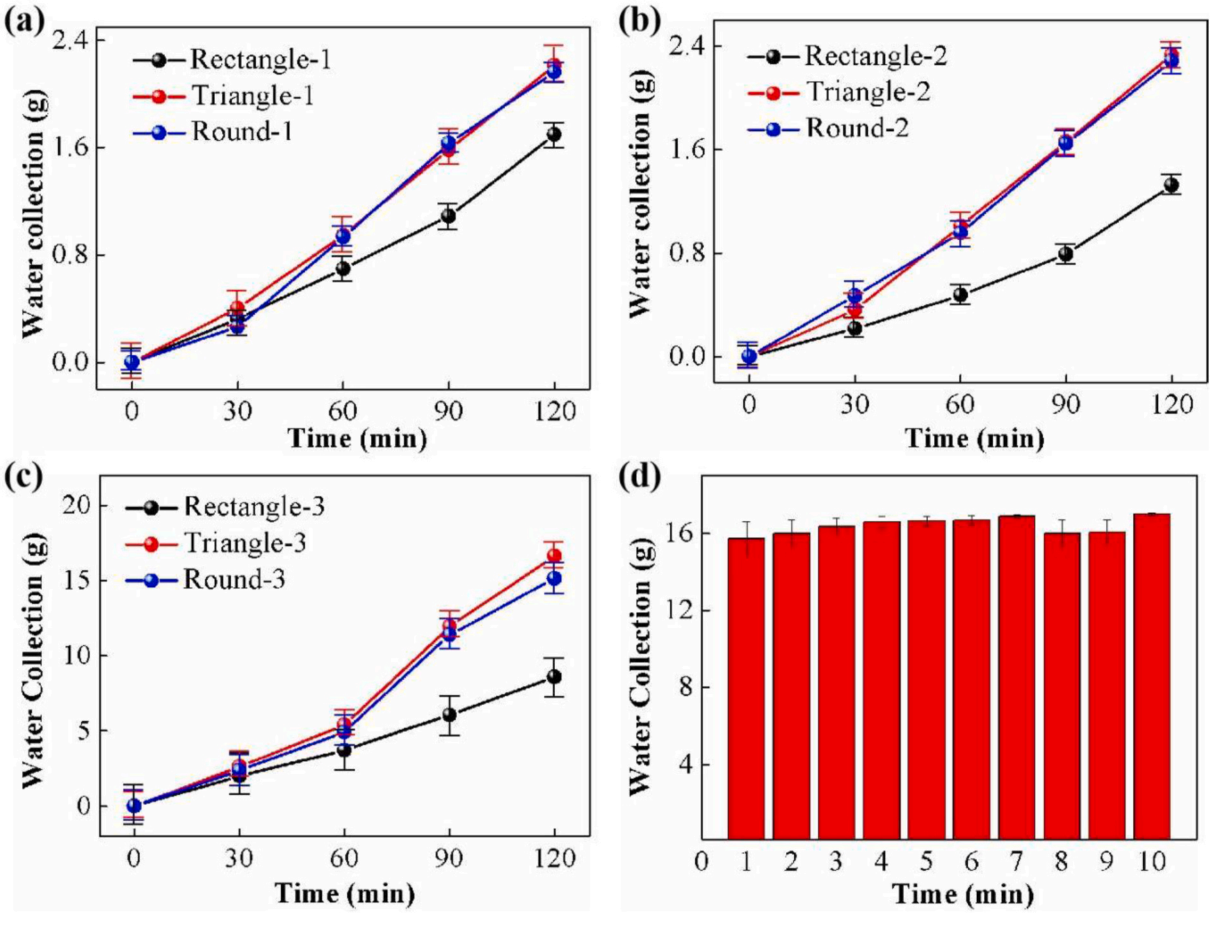

Figure 4. Effects of beetle back shape and hydrophilicity on water-collecting performance. (A) Curves of water collection of beetle back with time for 3D printing different structures on convex surface. (B) Curves of water collection of beetle back with time for 3D printing different structures on concave surface. (C) Curves of water collection of hydrogel beetle back with time for different structures. (D) Variation of water collection of hydrogel beetle back optimal model (Triangle-3) with different number of cycles.

