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Facile and Large-Scale Fabrication of a Cactus-Inspired Continuous Fog Collector

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Although clean drinking water is a basic human need, freshwater scarcity has been identified as a major global problem of the 21st century. Nature has long served as a source of inspiration for human beings to develop new technology. The cactus in the desert possesses a multifunctional integrated fog collection system originating from the cooperation of a Laplace pressure gradient and the wettability difference. In this contribution, inspired by the cactus, an artificial fog collector on a large scale is first fabricated through integrating cactus spine-like hydrophobic conical micro-tip arrays with the hydrophilic cotton matrix. The novel cactus-inspired fog collector can spontaneously and continuously collect, transport, and preserve fog water, demonstrating high fog collection efficiency and promising applications in the regions with drinking water scarcity. Furthermore, the present approach is simple, time-saving and cost-effective, which provides a potential device and new idea to solve the global water crisis.

1. Introduction

The global water crisis has emerged as a serious issue over the past decade. In 2013, the World Health Organization reported that over 768 million people still use unimproved drinking-water sources, especially for the population living in the regions such as desert, coast, and high mountain.[1] The risk of water shortages results not only from the insufficiency of the total water mass, more importantly, but from the inadequacy of water collection and preservation in those regions. Due to its large water capacity, fog is an available source of fresh water.[2]

In nature, some creatures have evolved elegant strategies for fog collection to survive. For example, the tenebrionid beetle (*Stenocara sp.*) living in the arid Namib Desert could collect drinking water from foggy air using hydrophilic/hydrophobic patterned structures.[3] Spider capture silks (*Uloborus walckenaerius*) have superior water collection ability arising from the special hierarchical fibre structures with periodic joints and spindle-knots.[4] The cactus (*Opuntia microdasys*) in desert possesses a continuous and efficient fog collection system originating from the cooperation of Laplace pressure gradient and the wettability difference.[5]

Nature is a school for human beings.[6] Optimized biological solutions provide inspiration for the design and fabrication of functional surfaces with water collection ability.[7] Our recent research works have revealed that geometrically conical-shape spines and hierarchically hydrophilic/hydrophobic dichotomy of the cactus cluster play an important role in the fog collection.[5] Firstly, driven by Laplace pressure difference, the water droplet could directionally move towards the base of the hydrophobic conical spines.[4b,8] Subsequently, the hydrophilic trichomes, a hair-like fiber cluster grown at the base of the spines, could rapidly absorb and transport the collected water into the stem of cactus. For the conventional gravity-driven fog collectors, water droplets with a large critical volume should be formed to overcome the binding forces of the surface, resulting in a higher risk of water re-evaporation and a decreasing area of fog-collecting surface.[9] Interestingly, the cactus has evolved multifunctional integrated fog collection system, which can spontaneously and continuously achieve the collection, transportation, and preservation of fog water. This optimized strategy could be adopted to design and fabricate an artificial continuous fog collector with a large scale for fog harvesting in water-deficit regions.

2. Results and Discussion

2.1. Fabrication of the Cactus Spine-like Conical Micro-Tips

Up to now, cactus spine-like conical micro-tips have been fabricated by chemical or electrochemical erosion of metal wire,[8] deep X-ray etching,[10] replica molding method,[11] etc. Although these reported methods can successfully prepare well-defined

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conical micro-tips and their arrays, most of them were time-consuming and cost-inefficient, showing a major limitation for the practical application. For example, the time interval of the electrochemical erosion of a single conical copper wire was approximately 20 min, even though without the further surface modification.[9b] Restricted by the mold and the procedure, the replica molding method might not be suitable for the tips with a long length (>1 mm) and large length-diameter ratio.[11b] In order to stimulate the practical application of bioinspired functional materials with fog collection, a cost- and time-effective production method should be developed.

Herein, inspired by the cactus, an effective and facile approach was developed to design and fabricate cactus spine-like conical micro-tips. The resultant conical micro-tips exhibited cactus spine-like fog collection ability driven by the Laplace pressure difference. Through the assembly of micro-tip arrays, an integrated fog collector similar to the cactus was first developed, demonstrating continuous collection, transportation, and preservation for the fog water. The proposed strategy opened a new avenue for the large-scale production of novel fog collectors in practical applications.

