J Bionic Eng 18 (2021) 501–533
DOI: https://doi.org/10.1007/s42235-021-0040-0

Journal of Bionic Engineering
http://www.springer.com/journal/42235

Bio-inspired Fog Harvesting Materials: Basic Research and Bionic Potential Applications

Kui Wan[1,2], Xuelian Gou[1,2], Zhiguang Guo[1,2*]

1. *Ministry of Education Key Laboratory for the Green Preparation and Application of Functional Materials*, *Hubei University*, *Wuhan* 430062, *China*
2. *State Key Laboratory of Solid Lubrication*, *Lanzhou Institute of Chemical Physics*, *Chinese Academy of Sciences*, *Lanzhou* 730000, *China*

Abstract

With the explosive growth of the world's population and the rapid increase in industrial water consumption, the world's water supply has fallen into crisis. The shortage of fresh water resources has become a global problem, especially in arid regions. In nature, many organisms can collect water from foggy water under harsh conditions, which provides us with inspiration for the development of new functional fog harvesting materials. A large number of bionic special wettable synthetic surfaces are synthesized for water mist collection. In this review, we introduce some water collection phenomena in nature, outline the basic theories of biological water harvesting, and summarize six mechanisms of biological water collection: increased surface wettability, increased water transmission area, long-distance water delivery, water accumulation and storage, condensation promotion, and gravity-driven. Then, the water collection mechanisms of three typical organisms and their synthesis are discussed. And their function, water collection efficiency, new developments in their biomimetic materials are narrated, which are cactus, spider and desert beetles. The study of multiple bionics was inspired by the discovery of Nepenthes' moist and smooth peristome. The excellent characteristics of a variety of biological water collection structures, combined with each other, are far superior to other single synthetic surfaces. Furthermore, the main problems in the preparation and application of biomimetic fog harvesting materials and the future development trend of materials fog harvesting are prospected.

Keywords: water crisis, superhydrophobic, special wettability, fog harvesting, mechanism, bionic potential, multiple bionics

1 Introduction

Water resources are the basic natural resources that are related to the survival and development of human society. The total amount of water resources in our country is large, but per capita possession of fresh water is very low, and the spatial and temporal distribution is very different. Human production and life are inseparable from water. Without water, everything does not exist[1–4]. Although the earth is a blue planet, and the ocean occupies about 70% of the total area, the available freshwater resources are very scarce, accounting for only 2.53% of the total water volume, and 98% of them are glaciers and deep groundwater which distribute at the poles, so that it is difficult to be exploited in areas and buried underground. With the rapid development of industry in the past century and the rapid increase in the population, the demand for fresh water resources in human society has also increased, and the existing fresh water resources have been unable to meet people's normal demand. According to the global water scarcity assessment, it was found that 4 billion people around the world live in an environment of extreme water scarcity for at least one month a year (Fig. 1), and half of them live in India and China, nearly 500 million people in the world face serious water shortage[5]. The shortage of water resources is an urgent issue. How to increase the access to water resources and allocate them rationally is a top priority[6,7].

It is not the strongest of the species that survive, but the one most responsive to change. In the long time, nature creatures have adapted to various extremely harsh living environments through continuous evolution, such as the desert and Gobi, showing their unique life

---

***Corresponding author:** Zhiguang Guo
E-mail: zguo@licp.cas.cn

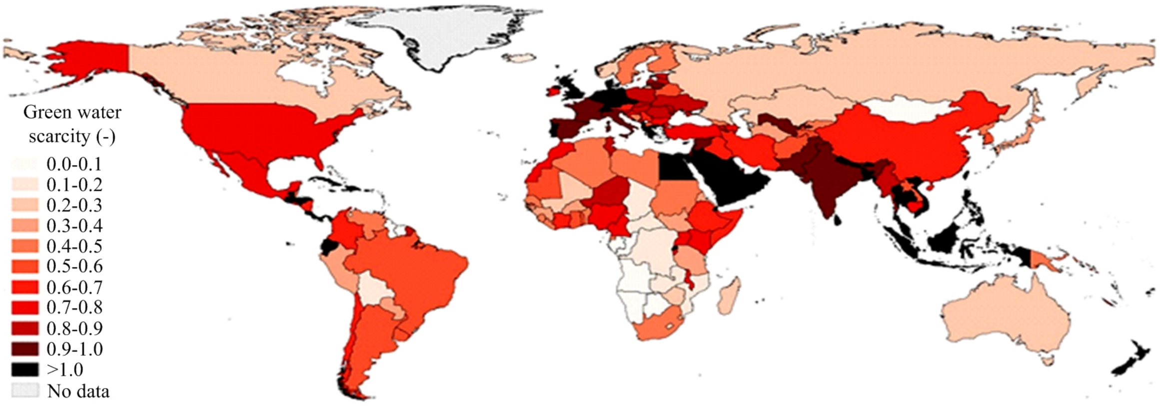


Fig. 1 Distribution of world freshwater resources. The picture was adapted with permission from Ref. [8]. Copyright 2019 by National Academy of Sciences.

characteristics[9,10]. Creatures in nature evolve to form special structures that can adapt to the environment. This also inspires us to study its water-collection mechanism from nature in order to face our increasingly serious water shortage problem, and bionics came from this. Bionics is a discipline that prepares corresponding substances by imitating the structure of organisms which was proposed by Steele[11]. The Webster Dictionary (1974) defines it as: imitating and synthesizing similar products by studying the production of substances and materials in nature (Enzyme or silk) formation, structure or function, as well as biological mechanisms and processes (protein synthesis or photosynthesis)[12]. With the development of advanced observation equipment and technology in the 20th century, biologists and materials scientists began to study the structural characteristics of the surface of natural superhydrophobic materials. In 1997, Barthlott *et al.* reported the super-hydrophobicity of the lotus leaf surface (Fig. 2a)[13]. Scientists studied the lotus leaf surface by SEM and found that the super-hydrophobicity of the lotus leaf is related to the surface microstructure. As we all know, plant epidermis is mainly composed of a stratum corneum network and a hydrophobic waxy compound. The stratum corneum wax is a film with a 2D structure or a block with a 3D structure or a combination of these two. The hydrophobic leaf also has an important function that it can still keep clean and self-cleaning ability in the dirty water, this is called the "lotus effect". Each epidermal cell on the surface of the lotus forms a single mastoid or a papillary shape through cell division and a large number of mastoids form micro-roughness. At the same time, the waxy compound can also produce nano-scale bumps. The roughness of the microstructure on the rough surface and the wax with low surface energy work together, and the roughness plays a dominant role in the "Lotus effect", making the surface of the lotus leaf superhydrophobic[14–20]. The static Water Contact Angle (WCA) and slide angle of the lotus leaf are about 164° and 3°, and we call this surface a superhydrophobic surface. A superhydrophobic surface that is a surface with a water contact angle greater than 150° and a slide angle less than 10°. Inspired by the "Lotus Effect", scientists began to study more superhydrophobic surfaces in nature. For example, rose petals' WCA is greater than 150°, but the surface has a large adhesion to water. The water droplets on the surface of the petals are spherical, and the water droplets will not roll off even if the petals are inverted. This phenomenon is called the "petal effect" (Fig. 2b)[21–25]. In addition, the rice leaf surface also has a self-cleaning properties, and the rolling of water droplets dripping on the rice surface also has a certain anisotropy (Fig. 2c)[26]. The discovery of the natural superhydrophobic microstructures has greatly illuminated the study of bionic superhydrophobic surface materials. Inspired by the phenomenon of super-hydrophobicity on the surface of plant leaves, scientists began to study the surface of animals. Finally, the study found that some animal surfaces are also superhydrophobic. Gao *et al*. found that the legs of the leech have a special layered structure (Fig. 2d) which is covered by a large number of directional multilayered bristles with micro-grooves. Each of micro-grooves is about 50 μm long, and the surface of the bristles has finer nano spiral groove[27].

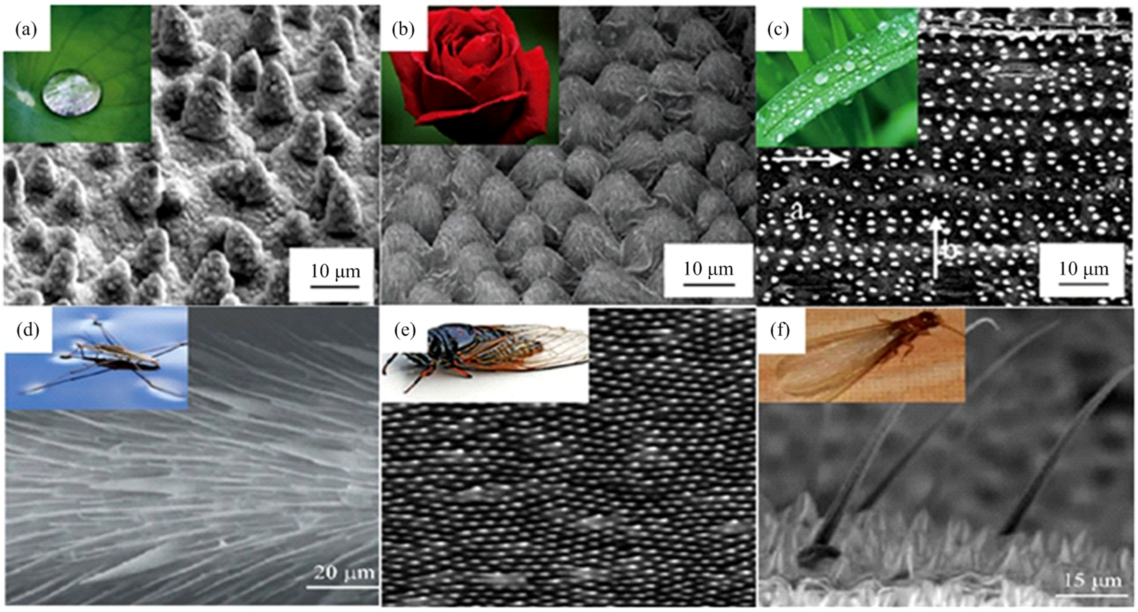


Fig. 2 SEM photograph of superhydrophobic biological surface with micro-nano structure: (a) Lotus leaf; (b) rose petal; (c) rice leaf; (d) water strider; (e) cicada wing; (f) termite wings. (a) was adapted with permission from Ref. [27]. Copyright 1997 by Springer Verlag. (b) was adapted with permission from Ref. [28]. Copyright 2008 by American Chemical Society. (c) was adapted with permission from Ref. [29]. Copyright 2013 by Royal Society of Chemistry. (d) was adapted with permission from Ref. [30]. Copyright 2004 by Nature Publishing Group. (e) was adapted with permission from Ref. [31]. Copyright 2004 by Elsevier. (f) was adapted with permission from Ref. [32]. Copyright 2010 by American Chemical Society.

Gao *et al*. also found that compound eyes of mosquitoes have the special functions of super-hydrophobicity and anti-fog (Fig. 2e). Even when exposed to moist environment, the mosquito eyes can still keep dry and clear vision. In this study, artificial mosquito compound eyes were prepared by using photolithography to simulate the compound eye structure of mosquitoes[28]. Waston *et al.* studied the microstructure of the surface of the cicada wing (Fig. 2f), and found that the hexagonal filled array structure is arranged on the cicada wing, and it is distributed at a pitch of 200 nm – 1000 nm. This special structure makes the cicada wing have super-hydrophobic properties[29]. It was found that the termite's wings had a large amount of body hair, micro-convex structures, and a large number of grooves. After the surface of the body hair is treated with the coating, its microstructure disappears, the adhesion of water droplets on the surface of the body hair increases and the hydrophobicity decreases. This indicates that the micro-nano rough structure formed by the grooves and micro-convex structures distributed on the surface of termite body hair is the main reason for its excellent super-hydrophobicity[30]. These materials are widely used in energy saving, oil-water separation and other fields because of their excellent super-hydrophobicity and self-cleaning properties[31–38].

Water is the source of life and the lifeblood of economic construction, so it is very important for production and life. The atmosphere is rich in fresh water, and it is not limited by the region, especially in the islands and coastal areas with high air humidity, so that it has become a hot spot to obtain fresh water resources. Up to now, people's utilization rate of fresh water in the air is very low, so it can be seen that there is great potential to fog collection technology to obtain fresh water resources. In nature, some organisms can collect water vapor to survive in extremely arid environment. For example, spontaneous directional movement of liquid in Sarracenia (Fig. 3a)[39] and Nepenthes[40] in marsh area, directional movement of droplets on the surface of butterfly wings (Fig. 3c)[41], *Setaria viridis* (Fig. 3b)[42], Australian tree frog (Fig. 3d)[43] and other creatures can collect water from the air. A typical phenomenon is that the Laplace pressure gradient and surface energy gradient formed by the surface structure are used by cactus spines[44] and spider silk[45] to collect water. The

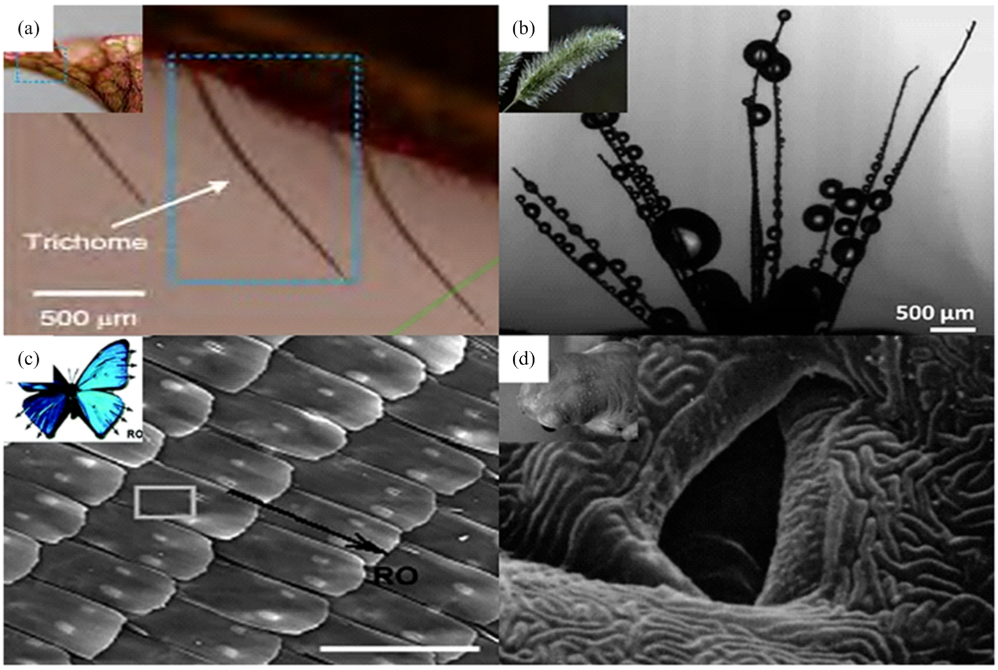


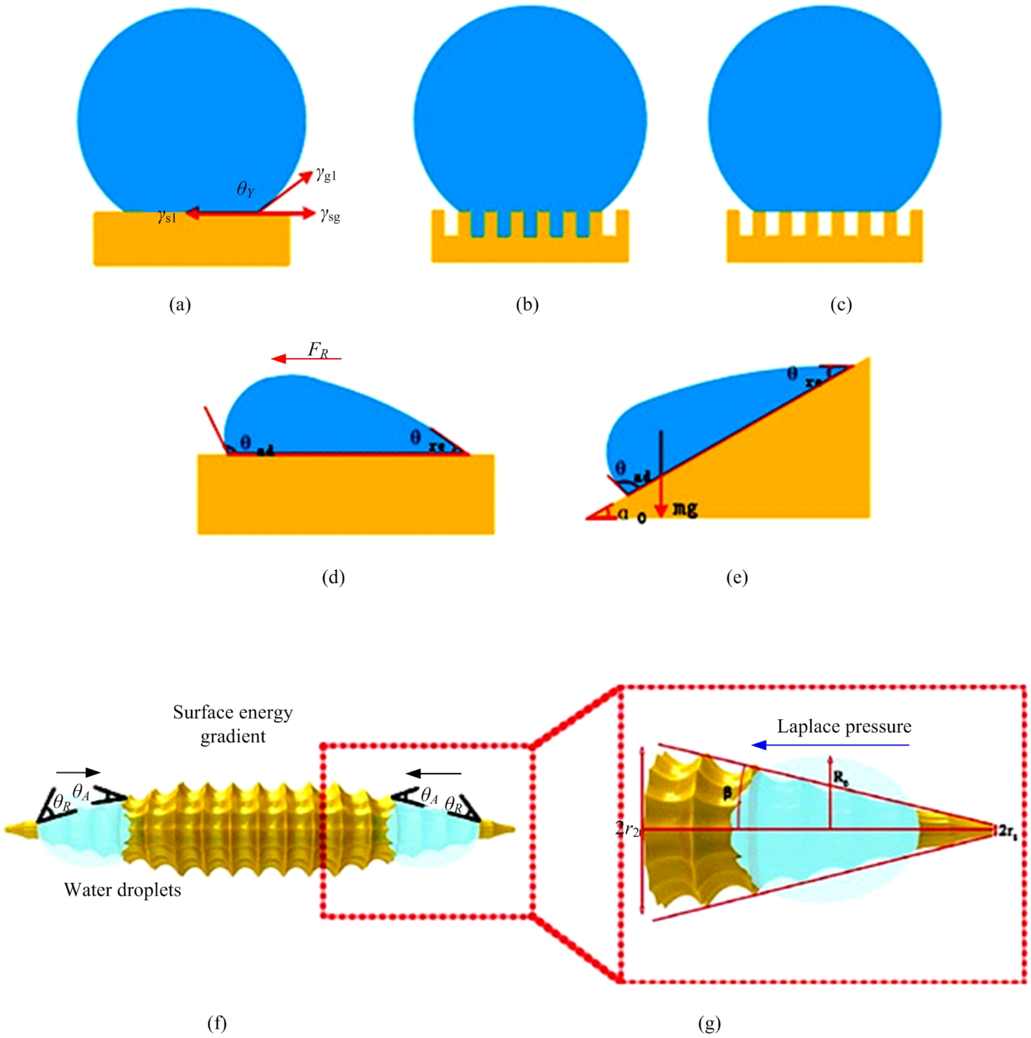
Fig. 3 Water-collecting creatures in nature and their SEM photos: (a) *Sarracenia fluff*; (b) *Setaria viridis*; (c) butterfly wings; (d) tree frog. (a) was adapted with permission from Ref. [47]. Copyright 2018 by Nature Publishing Group. (b) was adapted with permission from Ref. [42]. Copyright 2014 by Royal Society of Chemistry. (c) was adapted with permission from Ref. [41]. Copyright 2007 by Royal Society of Chemistry. (d) was adapted with permission from Ref. [43]. Copyright 2011 by University of Chicago.

hydrophilic and hydrophobic structure on the surface is used by Namib Desert beetle[46] to collect water. These organisms that can capture fog in the air provide a lot of afflatus for researchers, so many bionic fog harvesting materials have been developed.