the convex surface are more dense, while the size of rectangles on the concave surface is larger. As can be seen in Figure 4A and B, the triangular structure collects slightly more mass of fog water than the circular structure due to the greater curvature of the tip of the triangle and the smoother tip of the circle, so the Laplace pressure of the triangular structure is greater than that of the circular structure [21]. As shown in Figure S1, the trend is very stable when test other new samples. While the rectangle has the flattest tip, so it collects the least amount of water. Since the effect on water collection is not significant between the same structures on the convex and concave surfaces, we performed only hydrogel replicas of the convex structures at the center of our hydrogel replica beetle dorsum study.

The natural beetle back is a patterned surface that collects and then transports water from the hydrophilic region which is highly adhesive to water. We replicated the beetle dorsum with a very hydrophilic PVA hydrogel to obtain a hydrogel replica as in Figure 3G, H, I. As seen in Figure 4C, the water collection of the hydrogel replica with triangular structure (Triangle-3) is significantly enhanced to 16.65 g, which is 8 times higher than the previous Triangle-1 and Triangle-2. The water collection of Rectangle-3 is still lower than Triangle-3 and Round-3, confirming the effect of Laplace pressure and curvature on water collection. The water in the mist adheres heavily to the hydrophilic hydrogel and forms a water film on the surface, which accelerates the liquid transfer rate as the water continues to collect, thus enhancing the water collection; whereas the pristine resin surface is less hydrophilic and it is difficult for the water in the air to collect on the back surface of the beetle. Figure 4D shows that the optimal triangular structure hydrogel beetle back can stabilize the water collection on the 2 h surface above 16 g after 10 times mist water collection, and this structure shows excellent stable water collection performance. The detailed sequential optical images during water collecting process were provided in Figure S6. The movies about water collecting process can be seen in Supplementary Information.

Based on the structural characteristics of the beetle back, it's water collection process is divided into three stages: firstly, water in the air is adsorbed onto the hydrophilic bumps on the back (as shown in Figure 5a); secondly, small water droplets on the bumps continuously polymerize with air and adjacent water droplets to grow into large water droplets; thirdly, large water droplets of a certain size slide down the ridges of the bumps into the bottom transfer channel to slide down into the collection device. As shown in Figure 5b, for the strongly hydrophilic hydrogel beetle back surface, the water in the mist is adsorbed by the strongly hydrophilic raised surface and gradually grows to form a water film. At the same time, the water film surface attraction will further adsorb water, and when the water film spreads between the hydrophilic bump and the bottom transfer channel, it will be anchored on the surface because the three-phase contact line is too small, and the water film increases in the thickness direction and gradually slides down the transfer channel directionally. The whole process of water collection is through the cycle of adsorption→agglomeration→transfer, thus achieving a directional mist collection effect. The combination of commonly available gel materials and 3D printing technology to prepare a low-cost water collection system has a certain reference value for solving the drought problem in desert areas.

As shown in Figure 6, we have also compared the collecting efficiency of this beetle back with other structures [49, 50, 51, 52], although the efficiency of beetle back is a little bit lower than that of spider web, it still provide a biomimic strategy for water collecting.

4. Conclusion

In summary, based on the problem of water scarcity in life, we prepared a mock beetle back surface using 3D printing technology and investigated the curvature structure and hydrophilicity on the surface. The three-dimensional convex curvature of the back of the beetle has been optimized, and different structures of the back of the beetle have been designed. The results show that the hydrophilic triangular structure of the hydrogel surface has more robust water collection ability compared with other structures. The key factors