The scheme for the fabrication of cactus-inspired conical micro-tips is outlined in **Figure 1**a. Magnetic particle-assisted molding (MPAM) was previously proposed to fabricate cilia-inspired fibers through the combination of magnetic field-induced MPs arrangement and polymer solution evaporating-coating process.[12] In the present work, a modified organic-solvent-free MPAM process was developed to fabricate cactus-inspired conical micro-tips in large scale within a short time. A well-distributed mixture was deposited on the flat and geometric patterned polystyrene substrates through spin coating of a magnetic suspension containing polydimethylsiloxane (PDMS) and cobalt magnetic particles (MPs), resulting in the formation of disordered and ordered conical micro-tip arrays along the direction of the external magnetic field, respectively (Figure 1b,c). The geometric patterned polystyrene substrate was fabricated by common mechanical process with a polyvinylchloride tape, which have ordered square pits with the size of 0.5 mm (length) × 0.5 mm (width) × 0.13 mm (depth). The spacing between the nearest pits is about 0.5 mm. Once the MPs were filled in the geometric pattern, the magnetic induction line will selectively pass through the pattern due to the higher magnetic conductivity, resulting in the ordered micro-tip array. In comparison with the natural cactus spine or the conical metal tip, the resultant PDMS-MPs micro-tip arrays exhibited improved flexibility and elasticity owing to the presence of PDMS matrix, which allow us to manipulate easily and to assembly high-performance fog collectors in large scale.

In the experiment, a neodymium magnet (60 mm in diameter, 50 mm in thickness) with a superficial magnetic field intensity of ~0.5 Tesla was set as the source of the magnetic field. After applied the external magnetic field, the MPs in the blend tend to arrange along the direction of magnetic field. A proposed formation mechanism for conical micro-tips was schematically depicted in **Figure 2**e. MPs were initially organized in narrow primary arrays, which can be subsequently bound together by the PDMS pre-polymer-induced capillary force. Furthermore, the surface tension of the PDMS pre-polymer restricted the free arrangement of the MPs arrays. The proposed formation mechanism can be demonstrated by the environmental scanning electronic microscopy (ESEM) study. The bright dots in Figure 2 were MPs embedded in the PDMS matrix.

In accordance with the hypothesis, the blend of MPs and PDMS initially suffered from a MPs/PDMS separation process during the MPAM process. A narrow primary array with an average diameter of 58 ± 10 μm was formed through the aggregation of MPs. Moreover, driven by the capillary force, the binding of the preformed primary arrays led to a micro-tip with a sharp tip and a ridge-like structure on its surface (Figure 2a,b). The ESEM images of horizontal and longitudinal sections of the micro-tip also supported the proposed mechanism (Figure 2c, 2d), where the MPs primary arrays induced by the magnetic field can be directly observed inside the micro-tips.

It was found that the weight ratio of PDMS to MPs strongly affected the surface morphology of the micro-tips. Low or high PDMS contents resulted in the undesired viscosity and structures, which was unfavorable for the formation of conical micro-tips. In the present work, the weight ratio of PDMS to MPs was fixed at 1.5:1, 2:1 and 2.5:1. The corresponding structure parameters of the resultant samples were shown in Figure S1. The width ratio of base to half-height was used to evaluate the structure geometry of the resultant micro-tips. When