Freshwater is an indispensable natural resource for human survival and development, and occupies an extremely important position in the national economy and people's livelihood of various countries[11]. Seawater desalination is currently the most popular solution for obtaining freshwater, but according to current technology, the cost of desalination is too high, the energy consumption is large, and local conditions are not suitable, so that this method is unsuited for large-scale promotion. How to use high-efficiency water vapor condensation technology to collect water directly from humid air is the first choice to alleviate the problem of water shortage in arid areas. The research of bionic fog harvesting materials has opened a new way for us to solve the problem of water shortage. Based on the excellent water vapor collection characteristics of the above-mentioned biological micro-nano structure, the research on the preparation of micro-nano composited structures for fog harvesting has gradually became a research focus. In this review, the six major mechanisms of passive biological water collection which are based on the interface wetting theory and droplet transportation theory are summarized, and then water collecting mechanism, bionic method and improvement in recent years of three typical organisms are introduced respectively. Finally, the main problems in the preparation, application and the future development trend of biomimetic fog harvesting materials are prospected.

2 Theoretical basis

The fog harvesting mechanism of natural organisms can be explained by many models, including Young's equation, Wenzel model, Cassie model, contact angle and rolling angle, surface energy gradient model, Laplace pressure model and film condensation and drop condensation. Coagulation, consolidation, transportation and storage are involved in water collect processes. Among them, the water mist condensation theory is the same as the solid surface wettability theory; the transportation theory mainly includes the surface energy gradient and the Laplace tension equation; the driving



(a) (b) (c)

(d) (e)

(f) (g)

Fig. 4 Basic concept models of droplet wetting on solid surface. (a) Young's model; (b) Wenzel's model; (c) Cassie's model; (d) the state of droplet motion on horizontal and (e) inclined surfaces; (f) surface energy gradient model; (g) Laplace pressure model. (a – g) were adapted with permission from Ref. [64]. Copyright 2017 by Wiley-VCH Verlag.

force for water mist recovery and transportation is generated by the surface energy gradient, and the surface energy gradient is produced by the difference in surface roughness. These theoretical models can help us to better understand the water mist collection process, essentially explaining the static and dynamic contact of droplets on the surface. They provide a solid theoretical basis for us to further analyze the behavior of droplet coalescence, movement on the surface of the material and the process of mist water collection.

2.1 Wettability theory

In 1804, Young proposed an equation describing the function of interfacial tension between solid, liquid and gas, namely Young's equation (Fig. 4a)[48] through an in-depth study of the hydrophilicity and hydrophobicity of the surface of the substance. On a smooth surface with an ideal solid surface, the relationship between the contact angle of the droplet on the material, the interfacial tension of the solid, liquid, and gas three-phase contact surfaces is

$$\gamma_{sg} - \gamma_{sl} = \gamma_{gl} \cos\theta_Y . \tag{1}$$

In the formula, γ_{sg}, γ_{gl}, and γ_{sl} are respectively the surface tension between the solid-gas, liquid-gas, and the interfacial tension at the solid-liquid interface at a certain temperature. In the gas-liquid-solid three-phase equilibrium, the angle that the water droplet is between the liquid-air interface and the solid-liquid interface is θ_Y. Young's equation is an idealized model which is only applicable to ideal solid surfaces. The ideal solid surface refers to the uniform, smooth, immutable and isotropic composition of the solid surface. In practical applications, this surface is almost non-existent. For a solid surface with a certain roughness, the hydrophobic property of the surface is a combination of surface chemical composition and roughness. Therefore, there is a certain difference between the apparent contact angle and the intrinsic contact angle. On a rough surface, it is considered that the actual solid-liquid contact area is larger than the apparent contact area, and it is assumed that the droplet completely enters the cavity of the surface structure, so the effect of roughness on hydrophobicity must be considered.

For the actual surfaces, the effect of surface roughness on the wettability of a solid surface must be considered. In 1936, Wenzel took a closer look at the problems with the Young equation. It is assumed that the droplets can completely fill the grooves of the rough surface. Due to the presence of surface tension, the actual solid-liquid contact area is larger than the solid-liquid area of the ideal plane which results in a difference between the contact angle of the rough surface and the ideal surface. Therefore, Wenzel modified the Young equation (Fig. 4b), and when the system reached equilibrium, a Wenzel equation[49] that satisfies the apparent contact angle was obtained, as shown in Eq. (2):

$$\cos\theta_W = r\frac{\gamma_{\mathrm{sg}} - \gamma_{\mathrm{sl}}}{\gamma} = r\cos\theta_Y. \qquad (2)$$

Where θ_W is the apparent contact angle, θ_Y is the intrinsic contact angle, and r is the roughness factor which represents the ratio of the actual solid-liquid area on the rough surface to the apparent contact area. It is worth noting that the Wenzel equation only applies to surfaces with homogeneous chemical composition and roughness.

Based on the Wenzel model, Cassie and Baxter further expanded and modified the Young equation, and the concept of compound contact was proposed. A new rough surface structure model[50] was established. It is believed that if the droplets can't penetrate into the rough structure on the rough surface, the air will be trapped in the grooves on the surface to form an "air cushion", and the droplets will stay on the composite surface composed of solid and gas. This assumption was closer to the real state. When the roughness of the solid surface is uneven to a certain degree, the air is easily trapped in the valleys of the solid surface by the wetted liquid (Fig. 4c). When the composite surface is composed of solid and water, the Cassie Baxter equation can be expressed as:

$$\cos\theta_{\mathrm{CB}} = f_{\mathrm{sl}}\cos\theta_Y + f_{\mathrm{sl}} - 1. \qquad (3)$$

Where θ_{CB} is the apparent contact angle under the Cassie-Baxter model, and f_{sl} is the solid-liquid area fraction. Based on the Cassie Baxter model, it is easy to see that the droplet has a small solid-liquid contact area on the surface, so it is easy to roll.

2.2 Droplet movement on horizontal or inclined surfaces

When the droplet is on a horizontal surface, the contact angle will occur due to the inconsistent contact angle between the front and rear ends of the droplet (Fig. 4d). The resistance caused by the contact lag is F_{R}:

$$F_R = \pi R_0\gamma(\cos\theta_{re} - \cos\theta_{ad}). \qquad (4)$$

Where θ_{ad} is the forward siding angle, θ_{re} is the backward siding angle, and R_0 is the contact radius of the three-phase contact line.

Although contact angle is a commonly used criterion for evaluating the hydrophobic properties of solid surfaces, a complete process of judging its hydrophobic properties depends on a dynamic process. Siding angle[51–54] is another important index for evaluating the hydrophobic performance of the surface. It refers to a rolling tilt angle which is produced by a certain amount (volume or mass) of the droplet gradually tilts on flat surface. The smaller the siding angle, the more hydrophobic the solid will appear. When the solid surface is tilted until the droplet is about to roll without rolling, the contact angle at both ends of the droplet becomes the advanced contact angle (θ_{ad}), and the smaller becomes the receding contact angle (θ_{re}), The difference between them is called Contact Angle Hysteresis ($CAH = \theta_{ad} - \theta_{re}$) (Fig. 4e). There is a difference between the advancing contact angle and the receding contact angle. Generally, the advancing contact angle is larger than the receding contact angle, that is $\theta_{ad} > \theta_{re}$. If the difference between θ_{ad} and θ_{re} is larger, the droplets are less likely to fall off the solid surface, and the smaller the difference between θ_{ad} and θ_{re} is, the easier it is for the droplet to fall off the solid surface.

2.3 Surface energy gradient model

Wettability is that the surfaces of many organisms, including plants and animals, have unusual structural characteristics on the macro level and nanoscale which can control their own water action. Spider silk and cactus have similar water collection principles, and it was proved that their condensed sub-millimeter droplets were driven by surface energy gradients (Fig. 4f) and Laplace pressure differences. In the entire spider silk water collection process, the spindle head acts as a condensation point in the initial stage, and then as a gathering place for small water droplets at those nodes, and the nodes mainly act as condensation points on the contrary. This is because the spindle is more hydrophilic than the node and has a higher apparent surface energy. Due to the effect of the force caused by the surface energy gradient, the given surface roughness is different. The specific analysis[55,56] is:

$$F = \int_{L_j}^{L_k} \gamma(\cos\theta_A - \cos\theta_R)\mathrm{d}l. \tag{5}$$

Where γ is the surface tension of water. θ_A and θ_R are respectively the advancing and receding angles of the water droplets on the spider silk. dl is the integration factor which is the distance from the spindle to the spindle head. The difference in surface energy gradient caused by surface roughness will drive water droplets to move from areas of low hydrophilicity (nodes have relatively lower surface energy) to more hydrophilic areas (spindle heads have higher surface energy).

2.4 Laplace pressure model

The second driving force for the movement of the directional water may be due to the spindle geometry of the node, which causes the Laplace pressure difference (Fig. 4g)[57–59]. A spindle head can be regarded as composed of two opposite circular and conical materials. Such a cone with a certain curvature gradient will produce a Laplace pressure difference that acts on the water droplet, it can be understood by the following formula:

$$\Delta P = \int_{r_1}^{r_2} \frac{2\gamma}{r + R_0} \sin\beta \mathrm{d}z. \tag{6}$$

Where r is the local radius, R_0 is the radius of the water drop ($R_0 = (3V/4\pi)^{1/3}$, V is the volume of the water drop.) β is half the top angle of the spindle, and z is the integration factor along the diameter of the spindle head. Laplace pressure is much larger in places with large curvature (radius r_1 at nodes) than in places with low curvature (spindle radius r_2). Due to r_1 is smaller than r_2, this will inevitably cause an unbalanced Laplace pressure difference in the water droplet to push the water droplet from the node to the spindle head. The final result is that the surface energy gradient caused by the anisotropic surface structure and the Laplace pressure difference caused by the conical spindle head geometry work together to drive the water droplets from the node to the spindle head.

2.5 Film condensation and drop condensation

Condensation of water vapor can be divided into membrane condensation and drop condensation[60]. During the condensation process, if the condensate does not wet the wall surface well, it will only condense into small droplets on it, and then grow up or merge into larger droplets and fall off. The condensation mode is called droplet condensation. If the condensate can wet the wall surface, it will form a complete liquid film covering the liquid surface and flowing continuously. This condensation method is called film condensation[61–63]. Because the membrane condensation surface is always covered with a layer of liquid film, the heat transfer between the condensed steam and the condensation surface is carried out through the liquid film. But the liquid film heat transfer efficiency is very low, and the heat transfer process is hindered, so its heat transfer efficiency is much lower than that of drip condensation. In the past, it was generally believed that film condensation was formed when the contact angle of the condensation surface was less than 90°, and drop condensation was formed when the contact angle was greater than 90°. Cao *et al.* made a dynamic description of the condensation process from the perspective of chemical potential change. They combined with the relationship between the dropping diameter of droplets on the condensation surface and the contact angle, and concluded that drop condensation or partial drop condensation may still occur when the contact angle is 70.67° ~ 90°. Many organisms have this similar special surface structure, which can make the condensed water escape efficiently, and thus exhibit very excellent fog harvesting characteristics.

3 Basic water collection mechanism

In nature, organisms with the ability to collect water on the surface can be seen everywhere. They can absorb water from various sources, such as rain, fog, water vapor in the air and water in the environmental matrix[11]. For example, the transdermal absorption of amphibians, the surface transmission of toads, elephants, and beetles. All kinds of organisms obtain and process water in unique ways. These processes of collecting and treating water involve different, specific chemical or structural adaptations of the surface. According to general research, there are currently six water collection mechanisms related to biological water collection: (1) The increase in surface wettability; (2) increase of water transmission area; (3) long distance water delivery; (4) water accumulation and storage; (5) condensation promotion; (6) gravity-driven[65]. Specifically, due to certain microstructures (such as columnar and hexagonal dimples), the wettability of biological surfaces is increased, the contact angle becomes smaller[66]. The diffusion area of water can be increased by a similar microstructure. The structure of trenches and troughs facilitates long-distance transport of water, and biological water transport distances are usually between a few millimeters and a few centimeters[67]. It is important for us to distinguish between wetting effects and capillary phenomena. The wetting effect is the interaction of the liquid with the surface, and the capillary phenomenon is the force acting on the liquid in the channel structure. In addition to these water collection and transport mechanisms based on structure, hairy surfaces can also play a role in accumulating and storing water[68]. Condensation is to establish a thermal gradient adapted to environmental conditions by changing the microenvironment, thereby promoting condensation and water collection[69–72]. Finally, a specific posture is used to guide the water to collect water.

3.1 Surface wettability

Water absorption capacity of the surface requires a hydrophilic surface, regardless of the species. Hydrophilicity refers to an increase in the wettability of a surface which is caused by chemical properties, and it is often associated with certain microstructures[73]. For example, Australian spiny lizards and Texas polygonal lizards can draw water from dry deserts to survive[74]. Some lizards are known to passively absorb water from the environment. These lizards are collectively referred to as hygroscopic lizards. These lizards belong to different genera, but they all have the ability to collect water because of their unique surface microstructure. The horny skin of these lizards is hydrophilic and exhibits hexagonal microstructures (Fig. 5a) which are about 10 μm – 30 μm in diameter and 1 μm – 5 μm in depth[75]. Once the microstructure comes into contact with a small amount of water, the microstructure will be filled with water and show superhydrophilicity on the surface[76]. We call this process “pre-wetting” (Fig. 5b). The purpose of pre-wetting is to collect water from the air more quickly.

Surface wettability can also be adjusted by chemical modification. Some tree frogs significantly reduce the loss of evaporated water by secreting lipids through the skin. Lipid secretions are hygroscopic, which can cause the surface to absorb moisture and increase wettability after covering the surface of the organism[77]. For example, toad’s saliva, although this secretion was initially considered to be a defensive fluid, but later research found that toad’s saliva contains glycosaminoglycan, which is a hydrophilic substance that plays an important role in water balance[78]. It can reduce water evaporation and maintains wettability when applied to the surface.

3.2 Permeable surface microstructure

Surface structure not only affects the wettability of the surface, but also affects the wetting phenomenon in generally. Typical wetting phenomena include superhydrophobic and self-cleaning[79,80]. Water penetrates into surfaces with moderate chemical hydrophilicity and has

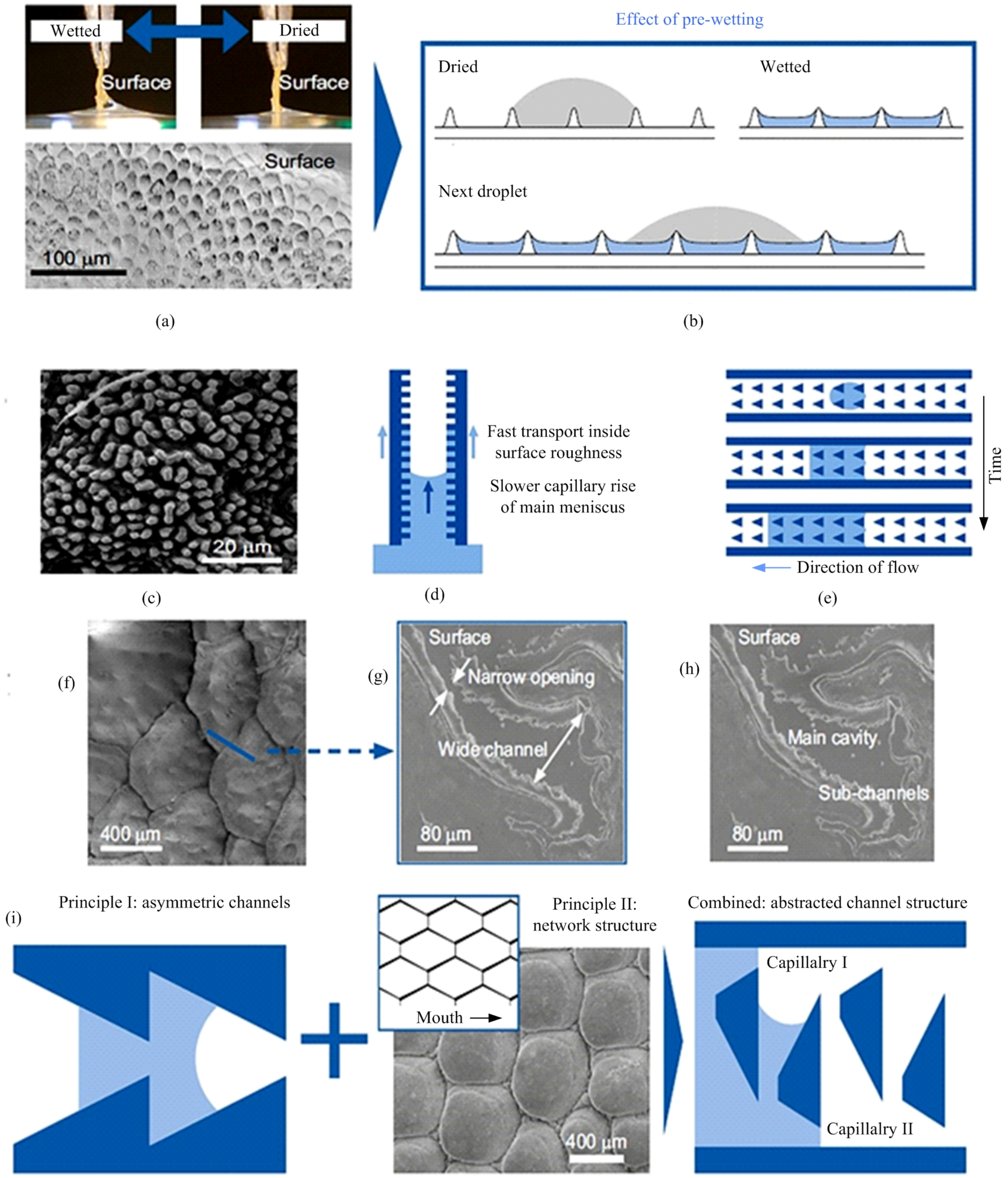


Fig. 5 (a) The scales of the Texas Horned Lizard are exposed to water under wet conditions and dried on silica gel to repeat this effect. (b) Scanning Electron Microscope (SEM) image of the sample surface in (a). (c) Pillar-like surface structures of the flat bug *Dysodius magnus*. (d) Different capillary rises in a capillary tube. (e) Asymmetric pillar structure for directional penetration of liquid and schematic flow of an applied droplet. (f) The ventral skin of the Australian thorny devil. (g) Semi-thin slice SEM pictures of skin samples (0.7 µm) after removal of epon embedding. (h) Hierarchical channel structure of main cavity and sub-channel. (i) The functional principle of directing and passively transporting water from the skin channel structure of Texas horn lizard. (a – i) were adapted with permission from Ref. [81]. Copyright 2014 by WIT Press.

a larger area than diffuses on smooth surfaces[82,83]. Such water penetration has been found in the surface structures of elephants, toads, and flatworms. Some *Bufo americanus* can collect moisture from the surrounding humid air. Their granular skin contains many grooves[84]. In these grooves, capillarity is formed, which creates the power to collect water, and the collected water is transported along the grooves to other parts, maximizing the skin wetting to expand the catchment area (amphibians often absorb water through the skin). The African elephant's epidermis is full of wrinkles and fissures. This form creates a uniform arrangement of pentagonal and hexagonal nodules. This structure is similar to toads and has water-absorbing properties to maintain surface wetting. In flat bug *Dysodius magnus*, the surface structure is distributed in columns (Fig. 5c), which supports hydrophilic wetting characteristics and water diffusion[85]. Although the diffusion of water on the surface is slower than that in the channels between segments, it is powerful in energy, so water can passively diffuse on the surface of the body to increase the diffusion area of water, which is beneficial to the collection of water (Figs. 5d and 5e).