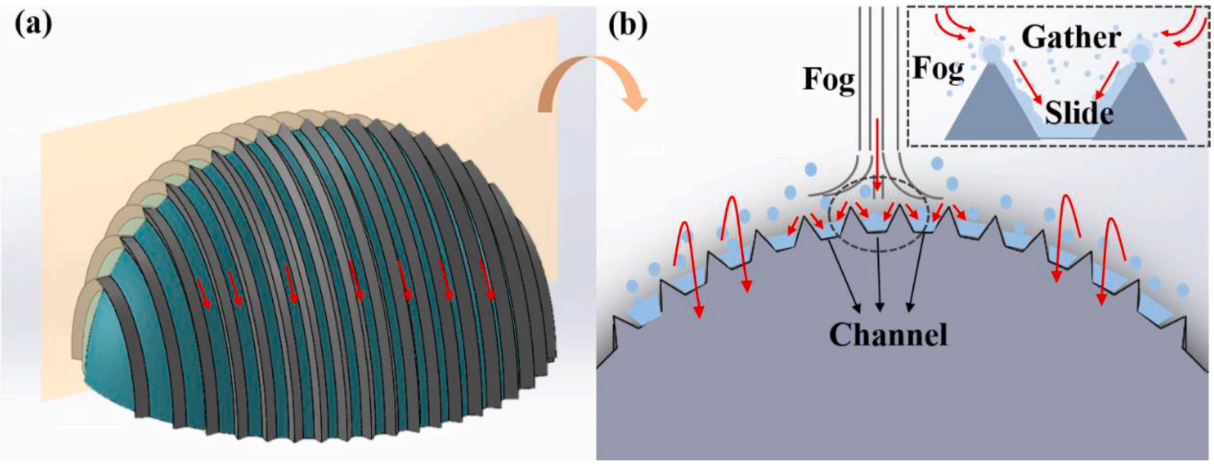

Figure 5. Mechanism of water collection on the back of beetles. (A) Model diagram of water transport on the back of a complete beetle, with red arrows showing the direction of transport. (B) Schematic diagram of the cross-section of the beetle's back when collecting water, with the inset showing the water collection process: adsorption→agglomeration→transport.

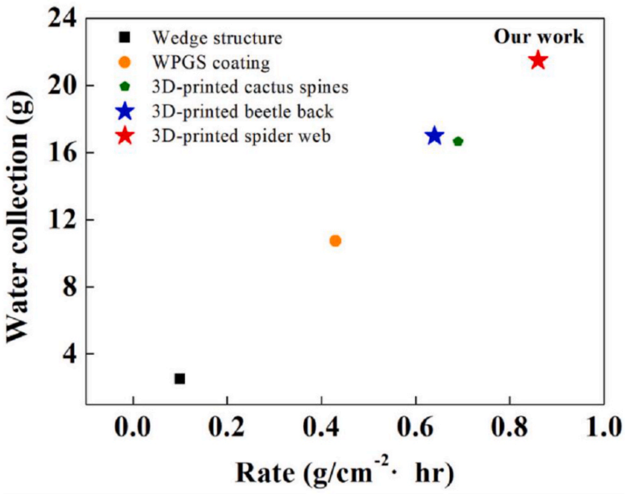

Figure 6. Comparision of the water collection effect between our work and previously reported works by other processing methods.

include: first, the unique arch-shaped structure of the beetle back plays the role of integrated curvature in the process of fog water collection and transportation; second, the Laplace pressure induced by the surface gradient of the triangular structure confers an effective water collection and transportation system on the beetle back surface; third, the hydrophilic hydrogel surface intensifies the adhesion of small droplets in the air, and the water film formed on the surface accelerates the droplet transport rate, thus enhancing the water collection water collection. The study of the structure on this surface will help ~~us~~ to design new materials and devices to collect water in fog and transport condensate efficiently. the introduction of 3D printing technology enables rapid fabrication and mass production, and may have a role in alleviating water scarcity in desert areas.

Declarations

Author contribution statement

Lian Jiang: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Chi Guo: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Meng Fu: Analyzed and interpreted the data.

Xiaojing Gong: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Seeram Ramakrishna: Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of interests statement

The authors declare no competing interests.

Additional information

Supplementary content related to this article has been published online at https://doi.org/10.1016/j.heliyon.2022.e12355.

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