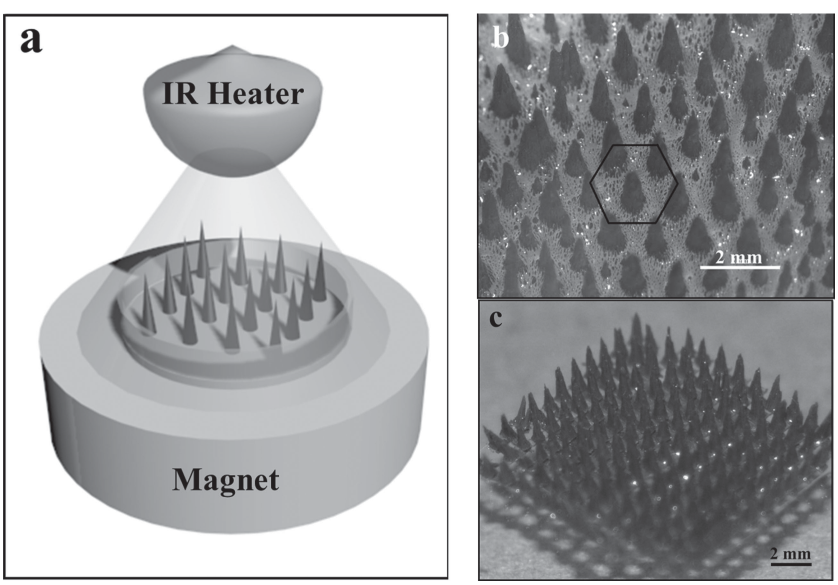

Figure 1. Scheme and optical photographs of the prepared micro-tip array. a) Schematic representation of the proposed magnetic particle-assisted molding for the fabrication of cactus spine-like conical micro-tip arrays. b) An optical photograph of the micro-tip array observed by a stereomicroscope; the hexagon with red edges indicated the freely arrangement of the micro-tips agree with the distribution of magnetic field on a non-patterned surface. c) An optical photograph of the orderly and squarely arranged micro-tips array grown on a geometric patterned polystyrene substrate.