3.3 Water transport

The diffusion of the collected water can be called a method of distributing the water. Capillary action is required for long-distance passive water transport. Capillary liquid transport can occur in very small cavities, where capillary forces dominate other forces[86]. The corresponding surface structure was found in the lizard's granular skin (Fig. 5f). On the lizards that collect water, the transport of water in the capillary prevents most of the body surface from wetting, so large areas of water are prevented from evaporating. And there is a skin channel network in hygroscopic lizards, which exists in the scales of the whole surface of lizards. Its width is between 100 μm and 300 μm (Fig. 5g). The channel can collect water by capillary action, and has a layered structure[87].The large channels between the scales can quickly absorb water into the high-capacity channel system, and the sub-channels that are composed of cavities formed by internal protrusions (Fig. 5h) serve as a relay station for capillary water transport to transport water to greater distances (Fig. 5i)[88]. Some crustacean dock cockroaches, such as *Ligia exotica* and *Ligia oceanica*, passively collect water from the wet surfaces of their coastal habitats. Water is transported in the open structures of the leg's epidermis, which function as capillaries. Further inspection revealed more details: hair and paddle-like microstructures on two adjacent legs collect and transport the attached water, the water is transported further along the swimming limbs (pleats) to the hindgut near the anus, and then absorbed.

3.4 Water accumulation and storage

It is also important in the storage and accumulation of water. Various surface structures can form cavities, and the collected water can accumulate. Such accumulation can be simple. For example, the entrainment between some snakes' body coils can store a small amount of water[89]. The amount of water that can be stored in the cavity of the animal's outer surface structure is called the cortical water holding capacity, and the lizard has the largest water holding capacity, because it has a more hierarchical skin structure or a higher density of skin channels[90,91].

In 2015, Ito *et al*. studied a variety of plants in arid regions, and pointed out that the surface of *Lychnis sibirica* growing in the arid steppe region of Mount Fujiin Japan has a unique water storage and accumulation function[92,93]. Under dry conditions, its tapered hair with internal microfibers is reversibly transformed into a vertically twisted crush plate, and the microfibers in the hair are responsible for the storage and release of water. The unique morphological change of the hair's tapered shape into a vertical twist depends on the humidity level in the air and the water content that is stored under humid environmental conditions. They observed the existence of hairs on the surface of the genus. It is found that there is a cubic structure inside under the scanning electron microscope, and under the sliced electron microscope of the vertical hair (Figs. 6d – 6f). Preliminary studies on fibrous substances show that these substances have the function of collecting and releasing water. When in a humid environment, the microfibers in prunus cirrhosa absorb moisture from the mist and water vapor, and fill the cubic structure to store water. In a dry environment, the hair automatically bends, and these cubic microstructures of water storage are compressed, and the water in them is squeezed to the surface of the leaves to meet the needs of biological survival (Figs. 6a – 6c). This water storage characteristic is also found in tomatoes, bitter gourds, and sweet potatoes, and will be used to develop biomimetic water storage materials[94–96].

Grouse mainly live in arid areas and feed on dry

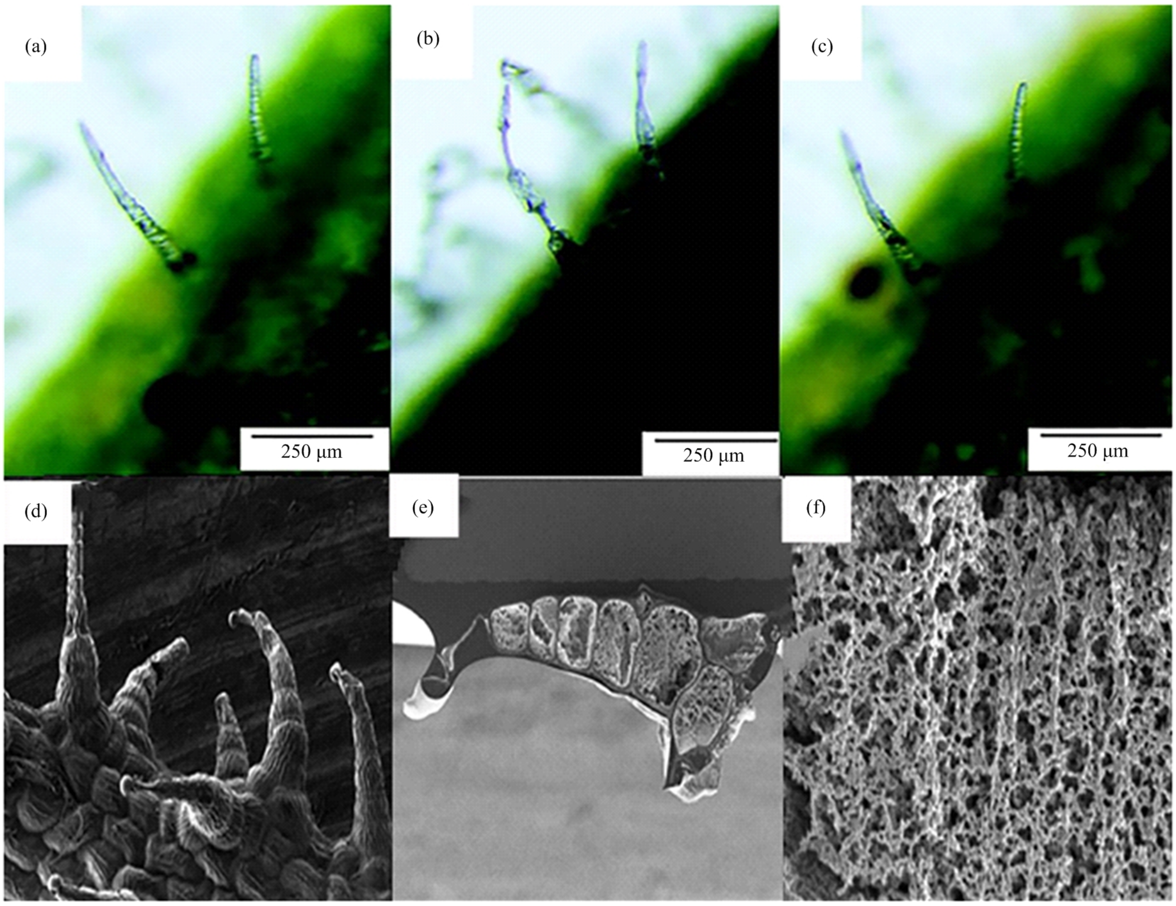


Fig. 6 *Lychnis sibirica*'s surface hair absorbs moisture from moist air and releases it when it dries. (a) Immediately after putting on a water droplet. (b) After 2 h, the dry hairs have a perpendicularly twisted structure at a 90° angle. (c) After 3 h field emission SEM images of hairs for (d) intact hairs. (e) A hair sliced vertically. (f) A higher magnification of (e). (a – f) were adapted with permission from Ref. [94]. Copyright 2015 by American Institute of Physics.

seeds. How does it get enough water to survive? It turns out that grouses have wettable chest hairs to store and accumulate water. Generally, they fly to the source of water to wet their feathers, and then fly back to the habitat to feed the cubs with water on the feathers[68]. Generally, the feathers of birds show a quasi-hierarchical structure, which is used to waterproof and prevent water penetration[97]. Unlike the sandgrouse, its feathers can store 30 mL of water, which is about 5% to 15% of its body weight. In a fibrous structure, water is not held by a single (structured) surface, so it may be related to feather volume, which are composed of many structures. At present, it is only known that there is a reversible physicochemical change of feather keratin in the process of water storage of grouse. The reason for the structural change is unclear, which is a major difficulty in current research[98].

3.5 Condensation

Water vapor condenses into droplets on animals and has been observed on some frogs, such as tree frogs and *L. caerulea*. The temperature gradient required for condensation is achieved through changes in thermal properties and time. These frogs also need to absorb water from the surrounding environment as much as possible while maintaining the reduction of water loss. When frogs cool down in the low temperature environment in the wild, and then enter a warm and humid hole, the temperature difference causes small droplets in the air to condense on the colder skin surface of the frog. Coincidentally, condensation is an important way for *Scaffiopus hammondii* and *Scaffiopus couchii* living in the desert to get water. According to research, the spikes on the skin of some hygroscopic lizards act as a condensation point. Although it is easier to condense and promote water under laboratory conditions than nature, it is still not enough to survive. Thorny devils can collect water which is about 0.2% of the body weight while the actual condensation results in a weight gain of 0.75%. This result shows that there are other ways of collecting water. After an in-depth study, it was found that the lizard uses condensed water to wet the lizard skin in advance in order to collect water more quickly.

With the development of bionics, more and more people have realized the superiority of biological structure. After long-term natural selection of the fittest, the organism has evolved a nearly perfect structure. In general, we believe that the fog cannot be compressed. The fog already contains many condensed fine droplets, which are light enough to be suspended in the air. Therefore, the mist can be collected without condensation. In 2001, Andrew reported in Nature that the periodic microstructure of the desert beetle has alternating hydrophilic and hydrophobic regions[65]. The hydrophilic area acts as a condensation point, which helps to collect fine mist from the air, and the hydrophobic area makes the accumulated droplets easy to roll off. This structure can collect tiny droplets in the mist with the help of wind to form a larger droplet that are used to maintain their own water requirements.

Membrane condensation is widely used, but the condensation efficiency is not high. Even if the surface tension is used to strengthen the corrugated pipe, finned tubes, its condensation heat transfer efficiency is still not as good as drop condensation. However, although droplet condensation has high condensation heat transfer efficiency, it is very unstable, and it is difficult to maintain it for a long time in the actual process. In recent years, researchers have worked hard to find new solutions to prepare efficient and continuous condensing structure surfaces, and have turned their attention to bionic fog harvesting condensation structures. Zhu and Guo[99] used the surface of the Namib desert beetle as a model to imitate the special condensation structure on its back and study the properties of its water collection. By adjusting the molar concentration ratio of hydrophobic substances and hydrophilic substances on the composite surface, it was found that the original concentration was 9:1 when the composite surface has the maximum condensation speed which is called the water collection efficiency.

3.6 Using of external forces

Some turtle species have been found to use gravity to transport water over crustaceans and eventually into their mouths[100]. In fact, animals expose themselves to external forces to collect water in a characteristic posture. The emergence of gravity supports the function of surface microstructures and the transport of channels. Namib beetles take this approach to collect moisture in the air. At night, they come to the windward side of the dune, and then use their bodies to make parallel furrows on the surface of the dunes, which are close to each other, just like plowing, with a ridge between every two furrows. As the temperature gradually decreases and the fog slowly comes, the water droplets condensed on this edge will be two to three times more than the water droplets on the surrounding flat sand. The water collected will occupy the weight 40% effect. The elevation angle was measured to be 23°[65].

4 Development of mist collector and bionic method

Passive water collection has caused extensive research by scientists. Many functional structures combined with bionics have been applied in various fields, such as liquid directional transport, oil-water separation, fog harvesting and so on. Great progress has been made.

Fog harvesting (condensed water suspended in the air) is considered to be an effective solution to the problem of water shortage in remote areas[101–103]. For example, the inspiration for the invention of the mist trap is not only derived from the microscopic surfaces of several plants, but also from the special surfaces of some animals. In recent years, researchers have conducted a lot of research on micro-nano structures on biological surfaces with excellent water vapor collection performance. Its excellent characteristics and production mechanism have been explored, a theoretical analysis model has been established, and various preparation methods for preparing biomimetic fog-harvesting materials have been developed[104–106].

4.1 Early fog collector based on natural plants

There are many arid places in the world, but they are often surrounded by dense fog. The organisms that have long time lived in the area have evolved a special ability to collect water. Many plants can draw water droplets from the air to obtain water sources[107]. For example, the redwood trees in California can form porous and large-area fog-traps with the lichens that grow on them. It can effectively intercept the small droplets in the dense fog and provide the source of redwood water to survive. It is found that in summer, about 19% of the moisture of California redwood comes from the condensation of small droplets in fog[108,109]. Humans have a long history of using fog water, but in-depth study of it has entered a long period of stagnation. Until 1901, Marloth *et al*. set up reed bundles on Table Mountain in South Africa to try to collect fog water, and achieved remarkable results[110]. Fog water collection has attracted widespread attention, and related research has begun to develop slowly around the world.

4.2 Net-based fog water collector

Since the 1990s, fog collection networks have been carried out in remote villages in some developing countries such as Africa, South America, and Asia. 75 double steel wire meshes were erected near a small fishing village called Chungungo in northern Chile as a water collecting surface, giving local villagers an average of about 30 litres of potable water per person per day[111]. Germany Kai Tiedemann and Anne Lummerich designed and manufactured a plastic net, which was set up in a thick fog. The fog condensed on the net and flows into the set water collection tank. This early fog collector mainly used nylon nets, polypropylene plastic nets to be fixed at a certain height and vertical wind direction to collect fog, and it used the contact of small droplets on the surface to fog harvesting. But when the wind direction changed, the efficiency of fog harvesting will be greatly reduced. Later, a full range of mist collectors were developed after improvement, which can be roughly divided into two types. One is using bearings to adjust the water collection surface to change with the wind direction at any time on the basis of the ordinary net-based mist water collector, and it always keep the water collection plane perpendicular to the direction of mist flow[112–114], and the other is arranging a number of metal rods with a certain length into a cylinder according to a certain distance, and the structural characteristics of the cylinder ensure that the incoming flow in all directions will be intercepted by the plane of the water collector. In addition, the wettability of the surface of the fog collector will also affect the efficiency of the fog collection, which is mainly reflected in the difficulty of droplets dripping on the water trap. When the contact angle hysteresis of the droplet on the net is small, it can smoothly slide off and drip, which reduces the clogging of the mesh and avoids the secondary scattering of small droplets. In response to this, Lalia *et al*.[115,116] prepared a porous film by electrospinning. The porosity of the film was used to fix a layer of oil with lubricating properties, which effectively reduced the contact angle of water droplets on the surface, and the fog-harvesting efficiency of the membrane is improved. The emergence of a wide variety of fog collectors has also temporarily alleviated the shortage of water resources in arid regions[117].

4.3 Fog water collector based on two-dimensional plane

The study found that the fog collector of the porous net is mostly the macro structure of the net, and the wettability of the surface microstructure constituting the net is rarely investigated. However, fog harvesting is actually the behavior of small droplets condensing on the surface, so the key point is the interface science issue. Surface microstructure and wetting performance are important factors for efficient water mist collection[118].

In 2001, Professor Parker and others discovered that the Namibian desert beetle can collect fog using alternating patterns of hydrophilicity and hydrophobicity on the back (Fig. 7a)[65]. The researchers observed that there were many irregularly arranged protrusions on the back of the beetle (Fig. 7b), and the distance between the protrusions was 0.5 μm – 1.5 μm. The surface of the protrusion is smooth and has a certain degree of hydrophilicity, and the side slopes and recesses of the protrusion gap are composed of hydrophobic waxy material with regular hexagonal hemispherical structure. The hydrophobic waxy material's diameter is about 10 μm (Fig. 7c). The small droplets in the mist are adsorbed after they touch the protrusions of the hydrophilic part, and the small droplets that contact the hydrophobic area will also be partially blown or rebounded to the

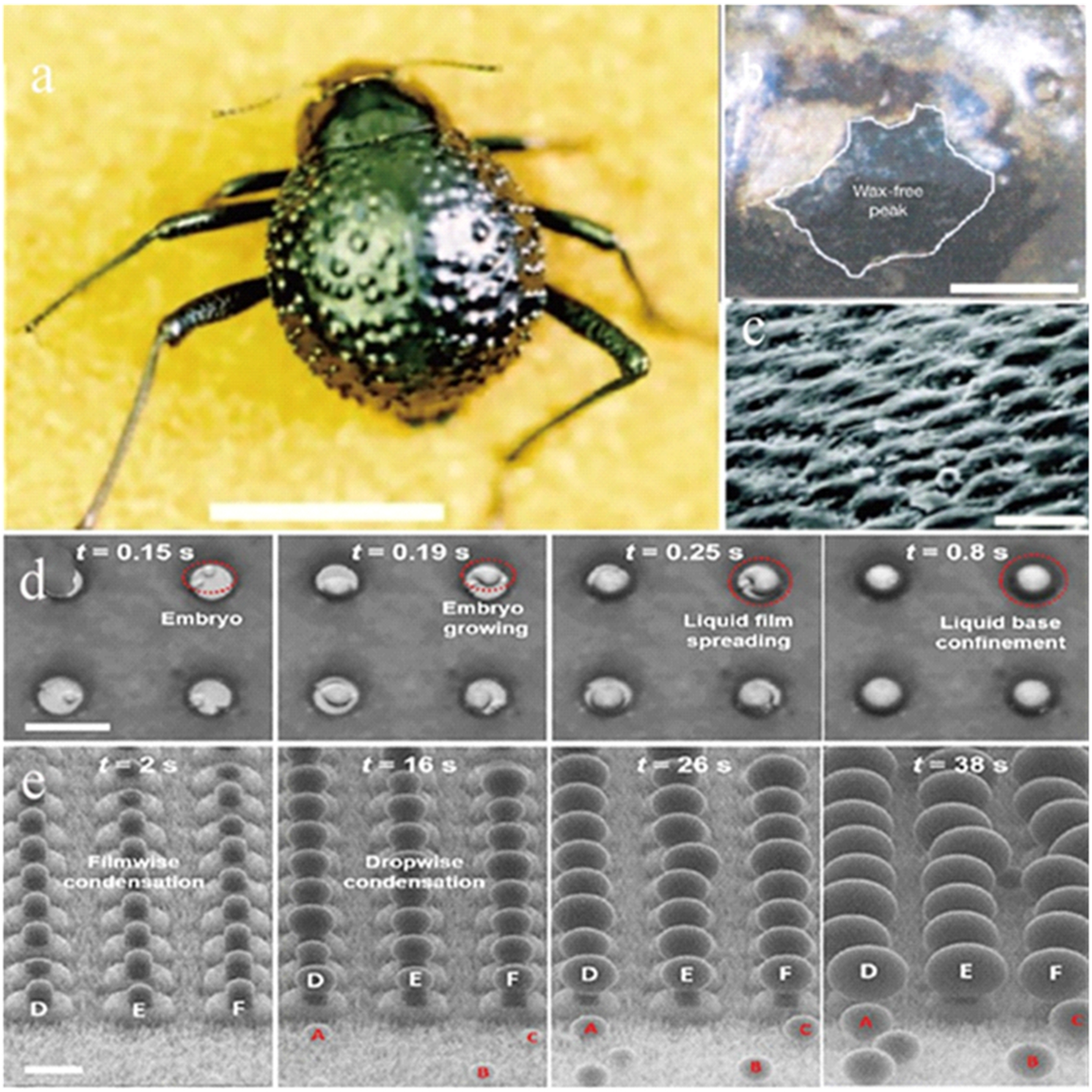


Fig. 7 Desert beetle back topography. (a) Peaks and troughs on the surface of the elytra; (b) a "bump" on the elytra; (c) SEM of the textured surface of the depressed area; (d) combined filmwise and dropwise condensation, selected time-lapse images of water vapor condensation in the custom-made chamber; (e) time-lapse images of water vapor condensation captured *via* ESEM. (a – c) were adapted with permission from Ref. [65]. Copyright 2001 by Nature Publishing Group. (d, e) were adapted with permission from Ref. [124]. Copyright 2015 by American Chemical Society.

hydrophilic area, so that the small droplets of the hydrophilic area grow up quickly. Finally, the water droplets cover the entire hydrophilic area on the bump of the beetle's back, and the moisture is transported from the base of the non-hydrophilic portion to the beetle's mouth to meet its water demand.

The fog harvesting method of Namib desert beetle has inspired the bionic material, and the corresponding hydrophobic surface material has also been produced. Professor Cohen[119] used a selective area polyelectrolyte multilayer electrostatic self-assembly method in 2006, Professor Badyal[120] used a two-step plasma chemical patterning method in 2007, and Professor Rtihe[121] of the University of Freiburg in Germany used surface hydrophobic modification plus selection in 2008 to synthesize the patterned surfaces with large differences in hydrophilicity and hydrophobicity. The method of photodecomposition in the sexual region separately prepares a patterned surface with large differences in hydrophilicity and hydrophobicity. These surfaces with differences in hydrophilicity and hydrophobicity accelerate the mist water collection rate.

In 2014, Hou *et al*.[122] used photolithography, ICP etching and other methods to prepare bionic beetle like surface structure that is alternated with hydrophilic silicon oxidecylindrical arrays and superhydrophobic nanowires, and studied the surface water vapor condensation characteristics. In this study, through the clever design, the pattern distribution of the hydrophilic and hydrophobic regions was controlled artificially by using the figure distribution of hydrophobic region, and the condensate droplets can be effectively separated from the surface. The condensation heat transfer coefficient was 63% higher than that of traditional droplet condensation. Choo *et al*.[57] prepared ZnO and TiO_2 double-layer nanostructures (Figs. 7d and 7e). After surface modification, they formed array patterns of different hydrophilic and hydrophobic nanostructures. Water vapor collection experiments were conducted to analyze the water collection performance of the dot array, grid, bifurcation and other graphic structures. The dot array structure has higher condensation and water collection performance, the grid structure is not conducive to droplet shedding, and the water collection performance is very poor.

But whether it is a net-based fog water collector or a beetle-like back fog water collector, it must rely on gravity to transfer the collected droplets. Only when the droplets have accumulated to a certain extent, the gravity received by itself can resist the interface to it[123], and the adhesion force will only drop and transfer. This dependence on gravity will undoubtedly reduce the speed of droplet condensation on the surface of the sewage collector, and the overall efficiency is not high. Therefore, seeking a fog collector that does not rely on gravity or reduce the influence of gravity is the key point for efficient mist collection.

4.4 Fog water collector based on one-dimensional fiber

4.4.1 One dimensional spider like rayon

In nature, there are various types of spiders, but their secretion spider silk has special water-collecting properties. Spider silk is a one-dimensional material. The diameter of spider silk fibers ranges from micrometers to millimeters. The differences between different spider silks are difficult to distinguish with the naked eye[125–127]. Spider silk fiber has many excellent characteristics, including high toughness, high strength, good elasticity, high temperature resistance, ultraviolet resistance, and easy biodegradation. It is called "biological steel" and is used in surgical sutures, body armor and parachute materials[128]. In 2010, Zheng *et al*.[104] discovered that the spindle-shaped spider silk structure has excellent water vapor condensation and collection performance, and found that the spider silk structure under dry conditions is different from that under fog conditions (Fig. 8). The hot-drawn nylon wire was used to prepare the periodic structure of the spindle, and the water vapor condensation and collection tests were carried out. The water collecting capacity of spider silk is attributed to a unique fiber structure consisting of periodic spindles and joints (Fig. 8a). The periodic spindles are composed of randomly disordered nanofibers (Fig. 8b), and the joints are composed of neatly arranged nanofibers (Fig. 8c). In a humid environment, the spider joint structure is first reconstructed on the spider silk, and water droplets condense on the reconstructed spider silk. Then, the tiny water droplets move toward the spindle joint under the driving force to realize water collection (Figs. 8e – 8h). A section of spider silk fiber is a microstructure composed of spindle nodes and joints. The force that drive the movement of small droplets on the surface of spider silk fiber is generated by the surface free energy gradient and Laplace pressure difference. The surface energy gradient can be caused by the difference of surface chemical composition[129] or surface roughness[130], which drives the small droplets to move to the wettable area with higher surface energy. This research that does not rely on external forces and relies on the gradient of surface structure to drive small droplets for directional collection. It provided a model for the design and development of a new type of fog collector[131–133].

Inspired by the phenomenon of biological water harvesting, research on fog harvesting has been carried out fiercely all over the world. The development of the fog water collector has gone through several stages of natural plant fog collector, web-based fog water collector, two-dimensional heterogeneous interface fog water collector, and one-dimensional spider silk fiber fog

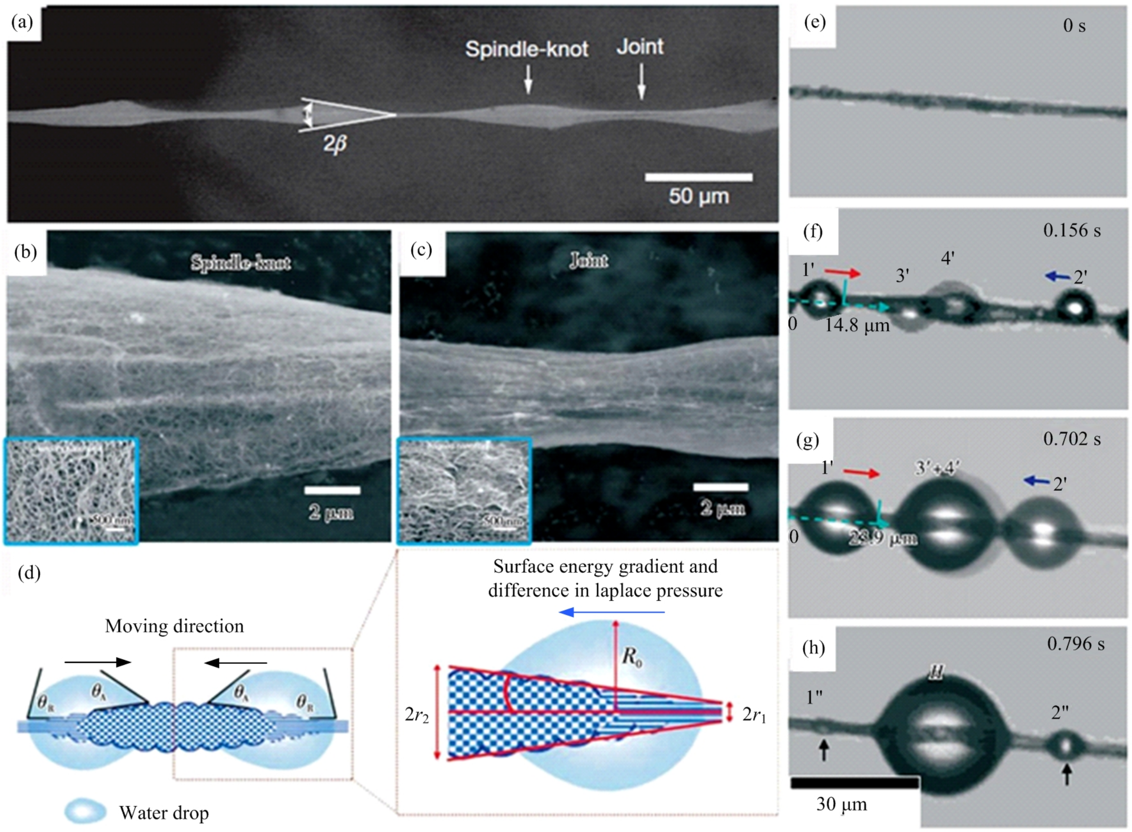


Fig. 8 Structure characteristics of spider silk (*Uloborus walckenaerius*) and directional movement of droplets. (a) Periodic wet reconstruction spider silk; (b) zoom image for the spindle-knot; (c) zoom image for the joint; (d) schematic diagram of droplet directional motion mechanism; (e – h) directional motion of water droplets on a single spindle-knot. (a – h) were adapted with permission from Ref. [104]. Copyright 2010 by Nature Publishing Group.

water collector. The key point began to focus on the structure and wettability of the surface of the material, the gravity dependence became less and less important, and fog harvesting efficiency became higher and higher. Among them, the discovery of the spider silk water collection mechanism and the extensive research on related biomimetic materials have brought a revolutionary breakthrough in fog harvesting and determined the central position of special interface materials in mist collection.

Inspired by the high water collecting efficiency of spider silk, many researchers have carried out researches on spider silk imitation, so there are many ways to imitate spider silk: emulsion-based coaxial microfluidic method (Fig. 9a), fluid-coating method (Fig. 9b), programmable microfluidic method (Fig. 9c), electrohydrodynamic method (Fig. 9d), inclined dip-coating method (Fig. 9e), combination of wetting and water drop template (Fig. 9f), and dip-coating method (Fig. 9g). Bai *et al.*[45] reported the preparation of spider silk structures by polymer stretching, electrospinning, microfluidic technology, *etc*. (Fig. 9h). They used polyvinyl acetate (material surface contact angle θ = 56.7˚), polymethyl methacrylate (θ = 68.4˚), polystyrene (θ = 93.3˚) and polyvinylidene fluoride (θ = 92.7˚) and other materials to prepare periodic spindle structures. Hou *et al.*[134,135] coated a layer of polymer solution on the surface of the fiber. After the first stretching, the fiber was treated with constant temperature and humidity chamber, and then stretched for the second time to prepare the periodic structure of spindles with different sizes alternating. The periodic structure of the single-scale spindle has better water vapor condensation and collection performance.

In 2011, Prof. Sang-Hoon Lee's research group imitated the principle of spider silk (Fig. 10), and they prepared biomimetic spider silk structural fibers with different chemical composition, morphology and structure, and studied the effect of spindle knot size on its

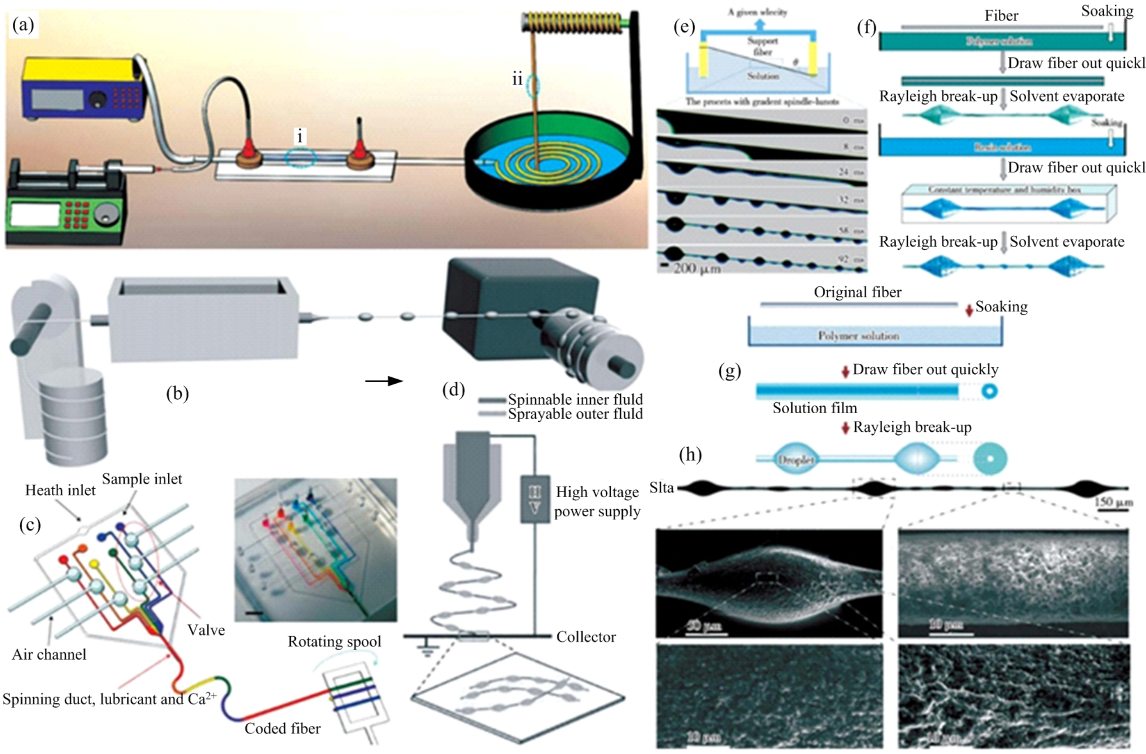


Fig. 9 The methods of biomimetic spider silk. (a) Emulsion-based coaxial microfluidic method; (b) fluid-coating method; (c) programmable microfluidic method; (d) electrohydrodynamic method; (e) inclined dip-coating method; (f) combination of wetting and water drop template; (g) dip-coating method; (h) biomimetic spider silk made by dip-coating method. (a) was adapted with permission from Ref. [136]. Copyright 2017 by Nature Publishing Group. (b – d) were adapted with permission from Ref. [137]. Copyright 2012 by Royal Society of Chemistry. (e) was adapted with permission from Ref. [138]. Copyright 2013 by Nature Publishing Group. (f) was adapted with permission from Ref. [137]. Copyright by Royal Society of Chemistry. (g) was adapted with permission from Ref. [139]. Copyright 2012 by Wiley-Blackwell. (h) was adapted with permission from Ref. [135]. Copyright 2012 by American Chemical Society.

mist water collection ability[137,140]. Compared with smooth fibers, these spider silk-like structures can significantly increase the efficiency of mist water collection. However, the uniformity and periodicity of these spindle knots limit the long-distance and large-scale transportation of collected droplets. Studies have shown that the spindle-shaped structure induces a slope effect and a curvature effect, which can restrain the contraction of the three-phase contact line of the droplet on the fiber surface, and leads to the lag of the droplet detachment on the fiber surface. In response to this problem, Zheng *et al.* improved the previously method for preparing bionic spider silk, and used multiple dipping[134] and tilting methods[138] to prepare bionic fibers with multi-level spindles. Due to the different capillary forces of the different-sized spindle knots on the droplets, the droplets suspended on the different-sized spindle knots will be directionally fused, which realizes the long-distance transportation of the collected liquid and improves the collection efficiency.

In 2013, Feng *et al.*[141] used azo-based polymers to prepare a light-controlled infiltration-like spider silk structure (Fig. 11a). Under ultraviolet (Fig. 11c) and visible light (Fig. 11b) irradiation, the material can freely switch between hydrophilic and hydrophobic properties. On the surface of the hydrophobic spindle, condensed droplets are collected at the thinner ends of the spindle, and while on the hydrophilic surface, they gather at the thicker position in the middle of the spindle, which indicates that the surface wettability has a positive effect on the water collection characteristics of the spider silk structure. The structure of spider silk to collect water has a very important role (Figs. 11d – 11g). It can change the surface roughness or chemical composition of the spindle junction[142] or introduce smart responsive molecules on the spindle junction[143,144]. Zheng *et al.* introduced thermally responsive polymer molecules containing PNIPAAm segments to the spindle junctions, and

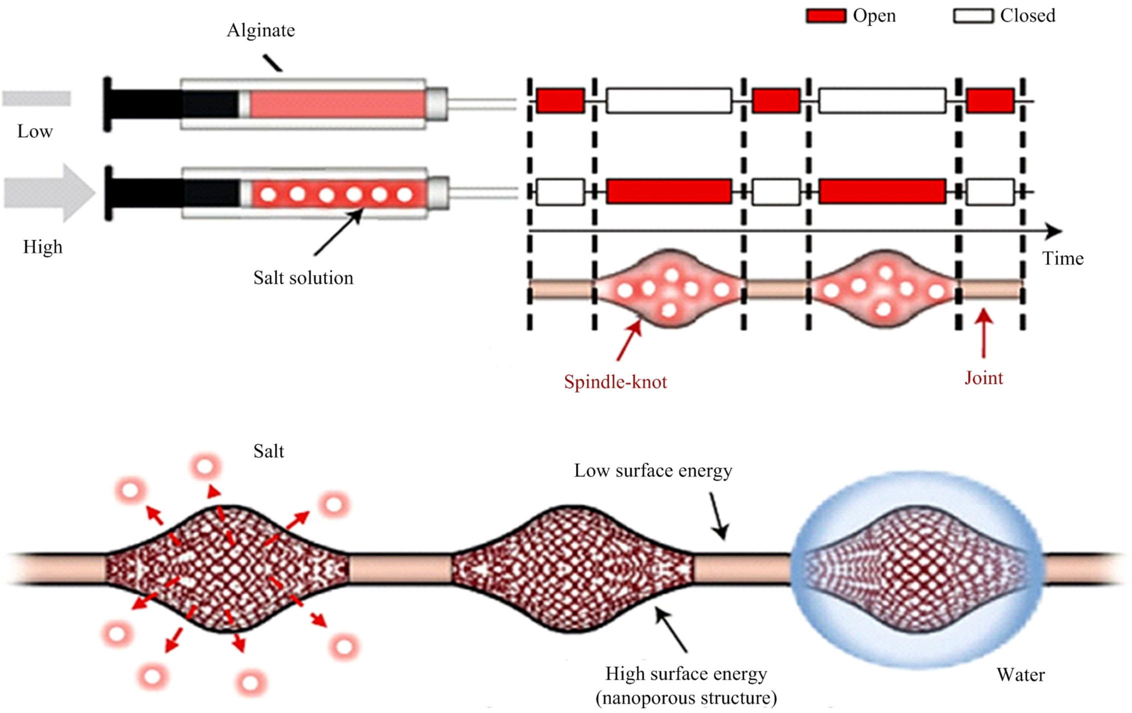


Fig. 10 Spider silk structure fiber prepared by microfluidic method. This image was adapted with permission from Ref. [144]. Copyright 2011 by Nature Publishing Group.

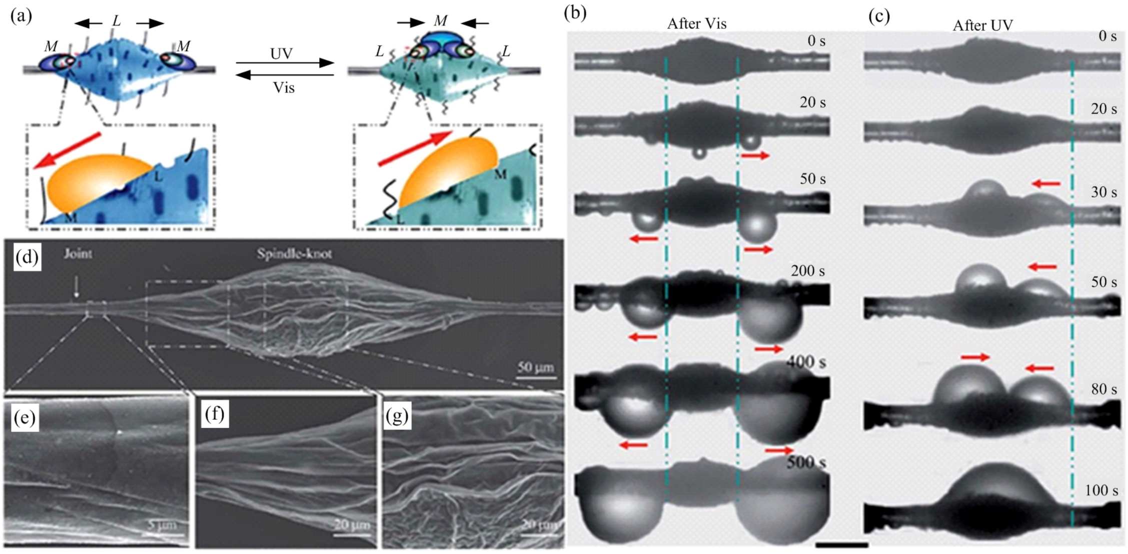


Fig. 11 Spider-like silk structure prepared by light-controlling infiltrating material, it focuses on water accumulation under light conditions. (a) After Vis irradiation, one side of the droplet moves toward the joint and away from the spindle knot in a period of 0 s – 500 s. (b) After UV irradiation, one side of the droplet moves to the center of the spindle node, and finally converges with another droplet in 100 seconds. (c) The directional aggregation of droplets was observed by controlling the wettability gradient. (d) The spindle-knot and joint of a fiber. (d – g) Morphology images: the joint has a relatively smooth surface. (a – g) were adapted with permission from Ref. [141]. Copyright 2013 by Royal Society of Chemistry.

light-responsive polymer molecules containing azobenzene segments to achieve precise control of the movement direction of small droplets on the bionic spider silk fiber[145]. These studies have enriched the research on the interface materials of bionic fog harvesting, and show the advantages of special interface

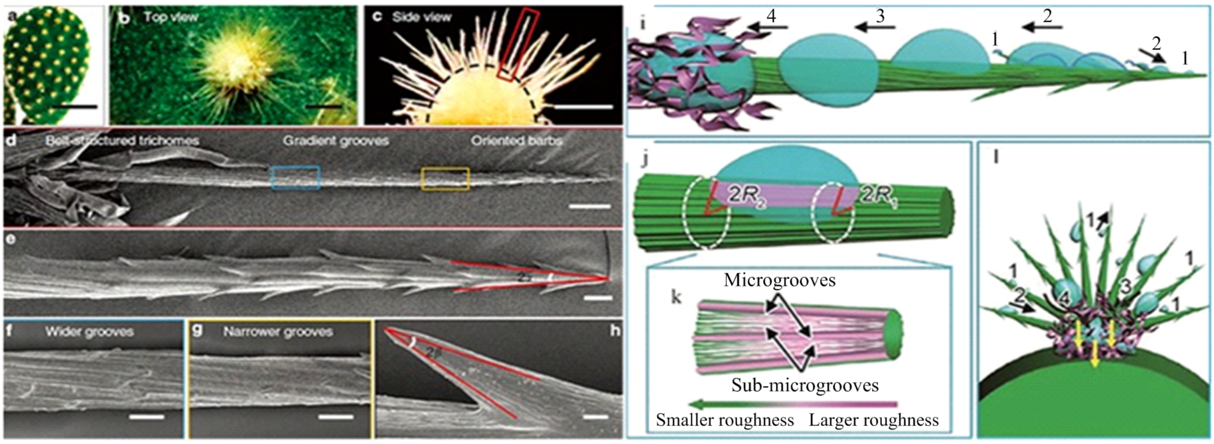


Fig. 12 (a) Macro optical map of cactus; (b) top view of the clustered thorns on the top of the cactus; (c) side view of clustered thorns on top of cactus; (d) structure of single thorn of cactus; (e) cactus single thorn front; (f) cactus single thorn with wider groove in the middle; (g) the cactus has a narrow thorn in the middle groove; (h) the angle of the tapered small thorn on the front end of the single thorn of the cactus; (i) the water droplets are transported from the front end of the cactus thorn to the end; (j) Laplace pressure difference driving force; (k) surface free energy gradient driving force; (l) cooperation between cactus thorn and burr. (a – l) were adapted with permission from Ref. [44]. Copyright 2012 by Nature Publishing Group.

materials in the efficient mist water collection.

4.4.2 One-dimensional imitation cactus structure material

Cactus like strong light, has heat resistance, strong vitality. Its suitable growth temperature is 20 °C – 30 °C. It is mainly distributed in the arid areas of tropical and subtropical areas such as the southern and southeastern coastal areas of the United States, the West Indies, Bermuda and northern South America, southern China and Southeast Asia (Fig. 12a)[146]. The cactus can survive in the arid desert, thanks to its efficient fog water collection system. The surface of the cactus is covered with regularly distributed thorns and tufts (Figs. 12b and 12c). Each thorn is mainly divided into three parts: a pointed part with directional barbs, a middle part with gradient grooves, and a root with trichomes (Figs. 12d–12h). In the fog water collection process, each part plays a different role. The ability of fog water collection stems from the multiple biological structures of the cactus. The combined effect of the Laplace pressure gradient and the surface free energy gradient, so that the droplets are oriented on the cactus thorn surface mobile[147,148]. The shape and movement trend of droplets on the surface of conical and cylindrical structures have aroused people's interest very early. A cactus thorn can be regarded as a cone with a linear groove on the surface. This structure makes the local radius of the droplets at both ends different, resulting in a Laplace pressure difference[55], close to the tip of the spike (radius R_1) is larger than that near the bottom end (radius R_2). In addition to the Laplace pressure gradient, the surface free energy gradient is another driving force for the directional movement of droplets on the thorn surface. The micro grooves on the surface of the cactus thorns have a width gradient. The grooves near the bottom of the thorns are sparser and rougher than the tips. Since the surface of the cactus thorns is covered with wood wax, the tips are rougher and hydrophobic, which means that the tips of the thorns have more roots than the roots. The lower surface free energy, this surface free energy gradient creates a driving force that moves the collected water droplets from the tip to the root (Fig. 12i)[57]. Under the combined effect of Laplace pressure gradient (Fig. 12j), surface roughness gradient (Fig. 12k) and capillary force of the tuft body (Fig. 12l), cactus spines complete the condensation, directional transport and absorption of water[149].

Studying the structure and function of the cactus water collection system will help to develop new and efficient water-collecting materials and devices. So far, the three main methods of chemical or electrochemical corrosion, template replication and electrospinning are widely used in the manufacture of cactus spinous microstructures. Inspired by the water collection method of

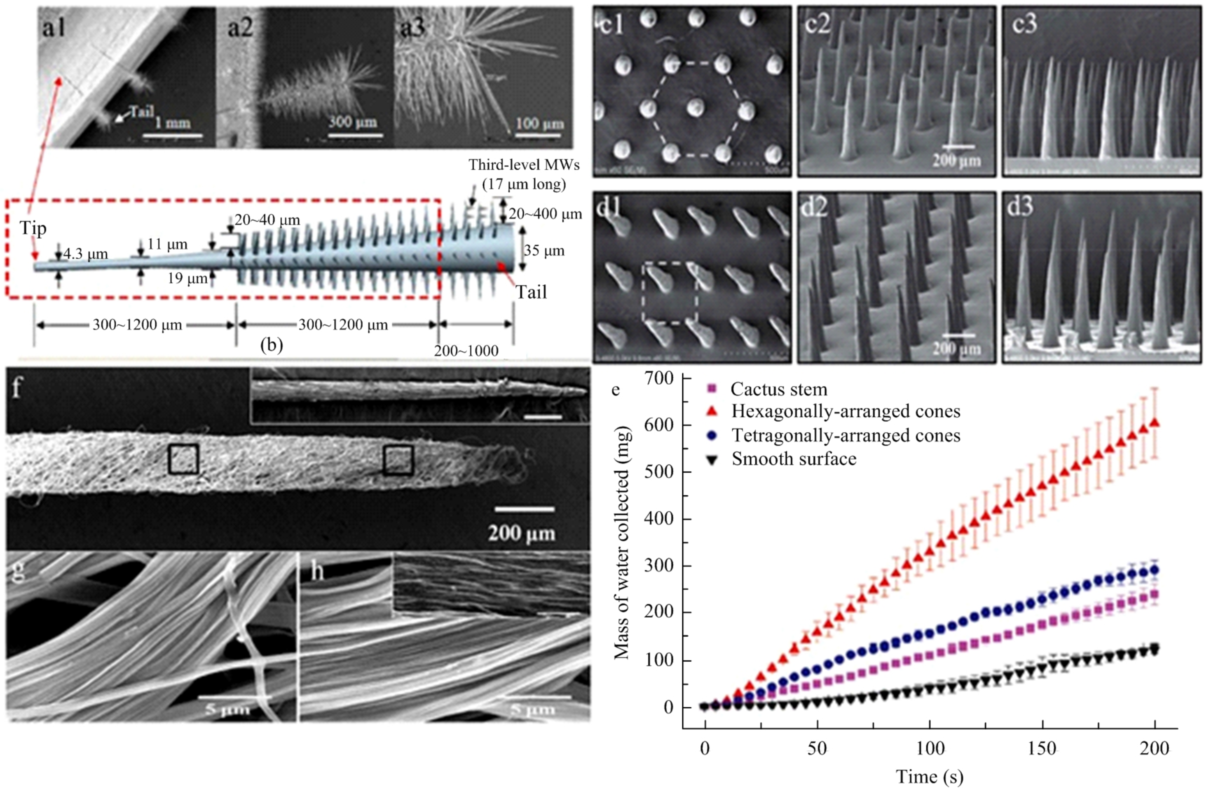


Fig. 13 Artificial cactus structure. (a1 – a3) Bionic cactus made by gas phase technology; (b) composite structure model; (c1 – c3) hexagonally arranged PDMS cone arrays; (d1 – d3) four directional PDMS cone array; (e) time chart of water quality collected from four different surfaces; (f) artificial cactus thorn structure made by electrospinning; (g – h) SEM image of multi groove structure of bionic cactus. (a – b) were adapted with permission from Ref. [150]. Copyright 2014 by American Chemical Society. (c – e) were adapted with permission from Ref. [152]. Copyright 2014 by Wiley-VCH Verlag. (f – h) were adapted with permission from Ref. [153]. Copyright 2015 by Wiley-VCH Verlag.

the cactus, Heng *et al.*[150] used gas phase technology to grow zinc oxide microrods on the substrate, and then grew zinc oxide (ZnO) nanowires on the zinc oxide microrods by controlling the relative position of the solid source and the substrate (Figs. 13a and 13b). In the fog water collection experiment, the water collection capacity of the artificial cactus structure and the natural cactus structure was compared, and the results showed that the artificial cactus structure had higher water absorption efficiency because the surface area of the branch structure of the industrial cactus was larger. Inspired by the dense cone thorns on the surface of cactus, Ju *et al.*[151] developed a simple method to prepare polydimethylsiloxane (PDMS) cone arrays in 2013. First, a stainless steel needle was fixed on the programmable drilling system, and holes were punched on the low-density polyethylene sheet, and then these structures were copied by using PDMS, and finally the PDMS cone array is obtained (Figs. 13c and 13d). In order to further test the fog harvesting on different surfaces, it was proved that the hexagonal arrangement of cone surfaces is more effective than other arrangements (Fig. 13e)[152]. At the same time, in order to verify the efficiency of static fog collection, Peng *et al.* used mechanical perforation and the last shift replication method to make a flexible tapered array with magnetic response. Under the action of an applied magnetic field and a Laplace pressure difference, the tapered array can produce periodicity vibration which can collect fog in windless areas. This technology can be used to collect water in some dry areas without wind. Guo *et al.*[153] used an electrospinning method to create a cactus-like thorn structure. Using the fine silver needle as the base, the polymer fiber is wound on the silver needle by electrospinning technology to prepare a cactus thorn structure and conduct a mist water collection experiment.

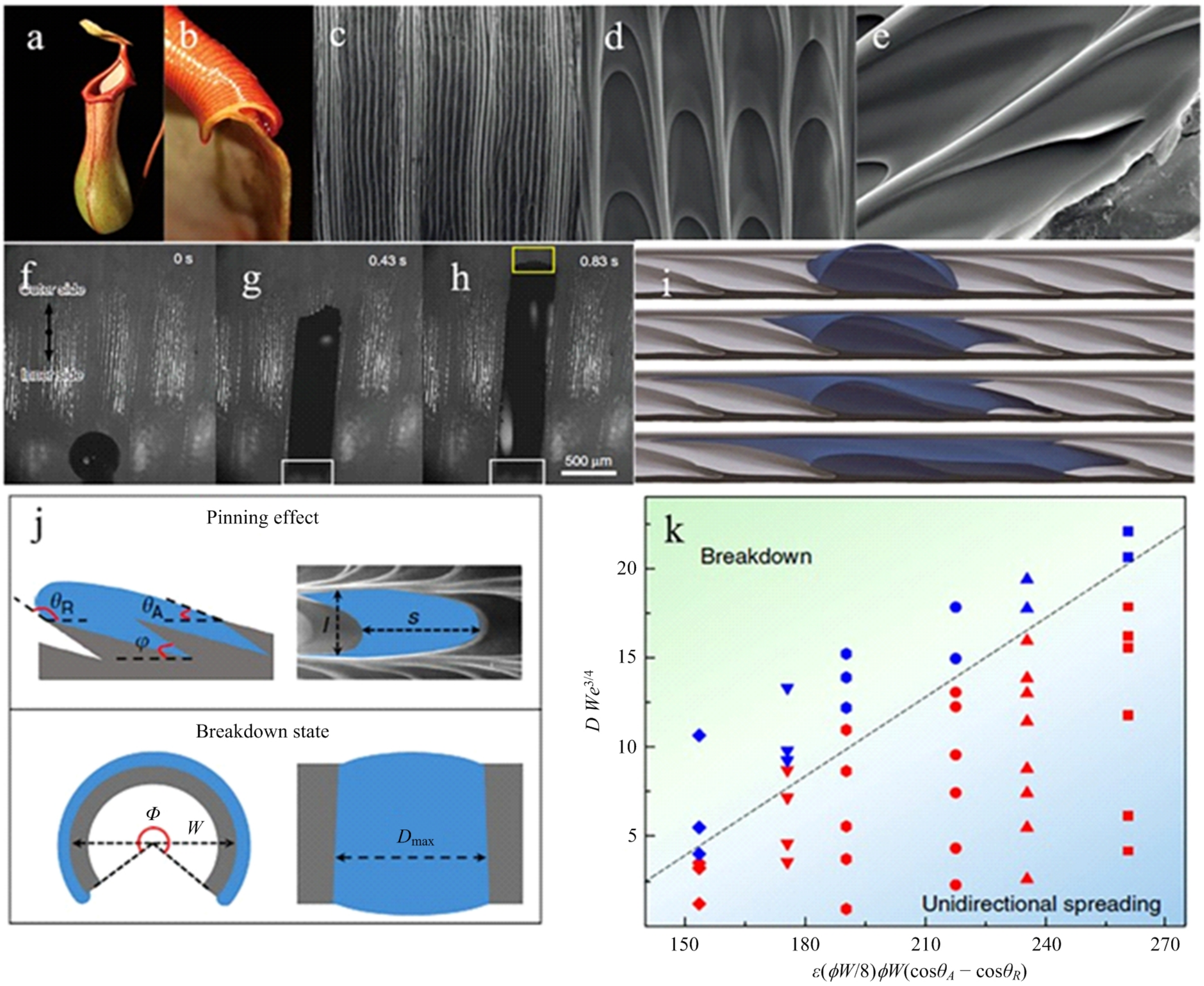


Fig. 14 (a) Nepenthes optical image; (b) optical image of transverse section from inside to outside of Nepenthes; (c) SEM image of first order groove; (d) the second and third layer micro grooves; (e) SEM image of arched edge microcavity of duck's beak; (f – h) in a single channel, droplets are transported from the inside out; (i) three dimensional simulation of droplet transport process; (j) schematic diagram of the pinning effect and damage state caused by sharp edges; (k) transition diagram between unidirectional spreading regime and breakdown regime. (a – i) were adapted with permission from Ref. [40]. Copyright 2016 by Nature Publishing Group. (j – k) were adapted with permission from Ref. [158]. Copyright 2018 by Springer Nature.

The multi-level groove structure on the surface of the bionic cactus spines allows the solid-liquid-gas three-phase contact line to be divided multiple times (Figs. 13f – 13h), which lead to a significant increase in the overall Laplace force of the water drops. In fog, the small droplets are captured at the tip of the needle, enriched, and gathered toward the bottom of the needle.

4.5 Nepenthes bionics

Nepenthes is famous for its ability to prey on insects. It has an extremely wet and smooth rim area near its opening[64,154–157]. Once the insect slips into the cage, it will be swallowed by Nepenthes. There are many phenomena of surface directional water flow in nature. Generally, we think that this phenomenon is related to the micro-nano-scale surface structure, driven by the surface energy gradient and the Laplace pressure gradient. The tropical carnivorous plant Nepenthes can capture insects using the microstructure and wettability of the pitcher's lip surface to meet basic nutritional needs. Jiang *et al.* revealed the secrets of the insects swallowed by Nepenthes by studying the structure of the mouth margin of Nepenthes (Figs. 14a and 14b). The study found that the root of the ability to carry liquid in the rim area of Nepenthes is due to its multi-scale micro-nano structure – an asymmetric groove composed of wedge-shaped blind holes (Figs. 14c – 14e). It can optimize and strengthen the capillary rise in the transport direction and organize the reverse liquid reflux, thus completing the unidirectional liquid film transport (Figs. 14f – 14k)[40,159,160]. Before the second microcavity is completely filled, this upper water layer (brown arrow) becomes the top water layer, and the I layer (green arrow) fills the third microcavity. Because the water is fixed in the proper place, reverse migration and transportation will not occur.

The special liquid delivery method at the mouth of Nepenthes has important reference significance for the development and design of a new directional flow delivery system, and it has a wide application prospect in the field of fog water collection and transportation[161–163]. However, the effect of the surface wettability and structural parameters of Nepenthes is not clear. Chen *et al.*[164] used a photolithography method to makeabionic structure of Nepenthes, and found that the unidirectional movement distance of droplets increased with the increase of the surface hydrophilicity of the rim. Coincidentally, this is consistent with the hydrophilicity test of temperature control and regulation of the rim of the pitcher plant made by Zhang *et al.*[160]. However, Li *et al.*[165] found that the liquid with the lowest surface tension (Perfluorohexane) can move directionally on hydrophilic and hydrophobic surfaces in the lip area of the imitation Nepenthes made by stereolithography, even for extremely viscous silicone oils. This proves that the rim area of Nepenthes possesses good directional movement ability of droplets[160,166,167].

Inspired by the unique multi-scale surface structure of Nepenthes, the preparation of bionic Nepenthes materials has been widely concerned by researchers. However, there are few reports on the surface of Nepenthes bionics with water collecting ability. The Nepenthes' surface is conducive to the removal of droplets, and is an ideal surface for mist water collection and transportation systems. In 2018, inspired by Nepenthes and rice leaves, Dai *et al.*[161] prepared a hydrophilic oriented smooth rough surface (SRS, which can quickly nucleate and remove water droplets) (Figs. 15a and 15b). The surface was composed of oriented microgrooves with nanostructures (Fig. 15c). The nanostructures were modified by a hydrophilic liquid lubricant called PDMS, which made the solid surface hydrophilic and can quickly collect moisture in the air. Because the liquid lubricant has good fluidity, the droplets can quickly slide down and be collected. The researchers also used rough surfaces to increase their surface area to collect more water. The test results confirmed that this hydrophilic rough surface can quickly collect moisture in the air and transfer it quickly. Unlike traditional superhydrophobic surfaces, SRS does not rely on air to help water droplets drip. And due to its large surface area, hydrophilic slip interface and directional liquid repellency, the water harvesting efficiency can reach more than three times that of existing superhydrophobic materials (Figs. 15d – 15g). It is superior to traditional liquid-repellent surfaces in applications[162].

The application of multiple bionics has enriched the research of water-collecting materials. Park *et al.*[168] combined the characteristics of desert beetles, cacti and Nepenthes to design a high-performance biomimetic material that can effectively collect water from the air (Fig. 16a). This material was inspired by the rugged shells of desert beetles, the misaligned structure of cactus spines, and the smooth surface of Nepenthes. The new material used the characteristics of these water-harvesting organisms and the lubricating liquid injection porous surface technology (SLIPS) to collect water in the air. Firstly, the uneven hydrophilic and hydrophobic structure on the back of desert beetle was simulated on the top to make the droplets grow rapidly. Then, an asymmetric slope was designed to guide the directional transportation of condensed water droplets by imitating the cactus thorn. Finally, inspired by the Nepenthes, the smooth lubricant was injected into the nanostructure for fixation. The protruding geometric shape of the beetle's back is conducive to the condensation of water droplets. The combination of the protruding geometry and the asymmetric structure of the cactus thorn and the nearly frictionless coating of Nepenthes made the new material has higher water collection efficiency and can transport more water (Figs. 16b – 16d). Compared to flat and smooth surfaces, surfaces containing smooth asymmetric bumps can collect more water; compared to flat areas with the same height, the uneven shell collects water droplets faster. That was to say that this kind of surface, which combined with the

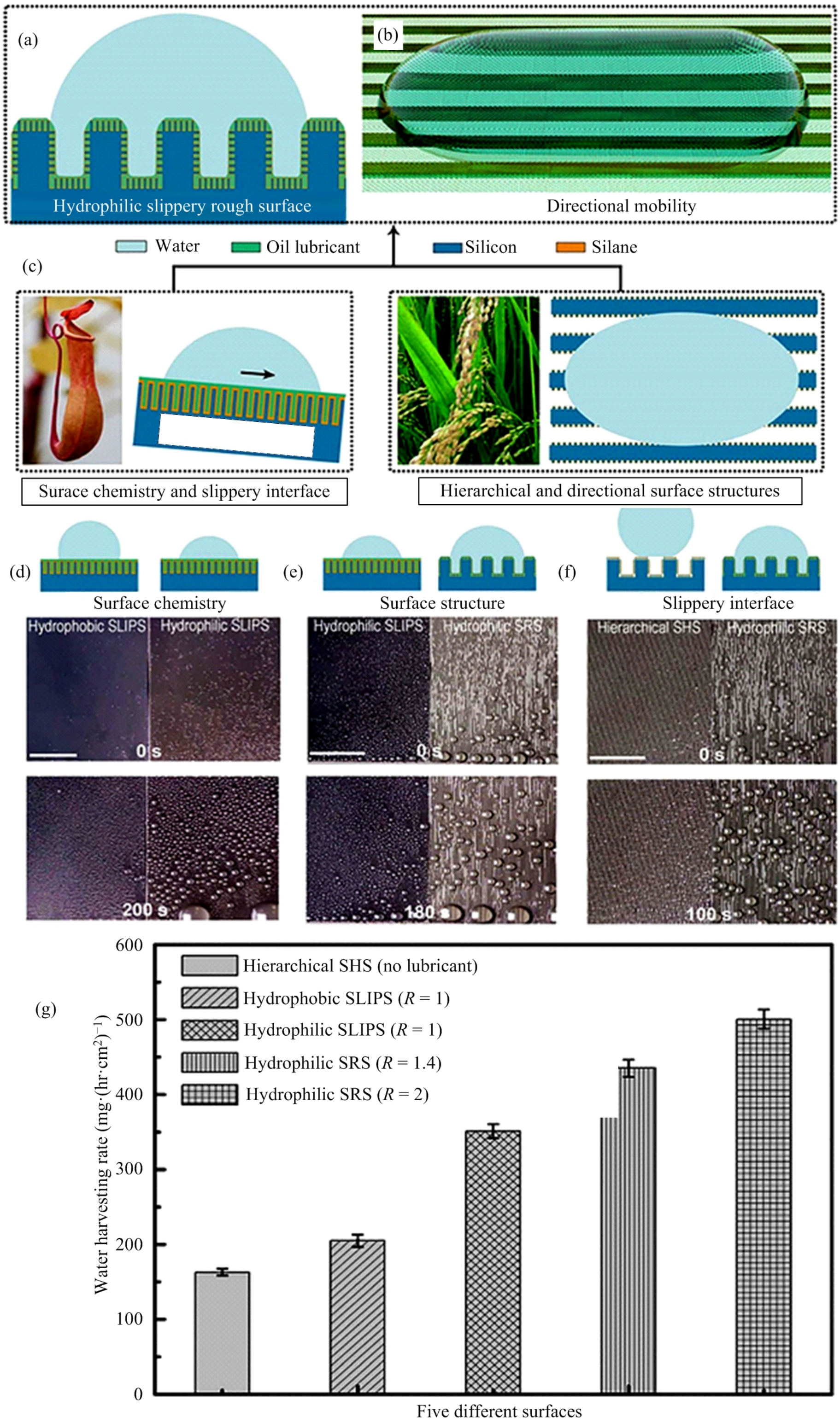


Fig. 15 Hydrophilic directional SRS inspired by Nepenthes and rice leaves. (a) Left side view of hydrophilic directional SRS; (b) top view of hydrophilic directional SRS; (c) the smooth surface of Nepenthes and the directional structure of rice leaves; (d) comparison of fog harvesting between hydrophilic SLIPS and hydrophobic SLIPS; (e) fog collection comparison between hydrophilic SLIPS and hydrophilic SRS; (f) fog collection comparison between layered SHS and hydrophilic directional SRS; (g) fog harvesting rates on different surfaces. (a – g) were adapted with permission from Ref. [161]. Copyright 2018 by American Association for the Advancement of Science.

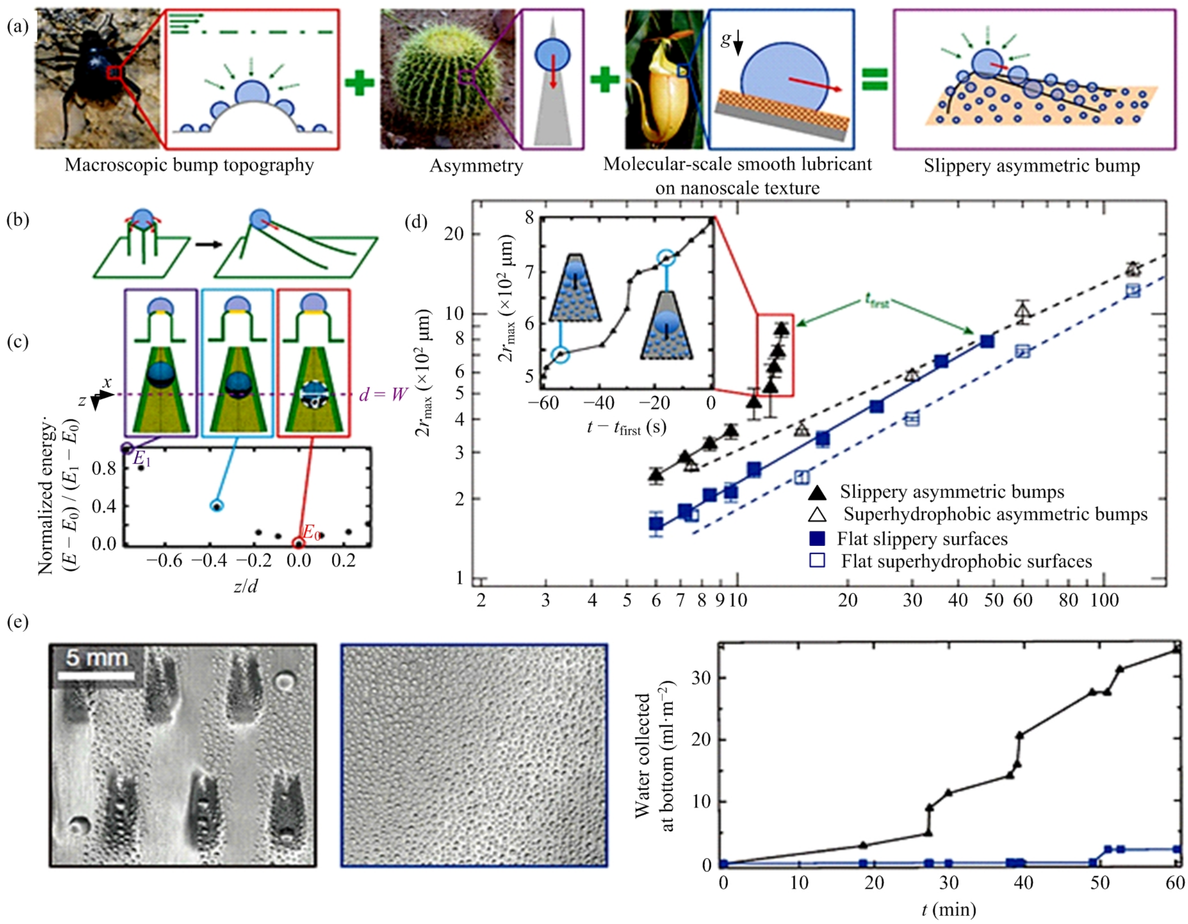


Fig. 16 (a) Design model of multiple bionic materials; (b) model diagram of capillary driven transport; (c) energy distribution of asymmetric bump-droplet-vapor system; (d) comparison of droplet formation rate and drop off rate between multi bionic surfaces and state-of-the-art surfaces; (e) an exemplary array of the slippery asymmetric bumps (The black line in the picture on the right), compared to the flat slippery surfaces (The blue line in the picture on the right). (a – e) were adapted with permission from Ref. [168]. Copyright 2016 by Nature Publishing Group.

excellent characteristics of three kinds of biological water collection, work synergistically and is far superior to other single synthetic surfaces (Fig. 16e)[169,170]. This also opened us new ideas for the development of our bionic water-collecting materials.

Similarly, Zhang *et al.*[171] used bottom-up alternate self-assembly, top-down photolithography and micro structure template replication to successfully develop a multi-bionic lubricating material with wettable hollow bump array for fog harvesting (Figs. 17a – 17d). The surface was composed of a centrally controlled hydrogel concave-convex array and an inverse opal film injected with lubricant as the base material (Figs. 17f – 17j). Among them, the hollow hydrophilic protrusions could quickly attract and capture water droplets from various directions according to the capillary driving force (Fig. 17e), and the smooth substrate played an important role in the rapid transportation of water droplets, so that the synergy of the two can significantly improve the fog collection efficiency.

Although fog harvesting material with a smooth system exhibits excellent water-collecting performance in a static environment, it is not suitable for a strong wind environment. In arid areas, such as deserts, there are usually strong winds, which can bring moist air needed for water collection. But because the strong wind blows away the captured water droplets, it reduces the water collection efficiency. Therefore, Wang *et al.*[172] drew inspiration from cactus, rice straw leaf, Nepenthes and butterflies, proposed a dynamic water collection system. They developed a water collection windmill structure for efficient water mist collection in static and

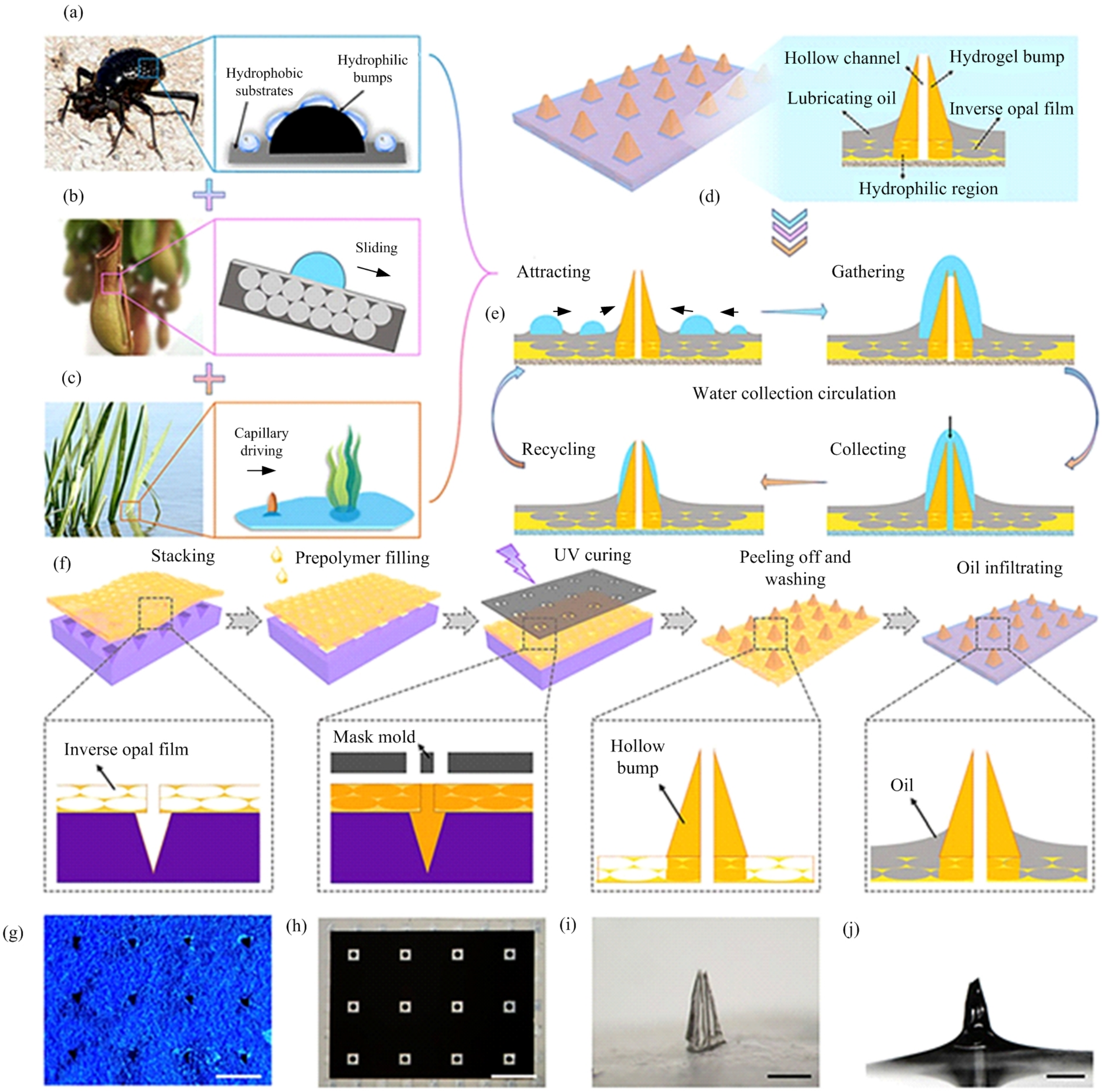


Fig. 17 Multi-biologically inspired wettable hollow concave-convex array preparation scheme. (a – c) The unique structure of three organisms; (d) schematic diagram of the surface structure of the new material; (e) schematic diagram of water delivery and water collection circulation on the surfaces; (f) schematic illustrations of the fabrication procedure; (g) optical image of perforated Pu inverse opal film; (h) optical image of neatly laminated negative film mold, PU film and mask; (i) polyurethane film hollow bump array composite material; (j) smooth surface injected with lubricating oil. (a – j) were adapted with permission from Ref. [171]. Copyright 2019 by National Academy of Sciences.

strong wind environments (Figs. 18a – 18e). When the windmill receives the impact of strong wind, the liquid droplets are gradually sprayed to the surrounding turbines under the action of the rotation of the blades and finally drip into the container (Figs. 18f, 18g, 18I, 18j). There are three types of blades: anisotropic grooved blades (AGS) processed by micromachining technology, superhydrophobic grooved blades modified by PDMS (SUB-AGS), and smooth grooved blades injected with hydrophilic fluid (HLIP-AGS). Compared with other surfaces, HLIS-AGS has super high fog harvesting efficiency (Figs. 18h and 18k). This is because the hydrophilic lubricant can not only serve as a buffer layer to prevent droplets from bouncing, but also as a sliding layer to facilitate water transport and the groove topography can prevent the random movement of water

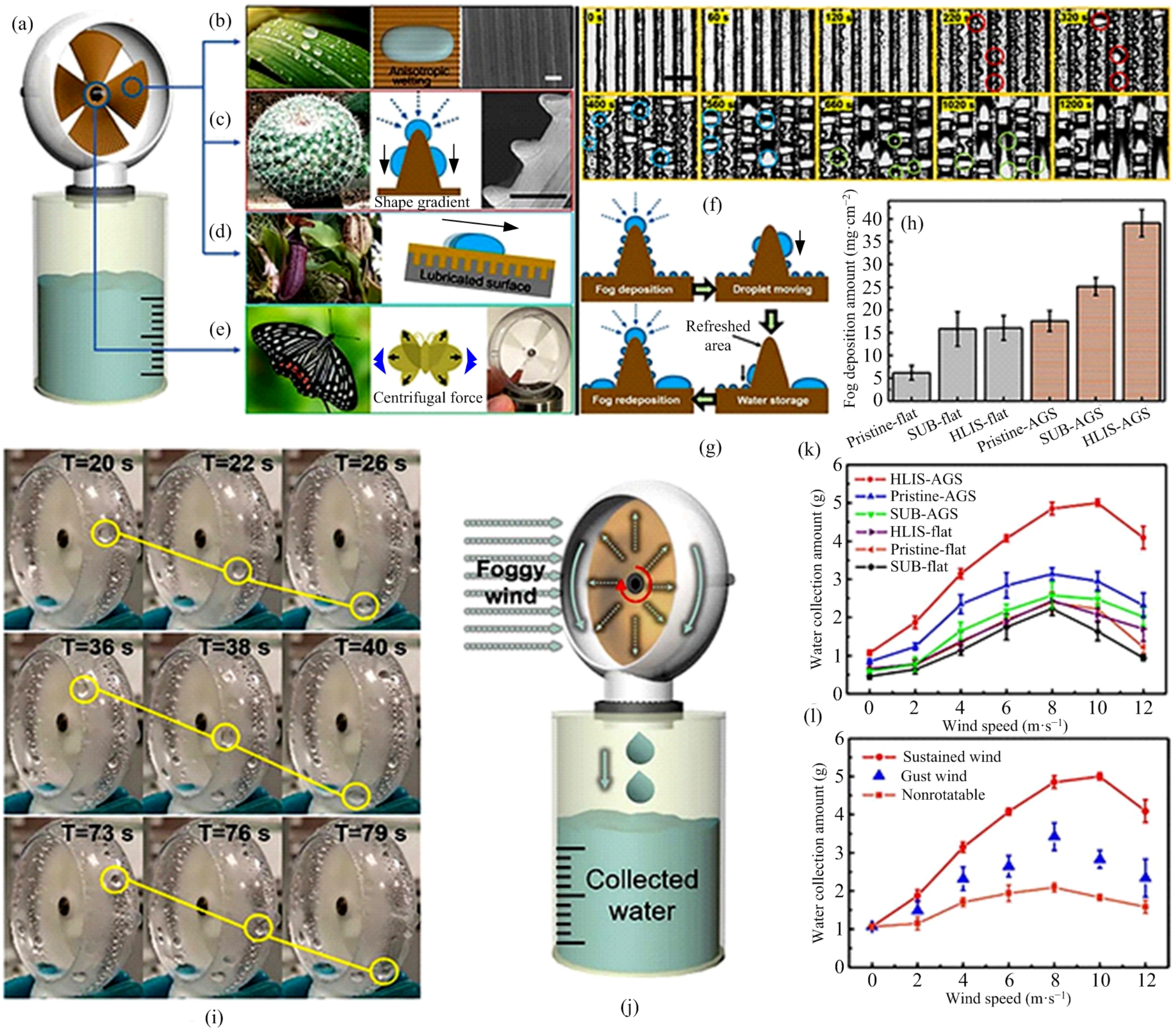


Fig. 18 (a – e) Conceptual scheme of water collection windmill design; (f) photograph taken under an optical microscope showing fog deposition on HLIS-AGS; (g) model of water mist collected on HLIS-AGS; (h) the amount of fog deposition on different surfaces; (i) water collection process on HLIS-AGS; (j) demonstration of the water collection process in wind; (k) the amount of fog collected within 5 minutes on different surfaces in an environment with increasing wind speed; (l) the demisting performance of the HLIS-AGS windmill under the conditions of continuous wind (lasting for 5 minutes) and static environment (lasting for 4 minutes and 50 seconds) and then gust (lasting for 10 seconds) are compared. A non-rotating HLIS-AGS windmill with fixed blades is used as a reference. (a – k) were adapted with permission from Ref. [172]. Copyright 2019 by American Chemical Society.

droplets to realize the directional drainage.

5 Conclusions: Challenges and opportunities for water mist collection

With the rapid economic growth and the lack of protection of water resources, water pollution has caused a serious shortage of water resources. How to efficiently obtain water resources is crucial for people and nature. The fog water collection technology has achieved tremendous development after decades of development. The technology is relatively mature, economical, and not geographically restricted, so it has received widespread attention. However, the fog harvesting technology has the problems of low efficiency and incomplete collection process. Therefore, how to deal with these problems and how to effectively use special fog harvesting surfaces and bionics are particularly important. In this review, we describe the relevant mechanisms of passive water collectors and the latest developments in the collection of biologically inspired water mist collection materials with water collection characteristics.

Inspired by nature, many functional materials with fog harvesting capacity have been made. However, they have not yet been widely used in industrialization. For example, most of the fog harvesting capacity tests of these water-collecting biomimetic materials are conducted under the condition that the humidity is greater than 60%, and the humidity in the actual arid areas in life is maintained at less than 20% all the year. The rapid transfer of droplets after collection is a key step to achieve continuous and efficient mist water collection. The next goal of the development of efficient and continuous mist water collection is to integrate a complete system of droplet "condensation – collection – transfer". Secondly, there are other external conditions such as wind speed, wind direction, temperature, which also need theoretical verification. Finally, the biomimetic materials have problems such as the fragility and failure of the surface structure, the preparation process is complicated and the cost is high. Therefore, the biomimetic fog harvesting materials still need to be strengthened.

The fog harvesting material has broad application prospects and is a research hotspot in the field of super hydrophobicity. Although some progress has been made in fog harvesting in recent years, efforts are still being made. The research is mainly carried out from the following aspects:(1) We should carefully dig out whether there are other types or similar fog harvesting structures or materials. (2) Existing fog harvesting materials are mainly concentrated on one-dimensional and two-dimensional surfaces. In the future, more attention should be paid to three-dimensional materials. (3) The application of multiple bionics needs to be considered in future research to make the overall water-collecting performance more excellent. (4) In the follow-up, further research work is needed in terms of structure, wettability and material to explore ways to improve the performance of droplet directional motion. (5) The disadvantage of artificial micro-nano structure surface is that the water collection process is not all-weather and fast. Researchers should study the practical application of materials more deeply to achieve the integrated development of industry and academia.

Acknowledgment

This work is supported by the National Nature Science Foundation of China (No. 51735013).

References

[1] Ridoutt B G, Pfister S. Reducing humanity's water footprint. *Environmental Science & Technology*, 2010, **44**, 6019–6021.

[2] Gilbertson L M, Zimmerman J B, Plata D L, Hutchison J E, Anastas P T. Designing nanomaterials to maximize performance and minimize undesirable implications guided by the Principles of Green Chemistry. *Chemical Society Reviews*, 2015, **44**, 5758–5777.

[3] Mansur A R, Oh D H. Combined effects of thermosonication and slightly acidic electrolyzed water on the microbial quality and shelf life extension of fresh-cut kale during refrigeration storage. *Food Microbiology*, 2015, **51**, 154–162.

[4] Carroll H A, Davis M G, Papadaki A. Higher plain water intake is associated with lower type 2 diabetes risk: A cross-sectional study in humans. *Nutrition Research*, 2015, **35**, 865–872.

[5] Mekonnen M M, Hoekstra A Y. Four billion people facing severe water scarcity. *Science Advances*, 2016, **2**, e1500323–e1500323.

[6] Frank E, Robert S. Fog water chemistry in the Namib desert, Namibia. *Atmospheric Environment*, 2015, **32**, 2595–2599.

[7] Reitano R. Water harvesting and water collection systems in mediterranean area. The case of Malta. *Procedia Engineering*, 2011, **2**, 81–88.

[8] Schyns J F, Hoekstra A Y, Booij M J, Hogeboom R J, Mekonnen M M. Limits to the world's green water resources for food, feed, fiber, timber, and bioenergy. *Proceedings of the*

National Academy of Sciences of the United States of America, 2019, **116**, 4893–4898.

[9] D'Alessio L, Rigol M. Dynamical preparation of Floquet Chern insulators. *Nature*, 2015, **6**, 8336–8336.

[10] Wise E L, Rayment I. Understanding the importance of protein structure to nature's routes for divergent evolution in TIM barrel enzymes. *Accounts of Chemical Research*, 2004, **37**, 149–158.

[11] Lipetz L E. Bionics. *Science*, 1963, **140**, 1419–1429.

[12] Wang S, Feng L, Jiang L. One-step solution-immersion process for the fabrication of stable bionic superhydrophobic surfaces. *Advanced Materials*, 2006, **18**, 767–770.

[13] Lin F, Li S, Li Y, Li H, Zhu D. Super-hydrophobic surfaces: From natural to artificial. *Advanced Materials*, 2002, **14**, 1857–1860.

[14] Yu M, Chen S, Zhang B, Qiu D L, Cui S X. Why a lotus-like superhydrophobic surface is self-cleaning? An explanation from surface force measurements and analysis. *Langmuir*, 2014, **30**, 13615–13621.

[15] Li D K, Guo Z G. Stable and self-healing superhydrophobic MnO2@fabrics: Applications in self-cleaning, oil/water separation and wear resistance. *Journal of Colloid and Interface Science*, 2017, **503**, 124–130.

[16] Guo Z G, Liu W M, Su B L. Why so strong for the lotus leaf? *Applied Physics Letters*, 2008, **93**, 201909.

[17] Roxana-Elena A M, Mihaela G, Cristina D P, Răzvan P, Lăcrămioara P. Superhydrophobic natural and artificial surfaces—A structural approach. *Materials*, 2018, **11**, 866.

[18] Jeevahan J, Chandrasekaran M, Joseph G B, Durairaj R B, Mageshwaran G. Superhydrophobic surfaces: A review on fundamentals, applications, and challenges. *Journal of Coatings Technology and Research*, 2018, **15**, 231–250.

[19] Gu Y Q, Zhang W Q, Mou J G, Zheng S H, Jiang L F, Sun Z Z, Wang E. Research progress of biomimetic superhydrophobic surface characteristics, fabrication, and application. *Advances in Mechanical Engineering*, 2017, **9**, 1–13.

[20] Xu Q, Zhang W W, Dong C B, Sreeprasad T S, Xia Z H. Biomimetic self-cleaning surfaces: Synthesis, mechanism and applications. *Journal of the Royal Society Interface*, 2016, **13**, 20160300.

[21] Yao X, Song Y L, Jiang L. Applications of bio-inspired special wettable surfaces. *Advanced Materials*, 2011, **23**, 719–734.

[22] Feng L, Zhang Y N, Xi J M, Zhu Y, Wang N, Xia F, Jiang L. Petal effect: A superhydrophobic state with high adhesive force. *Langmuir*, 2008, **24**, 4114–4119.

[23] Mandsberg N K, Taboryski R. The rose petal effect and the role of advancing water contact angles for drop confinement. *Surface Topography Metrology and Properties*, 2017, **5**, 024001.

[24] Ebert D, Bhushan B. Wear-resistant rose petal-effect surfaces with superhydrophobicity and high droplet adhesion using hydrophobic and hydrophilic nanoparticles. *Journal of Colloid and Interface Science*, 2012, **384**, 182–188.

[25] Lu X Y, Cai H Y, Wu Y Z, Teng C, Jiang C C, Zhu Y, Jiang L. Peach skin effect: A quasi-superhydrophobic state with high adhesive force. *Science Bulletin*, 2015, **60**, 453–459.

[26] Bixler G D, Bhushan B. Fluid drag reduction and efficient self-cleaning with rice leaf and butterfly wing bioinspired surfaces. *Nanoscale*, 2013, **5**, 7685–7710.

[27] Barthlott W, Neinhuis C. Purity of the sacred lotus, or escape from contamination in biological surfaces. *Planta*, 1997, **202**, 1–8.

[28] Feng L, Zhang Y N, Xi J M, Zhu Y, Wang N, Xia F, Jiang L. Petal effect? A superhydrophobic state with high adhesive force. *Langmuir*, 2008, **24**, 4114–4119.

[29] Bixler G D, Bhushan B. Rice- and butterfly-wing effect inspired self-cleaning and low drag micro/nanopatterned surfaces in water, oil, and air flow. *Nanoscale*, 2014, **6**, 76–96.

[30] Gao X F, Jiang L. Biophysics: Water-repellent legs of water striders. *Nature*, 2004, **432**, 36.

[31] Watson G S, Watson J A. Natural nano-structures on insects – possible functions of ordered arrays characterized by atomic force microscopy. *Applied Surface Science*, 2004, **235**, 139–144.

[32] Watson G S, Cribb B W, Watson J A. How micro/nanoarchitecture facilitates anti-wetting: An elegant hierarchical design on the termite wing. *Applied Surface Science*, 2010, **4**, 129–136.

[33] Su Y W, Ji B H, Huang Y G, Hwang K. Nature's Design of hierarchical superhydrophobic surfaces of a water strider for low adhesion and low-energy dissipation. *Langmuir*, 2010, **26**, 18926–18937.

[34] Gao X, Xin Y, Xi Y, Liang X, Lei J. The dry-style antifogging properties of mosquito compound eyes and artificial analogues prepared by soft lithography. *Advanced Materials*, 2007, **19**, 2213–2217.

[35] Darmanin T, Guittard F. Recent advances in the potential applications of bioinspired superhydrophobic materials. *Journal of Materials Chemistry A*, 2014, **2**, 16319–16359.

[36] Zhang P, Lv F Y. A review of the recent advances in superhydrophobic surfaces and the emerging energy-related applications. *Energy*, 2015, **82**, 1068–1087.

[37] Celia E, Darmanin T, Elisabeth T, Amigoni S, Guittard F. Recent advances in designing superhydrophobic surfaces. *Journal of Colloid and Interface Science*, 2013, **402**, 1–18.

[38] Zhang B, Jiang Y J, Jian H. Facile fabrication of PVAc-g-PVDF coating on surface modified cotton fabric for applications in oil/water separation and heavy metal ions removal. *Fibers and Polymers*, 2017, **18**, 1754–1762.

[39] Chen H W, Ran T, Gan Y, Zhou J J, Zhang Y, Zhang L W, Zhang D Y, Jiang L. Ultrafast water harvesting and transport in hierarchical microchannels. *Nature Materials*, 2018, **17**, 935–942.

[40] Chen H W, Zhang P F, Zhang L W, Liu H L, Jiang Y, Zhang D Y, Han Z W, Jiang L. Continuous directional water transport on the peristome surface of Nepenthes alata. *Nature*, 2016, **532**, 85–89.

[41] Zheng Y M, Gao X F, Jiang L. Directional adhesion of superhydrophobic butterfly wings. *Soft Matter*, 2007, **3**, 178-182.

[42] Xue Y, Wang T, Shi W W, Sun L L, Zheng Y M. Water collection abilities of green bristlegrass bristle. *RSC Advances*, 2014, **4**, 40837–40840.

[43] Tracy C R, Laurence N, Christian K A. Condensation onto the skin as a means for water gain by tree frogs in tropical Australia. *American Naturalist*, 2011, **178**, 553–558.

[44] Jie J, Bai H, Zheng Y M, Zhao T Y, Fang R C, Jiang L. A multi-structural and multi-functional integrated fog collection system in cactus. *Nature Communications*, 2012, **3**, 1247.

[45] Bai H, Ju J, Zheng Y M, Jiang L. Functional fibers: Functional fibers with unique wettability inspired by spider silks. *Advanced Materials*, 2012, **24**, 2786–2791.

[46] Hamilton W J, Seely M K. Fog basking by the Namib Desert beetle, Onymacris unguicularis. *Nature*, 1976, **262**, 284–285.

[47] Ang B T W, Yap C H, Lee W S V, Xue J. Bioinspired dual-tier coalescence for water-collection efficiency enhancement. *Langmuir*, 2018, **34**, 13409–13415.

[48] Young T. An essay on the cohesion of fluids. *Philosophical Transactions of the Royal Society of London*, 1805, **5**, 65–87.

[49] Wenzel R N. Resistance of solid surfaces to wetting by water. *Transactions of the Faraday Society*, 1936, **28**, 988–994.

[50] Cassie A B D, Baxter S. Wettability of porous surfaces. *Transactions of the Faraday Society*, 1944, **40**, 0546–0550.

[51] Singh R A, Yoon E S, Kim H J, Kong H, Park S, Jeong H E, Suh K Y. Enhanced tribological properties of lotus leaf-like surfaces fabricated by capillary force lithography. *Surface Engineering*, 2007, **23**, 161–164.

[52] Zhang Q X, Chen Y X, Guo Z, Liu H L, Wang D, Huang X. Bioinspired multifunctional hetero-hierarchical micro/nanostructure tetragonal array with self-cleaning, anticorrosion, and concentrators for the SERS detection. *Applied Materials & Interfaces*, 2013, **5**, 10633–10642.

[53] Eick J D, Good R J, Neumann A W. Thermodynamics of contact angles. II. Rough solid surfaces. *Journal of Colloid and Interface Science*, 1975, **53**, 235–248.

[54] Togonal A S, He L, Cabarrocas P R, Rusli. Effect of wettability on the agglomeration of silicon nanowire arrays fabricated by metal-assisted chemical etching. *Langmuir*, 2014, **30**, 10290–10298.

[55] Michielsen S, Zhang J, Du J, Lee H J. Gibbs free energy of liquid drops on conical fibers. *Langmuir*, 2011, **27**, 11867–11872.

[56] Carroll B J. Spreading of liquid droplets on cylindrical surfaces: Accurate determination of contact angle. *Journal of Applied Physics*, 1991, **70**, 495–495.

[57] Sun T L, Feng L, Gao X F, Jiang L. Bioinspired surfaces with special wettability. *Accounts of Chemical Research*, 2005, **38**, 644–652.

[58] Grunze M. Surface science: Driven liquids. *Science*, 1999, **283**, 41–42.

[59] Zheng Y, Bai H, Huang Z, Tian X, Nie F Q, Zhao Y, Zhai J, Jiang L. Directional water collection on wetted spider silk. *Nature*, 2010, **463**, 640–643.

[60] Tower R E. The effect of plate inclination on heat transfer during dropwise condensation of steam. *Journal of Industrial and Engineering Chemistry*, 1969, **28**, 307–315.

[61] Kukushkin S A, Osipov A V. Thin-film condensation processes. *Physics-Uspekhi*, 1998, **41**, 983–1014.

[62] Kukushkin S A, Osipov A V. New phase formation on solid surfaces and thin film condensation. *Progress in Surface Science*, 1996, **51**, 1–107.

[63] Zinsmeister G. A contribution to Frenkel’s theory of condensation. *Vacuum*, 1966, **16**, 529–535.

[64] Zhang S N, Huang J Y, Chen Z, Lai Y K. Bioinspired special wettability surfaces: From fundamental research to water harvesting applications. *Small*, 2017, **13**, 1602992.

[65] Parker A R, Lawrence C R. Water capture by a desert beetle. *Nature*, 2001, **414**, 33–34.

[66] Zu Y Q, Yan Y Y, Li J Q, Han Z W. Wetting behaviours of a single droplet on biomimetic micro structured surfaces. *Journal of Bionic Engineering*, 2010, **7**, 191–198.

[67] Chandra D, Yang S. Dynamics of a droplet imbibing on a rough surface. *Langmuir*, 2011, **27**, 13401–13405.

[68] Maclean G L. Water transport by sandgrouse. *Bioscience*, 1983, **33**, 365–369.

[69] Liu C C, Xue Y, Chen Y, Zheng Y M. Effective directional self-gathering of drops on spine of cactus with splayed capillary arrays. *Scientific Reports*, 2015, **5**, 17757.

[70] Zhong L, Feng J, Guo Z. An alternating nanoscale (hydrophilic-hydrophobic)/hydrophilic Janus cooperative copper mesh fabricated by a simple liquidus modification for efficient fog harvesting. *Journal of Materials Chemistry A*, 2019, **7**, 8405–8413.

[71] Huang J, Lai Y, Pan F, Yang L, Chi L. Multifunctional superamphiphobic TiO_2 nanostructure surfaces with facile wettability and adhesion engineering. *Small*, 2014, **10**, 4865–4873.

[72] Lai Y, Lin C, Huang J, Zhuang H, Nguyen T. Markedly controllable adhesion of superhydrophobic spongelike nanostructure TiO_2 films. *Langmuir*, 2008, **24**, 3867–3873.

[73] Yamamoto M, Nishikawa N, Mayama H, Nonomura Y, Uchida K. Theoretical explanation of the lotus effect: Superhydrophobic property changes by removal of nanostructures from the surface of a lotus leaf. *Langmuir*, 2015, **31**, 7355–7363.

[74] Tan W, Desai T A. Layer-by-layer microfluidics for biomimetic three-dimensional structures. *Biomaterials*, 2004, **25**, 1355–1364.

[75] Sherbrooke W C. Rain-harvesting in the lizard, phrynosoma cornutum: Behavior and integumental morphology. *Journal of Herpetology*, 1990, **24**, 302–308.

[76] Sherbrooke W C, Scardino A J, Nys R D, Schwarzkopf L. Functional morphology of scale hinges used to transport water: Convergent drinking adaptations in desert lizards (Moloch horridusand Phrynosoma cornutum). *Zoomorphology*, 2007, **126**, 89–102.

[77] Withers P C, Hillman S S, Drewes R C. Evaporative water loss and skin lipids of anuran amphibians. *Journal of Experimental Zoology*, 1984, **232**, 11–17.

[78] Toledo R C, Jared C. Cutaneous adaptations to water balance in amphibians. *Comparative Biochemistry and Physiology Part A*: *Physiology*, 1993, **105**, 593–608.

[79] Solga A, Cerman Z, Striffler B F, Spaeth M, Barthlott W. The dream of staying clean: Lotus and biomimetic surfaces. *Bioinspiration & Biomimetics*, 2007, **2**, S126–S134.

[80] Bhushan B, Jung Y C, Niemietz A, Koch K. Lotus-like biomimetic hierarchical structures developed by the self-assembly of tubular plant waxes. *Langmuir*, 2009, **25**, 1659–1666.

[81] Comanns P, Winands K, Arntz K, Klocke F, Baumgartner W. Laser-based biomimetic functionalization of surfaces: From moisture harvesting lizards to specific fluid transport systems. *International Journal of Design & Nature and Ecodynamics*, 2014, **9**, 206–215.

[82] Vinogradova O I, Belyaev A V. Wetting, roughness and flow boundary conditions. *Journal of Physics Condensed Matter*, 2011, **23**, 184104.

[83] Kamusewitz H, Possart W. Wetting and scanning force microscopy on rough polymer surfaces: Wenzel's roughness factor and the thermodynamic contact angle. *Applied Physics A*, 2003, **76**, 899–902.

[84] Viborg A L, Hillyard S D. Cutaneous blood flow and water absorption by dehydrated toads. *Physiological and Biochemical Zoology*, 2005, **78**, 394–404.

[85] Hischen F, Reiswich V, Kupsch D, Mecquenem N, Riedel M, Himmelsbach M, Weth A, Heiss E, Armbruster O, Heitz J. Adaptive camouflage: What can be learned from the wetting behaviour of the tropical flat bugs Dysodius lunatus and Dysodius magnus. *Biology Open*, 2017, **6**, 1209–1218.

[86] Tian W C, Finehout E. Current and future trends in microfluidics within biotechnology research. *Microfluidics for Biological Applications*, 2009, **11**, 385–411.

[87] Bentley P J, Blumer W F C. Uptake of water by the lizard, moloch horridus. *Nature*, 1962, **19**, 699–700.

[88] Sherbrooke W C. Rain-drinking behaviors of the Australian thorny devil (Sauria: Agamidae). *Journal of Herpetology*, 1993, **27**, 270–275.

[89] Glaudas X. Rain-harvesting by the southwestern speckled rattlesnake (Crotalus mitchellii pyrrhus). *Southwestern Naturalist*, 2009, **54**, 518–521.

[90] Comanns P, Effertz C, Hischen F, Staudt K, Böhme W, Baumgartner W. Moisture harvesting and water transport through specialized micro-structures on the integument of lizards. *Beilstein Journal of Nanotechnology*, 2011, **2**, 204–214.

[91] Sherbrooke W. Integumental water movement and rate of water ingestion during rain harvesting in the Texas horned lizard, Phrynosoma cornutum. *Amphibia-Reptilia*, 2004, **25**, 29–39.

[92] Hou Y P, Chen Y, Xue Y, Zheng Y M, Jiang L. Water collection behavior and hanging ability of bioinspired fiber. *Langmuir*, 2012, **28**, 4737–4743.

[93] Hou Y P, Chen Y, Xue Y, Wang L, Zheng Y M, Jiang L. Stronger water hanging ability and higher water collection efficiency of bioinspired fiber with multi-gradient and multi-scale spindle knots. *Soft Matter*, 2012, **8**, 11236–11239.

[94] Ito F, Komatsubara S, Shigezawa N, Morikawa H, Mura-

kami Y, Yoshino K, Yamanaka S. Mechanics of water collection in plants via morphology change of conical hairs. *Applied Physics Letters*, 2015, **106**, 133701.

[95] Huang Z, Zhang X T, Hu X J. Dual-scale micro/nanostructures for high-efficiency water collection. *Materials Research Bulletin*, 2017, **92**, 19–22.

[96] Vogel S, Müller-Doblies U. Desert geophytes under dew and fog: The "curly-whirlies" of Namaqualand (South Africa). *Flora-Morphology*, *Distribution*, *Functional Ecology of Plants*, 2011, **206**, 3–31.

[97] Rijke A M. The water repellency of water-bird feathers. *The Auk*, 1987, **104**, 140–142.

[98] Cade T J, Maclean G L. Transport of water by adult sandgrouse to their young. *The Condor*, 1967, **69**, 323–343.

[99] Zhu H, Guo Z G. Hybrid engineered materials with high water-collecting efficiency inspired by Namib Desert beetles. *Chemical Communications*, 2016, **52**, 6809–6812.

[100] Auffenberg W. A note on the drinking habits of some land tortoises. *Animal Behaviour*, 1963, **11**, 72–73.

[101] Gandhidasan P, Abualhamayel H I. Exploring fog water harvesting potential and quality in the Asir region, kingdom of Saudi Arabia. *Pure and Applied Geophysics*, 2012, **169**, 1019–1036.

[102] Fessehaye M, Abdul-Wahab S A, Avage M J S, Kohler T, Gherezghiher T, Hurni H. Fog-water collection for community use. *Renewable and Sustainable Energy Reviews*, 2014, **29**, 52–62.

[103] Domen J K, Stringfellow W T, Camarillo M K, Gulati S. Fog water as an alternative and sustainable water resource. *Clean Technologies and Environmental Policy*, 2014, **16**, 235–249.

[104] Zheng Y M, Bai H, Huang Z B, Tian X L, Nie F Q, Zhao Y, Zhai J, Jiang L. Directional water collection on wetted spider silk. *Nature*, 2010, **463**, 640–643.

[105] Liu W J, Fan P X, Cai M Y, Luo X, Chen C H, Pan R, Zhang H J, Zhong M L. An integrative bioinspired venation network with ultra-contrasting wettability for large-scale strongly self-driven and efficient water collection. *Nanoscale*, 2019, **11**, 8940–8949.

[106] Gurera D, Bhushan B. Multistep wettability gradient on bioinspired conical surfaces for water collection from fog. *Langmuir*, 2019, **35**, 16944–16947.

[107] Martorell C, Ezcurra E. Rosette scrub occurrence and fog availability in arid mountains of Mexico. *Journal of Vegetation Science*, 2002, **13**, 651–662.

[108] Si J H, Feng Q, Cao S K, Yu T F, Zhao C Y. Water use sources of desert riparian *Populus euphratica* forests. *Environmental Monitoring and Assessment*, 2014, **186**, 5469–5477.

[109] Ewing H A, Weathers K C, Templer P H, Dawson T E, Firestone M K, Elliott A M, Boukili V K S. Fog water and ecosystem function: Heterogeneity in a california redwood forest. *Ecosystems*, 2009, **12**, 417–433.

[110] Olivier J. Fog-water harvesting along the West Coast of South Africa: A feasibility study. *Water SA*, 2002, **28**, 349–360.

[111] Schemenauer R S, Cereceda P. The quality of fog water collected for domestic and agricultural use in Chile. *Journal of Applied Meteorology and Climatology*, 1992, **31**, 275–290.

[112] Schemenauer R S, Cereceda P. A proposed standard fog collector for use in high-elevation regions. *Journal of Applied Meteorology*, 1994, **33**, 1313–1322.

[113] Estrela M J, Valiente J A, Corell D, Millan M M. Fog collection in the western Mediterranean basin (Valencia region, Spain). *Atmospheric Research*, 2008, **87**, 324–337.

[114] Valiente J, Estrela M, Corell D, Fuentes D, Valdecantos A. Fog water collection and reforestation at mountain locations in a western Mediterranean basin region. *Erdkunde*, 2011, **65**, 277–290.

[115] Lalia B S, Kochkodan V, Hashaikeh R, Hilal N. A review on membrane fabrication: Structure, properties and performance relationship. *Desalination*, 2013, **326**, 77–95.

[116] Lalia B S, Anand S, Varanasi K K, Hashaikeh R. Fog-harvesting potential of lubricant-impregnated electrospun nanomats. *Langmuir*, 2013, **29**, 13081–13088.

[117] Wang Y F, Wang X W, Lai C L, Hu H W, Kong Y Y, Fei B, Xin J H. Biomimetic water-collecting fabric with light-induced superhydrophilic bumps. *ACS Applied Materials & Interfaces*, 2016, **8**, 2950–2960.

[118] Rykaczewski K, Scott J H J, Rajauria S, Chinn J, Chinn A M, Jones W. Three dimensional aspects of droplet coalescence during dropwise condensation on superhydrophobic surfaces. *Soft Matter*, 2011, **7**, 8749–8752.

[119] Zhai L, Berg M C, Cebeci F C, Kim Y, Milwid J M, Rubner M F, Cohen R E. Patterned superhydrophobic surfaces: Toward a synthetic mimic of the Namib Desert beetle. *Nano Letters*, 2006, **6**, 1213–1217.

[120] Garrod R P, Harris L G, Schofield W C E, McGettrick J, Ward L J, Teare D O H, Badyal J P S. Mimicking a Stenocara Beetle's back for microcondensation using plasmachemical patterned superhydrophobic − superhydrophilic surfaces. *Langmuir*, 2007, **23**, 689–693.

[121] Kondrashov V, Rühe J. Microcones and nanograss: Toward

mechanically robust superhydrophobic surfaces. *Langmuir*, 2014, **30**, 4342–4350.

[122] Hou Y M, Yu M, Chen X M, Wang Z K, Yao S H. Recurrent filmwise and dropwise condensation on a beetle mimetic surface. *ACS Nano*, 2015, **9**, 71–81.

[123] Gandhidasan P, Abualhamayel H I, Patel F. Simplified modeling and analysis of the fog water harvesting system in the Asir Region of the Kingdom of Saudi Arabia. *Aerosol and Air Quality Research*, 2018, **18**, 200–213.

[124] Zhao Q, Zhang D C, Lin J F, Wang G M. Dropwise condensation on LB film surface. *Chemical Engineering and Processing*: *Process Intensification*, 1996, **35**, 473–477.

[125] Schacht K, Scheibel T. Controlled hydrogel formation of a recombinant spider silk protein. *Biomacromolecules*, 2011, **12**, 2488–2495.

[126] Elices M, Guinea G V, Plaza G R, Karatzas C, Riekel C, Agulló-Rueda F, Daza R, Pérez-Rigueiro J. Bioinspired fibers follow the track of natural spider silk. *Macromolecules*, 2011, **44**, 1166–1176.

[127] Metwalli E, Slotta U, Darko C, Roth S V, Scheibel T, Papadakis C M. Structural changes of thin films from recombinant spider silk proteins upon post-treatment. *Applied Physics A*, 2007, **89**, 655–661.

[128] Zhou C, Wu J. Bioinspired micro-nano fibrous adhesion materials. *Progress in Chemistry*, 2018, **30**, 1863–1873.

[129] Daniel S, Chaudhury M K, Chen J C. Fast drop movements resulting from the phase change on a gradient surface. *Science*, 2001, **291**, 633–636.

[130] Yang J T, Chen J C, Huang K J, Yeh J A. Droplet manipulation on a hydrophobic textured surface with roughened patterns. *Journal of Microelectromechanical Systems*, 2006, **15**, 697–707.

[131] Chen W, Guo Z G. Hierarchical fibers for water collection inspired by spider silk. *Nanoscale*, 2019, **11**, 15448–15463.

[132] Chen Y, Zheng Y M. Bioinspired micro-/nanostructure fibers with a water collecting property. *Nanoscale*, 2014, **6**, 7703–7714.

[133] Bosia F, Buehler M J, Pugno N M. Hierarchical simulations for the design of supertough nanofibers inspired by spider silk. *Physical Review E*, 2010, **82**, 056103.

[134] Huang Z B, Chen Y, Zheng Y M, Jiang L. Capillary adhesion of wetted cribellate spider capture silks for larger pearly hanging-drops. *Soft Matter*, 2011, **7**, 9468–9473.

[135] Hou Y P, Chen Y, Xue Y, Zheng Y M, Jiang L. Water collection behavior and hanging ability of bioinspired fiber. *Langmuir*, 2012, **28**, 4737–4743.

[136] Tian Y, Zhu P G, Tang X, Zhou C M, Wang J M, Kong T T, Xu M, Wang L Q. Large-scale water collection of bioinspired cavity-microfibers. *Nature Communications*, 2017, **8**, 1080.

[137] Hou Y P, Chen Y, Xue Y, Wang L, Zheng Y M, Jiang L. Stronger water hanging ability and higher water collection efficiency of bioinspired fiber with multi-gradient and multi-scale spindle knots. *Soft Matter*, 2012, **8**, 11236–11239.

[138] Chen Y, Wang L, Xue Y, Jiang L, Zheng Y M. Bioinspired tilt-angle fabricated structure gradient fibers: Micro-drops fast transport in a long-distance. *Scientific Reports*, 2013, **3**, 2927.

[139] Tian X L, Chen Y, Zheng Y M, Bai H, Jiang L. Controlling water capture of bioinspired fibers with hump structures. *Advanced Materials*, 2011, **23**, 5486–5491

[140] Breslauer D N, Muller S J, Lee L P. Generation of monodisperse silk microspheres prepared with microfluidics. *Biomacromolecules*, 2010, **11**, 643–647.

[141] Feng S L, Hou Y P, Xue Y, Gao L C, Jiang L, Zheng Y M. Photo-controlled water gathering on bio-inspired fibers. *Soft Matter*, 2013, **9**, 9294–9297.

[142] Bai H, Tian X L, Zheng Y M, Ju J, Zhao Y, Jiang L. Direction controlled driving of tiny water drops on bioinspired artificial spider silks. *Advanced Materials*, 2010, **22**, 5521–5525.

[143] Chen Y, Li D, Wang T, Zheng Y M. Orientation-induced effects of water harvesting on humps-on-strings of bioinspired fibers. *Scientific Reports*, 2016, **6**, 19978.

[144] Kang E, Jeong G S, Choi Y Y, Lee K H, Khademhosseini A, Lee S H. Digitally tunable physicochemical coding of material composition and topography in continuous microfibres. *Nature Materials*, 2011, **10**, 877.

[145] Wu Y C, Chen X, Su B, Song Y L, Jiang L. Elaborately aligning bead-shaped nanowire arrays generated by a superhydrophobic micropillar guiding strategy. *Advanced Functional Materials*, 2012, **22**, 4569–4576.

[146] Cui Y, Li D W, Ba H. Bioinspired smart materials for directional liquid transport. *Industrial & Engineering Chemistry Research*, 2017, **56**, 4887–4897.

[147] Li J, Sun Q M, Chen L, Feng J T, Han D. Bioinspired one-dimensional nano-wrinkles guide liquid behaviors at the liquid–solid interfaces. *Journal of Nanoscience and Nanotechnology*, 2016, **16**, 885–891.

[148] Ju J, Zheng Y M, Jiang L. Bioinspired one-dimensional materials for directional liquid transport. *Accounts of Chemical Research*, 2014, **47**, 2342–2352.

[149] Xia F, Jiang L. Bio-inspired, smart, multiscale interfacial (BSMI) materials. *Advanced Materials*, 2008, **20**,

2842–2858.

[150] Heng X, Xiang M M, Lu Z H, Luo C. Branched ZnO wire structures for water collection inspired by cacti. *ACS Applied Materials & Interfaces*, 2014, **6**, 8032–8041.

[151] Li K, Ju J, Xue Z X, Ma J, Feng L, Gao S, Jiang L. Structured cone arrays for continuous and effective collection of micron-sized oil droplets from water. *Nature Communications*, 2013, **4**, 2276.

[152] Ju J, Yao X, Yang S, Wang L, Sun R Z, He Y X, Jiang L. Cactus stem inspired cone-arrayed surfaces for efficient fog collection. *Advanced Functional Materials*, 2014, **24**, 6933–6938.

[153] Bai F, Wu J T, Gong G M, Guo L. Biomimetic "cactus spine" with hierarchical groove structure for efficient fog collection. *Advanced Science*, 2015, **2**, 1500047.

[154] Miguel S, Hehn A, Bourgaud F. Nepenthes: State of the art of an inspiring plant for biotechnologists. *Journal of Biotechnology*, 2018, **265**, 109–115.

[155] MasaroviováA P E, Hudák J. Carnivorous syndrome in Asian pitcher plants of the genus Nepenthes. *Annals of Botany*, 2007, **100**, 527–536.

[156] Zhou S, Yu C L, Li C X, Dong Z C, Jiang L. Programmable unidirectional liquid transport on peristome-mimetic surfaces under liquid environments. *Journal of Materials Chemistry A*, 2019, **7**, 18244–18248.

[157] Ulrike B, Christoph W, Walter F. Effect of pitcher age on trapping efficiency and natural prey capture in carnivorous Nepenthes rafflesiana plants. *Annals of Botany*, 2009, **103**, 1219–1226.

[158] Li J Q, Zheng H X, Yang Z B, Wang Z K. Breakdown in the directional transport of droplets on the peristome of pitcher plants. *Communications Physics*, 2018, **1**, 1–7.

[159] Chen H W, Zhang W L, Yi Z, Zhang P F, Zhang D Y, Lei J. Uni-directional liquid spreading control on a bio-inspired surface from the peristome of Nepenthes alata. *Journal of Materials Chemistry A*, 2017, **5**, 694–6920.

[160] Zhang P F, Zhang L W, Chen H W, Dong Z C, Zhang D Y. Surfaces inspired by the Nepenthes peristome for unidirectional liquid transport. *Advanced Materials*, 2017, **29**, 1702995.

[161] Dai X M, Sun N, Nielsen S O, Stogin B B, Wong T S. Hydrophilic directional slippery rough surfaces for water harvesting. *Science Advances*, 2018, **4**, eaaq0919.

[162] Pant R, Roy P K, Nagarajan A, Khare K. Slipperiness and stability of hydrophilic surfaces coated with a lubricating fluid. *RSC Advances*, 2016, **6**, 15002–15007.

[163] Li C X, Li N, Zhang X S, Dong Z C, Chen H W, Jiang L. Uni-directional transportation on peristome-mimetic surfaces for completely wetting liquids. *Angewandte Chemie International Edition*, 2016, **55**, 14988–14992.

[164] Chen H, Zhang L, Zhang P, Zhang D, Jiang L. A novel bioinspired continuous unidirectional liquid spreading surface structure from the peristome surface of Nepenthes alata. *Small*, 2017, **13**, 1601676.

[165] Li C X, Li N, Zhang X S, Dong Z C, Chen H W, Jiang L. Cover picture: Uni-directional transportation on peristome-mimetic surfaces for completely wetting liquids. *Angewandte Chemie International Edition*, 2016, **55**, 14875–14875(1).

[166] Zhang P F, Chen H W, Li L, Liu H L, Liu G, Zhang L W, Zhang D Y, Jiang L. Bioinspired smart Peristome surface for temperature-controlled unidirectional water spreading. *ACS Applied Materials & Interfaces*, 2017, **9**, 5645–5652.

[167] Zhang P F, Chen H W, Zhang D Y. Investigation of the Anisotropic morphology-induced effects of the slippery zone in pitchers of *Nepenthes alata*. *Journal of Bionic Engineering*, 2015, **12**, 79–87.

[168] Park K C, Kim P, Grinthal A, He N, Fox D, Weaver J C, Aizenberg J. Condensation on slippery asymmetric bumps. *Nature*, 2016, **531**, 78–82.

[169] Guo L, Tang G H. Dropwise condensation on bioinspired hydrophilic-slippery surface. *RSC Advances*, 2018, **8**, 39341–39351.

[170] Cha H, Vahabi H, Wu A, Chavan S, Miljkovic N. Dropwise condensation on solid hydrophilic surfaces. *Science Advances*, 2020, **6**, eaax0746.

[171] Zhang X X, Sun L Y, Wang Y, Bian F K, Wang Y T, Zhao Y J. Multibioinspired slippery surfaces with wettable bump arrays for droplets pumping. *Proceedings of the National Academy of Sciences*, 2019, **116**, 20863–80868.

[172] Wang Y F, Liang X, Ma K K, Zhang H R, Wang X, Xin J H, Zhang Q, Zhu S P. Nature-inspired windmill for water collection in complex windy environments. *ACS Applied Materials & Interfaces*, 2019, **11**, 17952–17959.