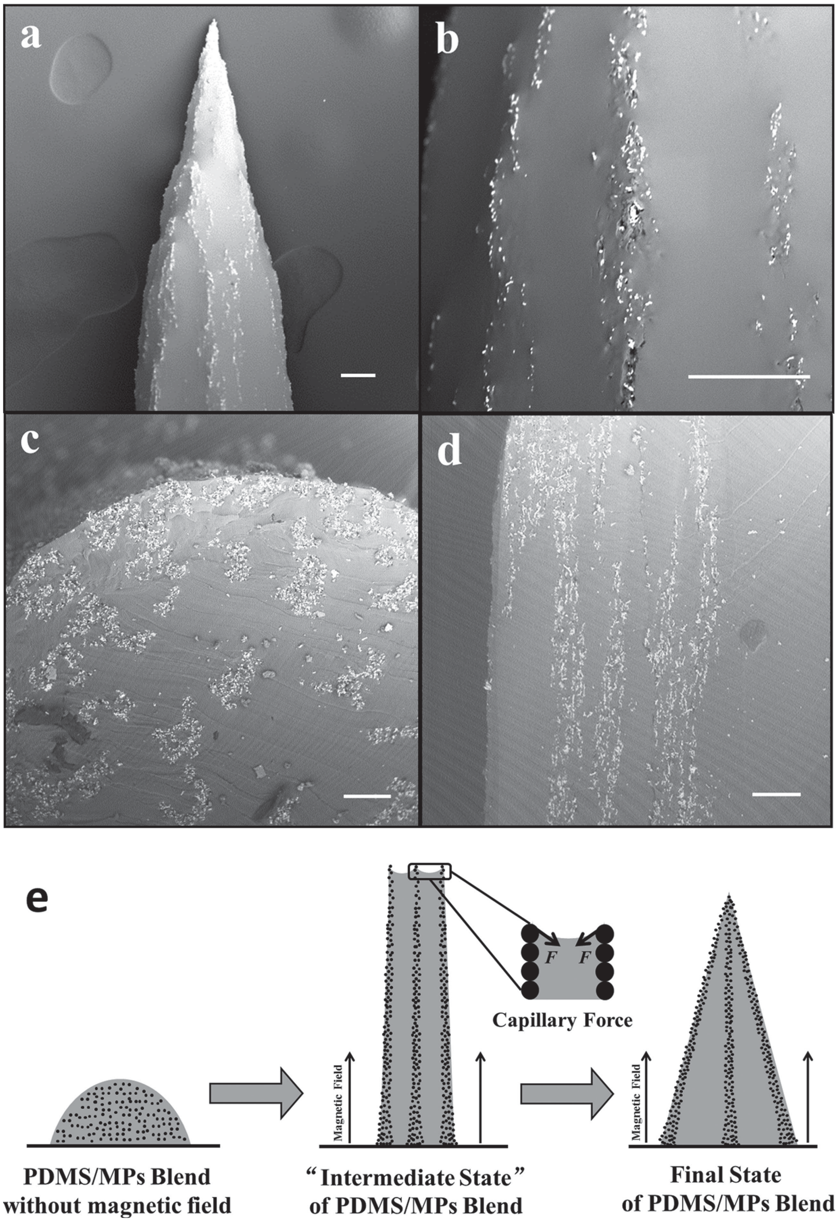

Figure 2. The ESEM images and the schematic mechanism of the resultant micro-tip. a) The morphology of the tip-site and b) the "ridge" structure of the micro-tip. The images of c) the cross-section and d) the longitudinal section of the micro-tip; the bright dots "domains" and "stripes" indicated the MPs capillary successfully forming during the micro-tip formation. The scale bars in above images were 50 μm. e) The diagram of the micro-tip formation mechanism.

the weight content of PDMS was increased from 60% to 71%, the width ratio decreased from 0.80 ± 0.04 to 0.52 ± 0.01, and the morphology of micro-tips transformed from bullet-like to conical-like structures (Figure S1), respectively. Generally speaking, the density of the MPs influenced the height of the micro-tips, i.e. the higher density resulted in a higher micro-tip. For instance, when the weight content of PDMS was fixed at 67%, the height of the micro-tips increased from 1.22 ± 0.17 mm to 2.76 ± 0.24 mm as the MPs density ranged from 55 g/m^2 to 275 g/m^2, respectively. In this work, the optimal PDMS content was fixed at 67%. The height and apex angle of the resultant conical micro-tip was approximately 1.7 mm and 14°, respectively. Further comprehensive investigations of the fog collection were conducted by using these hydrophobic conical micro-tip arrays.

According to the previous reports, the conical-shape structure provided an obvious Laplace pressure difference arising from its curvature (**Figure 3**d).[4b,5] For hydrophobic conical tip, the driven factor formed by Laplace pressure can be expressed by Equation (1).

$$\Delta P_{\text{Laplace}} = (1/R_t - 1/R_b) \quad (1)$$

The R_t and R_b represent the inner radius of the water droplet on a conical tip (Figure 3d), where the "t" and "b" represent the tip and base site respectively. At the static condition, this Laplace pressure difference was counteracted by the contact angle hysteresis (CAH).

2.2. Evaluation of the Fog Collection Behavior of the Conical Micro-tip Array

To get rid of the influence of the flow direction on the droplet motion, the fog flow was fixed vertically to the micro-tip array. Similar to the fog collection behavior of cactus spine found in nature, fog droplets preferred to be captured by the tip site.[5] The movement of water droplets is mainly dependent on the Laplace pressure difference, while the effect of gravity in this process can be negligible. Driven by the Laplace pressure difference, all the water droplets moved towards the base of the micro-tips during the continuous fog collection, even the micro-tip array was turned upside down (Figure 3a,b). In the absence of Laplace pressure difference, the water droplet was hard to move without any exotic factors on hydrophobic surfaces owing to the large CAH.[4a,13] In the present work, during the fogging process, the fusion of the tiny droplets could release their surface energy, which favored the motion of the water droplet, namely a "fusion" and "motion" process (Figure S2). The continuous and spontaneous transportation of water droplet was achieved through the successive "fusion" and "motion" process. The average water collection rate of a single tip was about 7~9 μg/s, and the rate was influenced by the position of the micro-tips, i.e., the frontal micro-tip has a higher rate (>15 μg/s) than the rear one (~5 μg/s). It was a reasonable explanation that the fog flow was interfered by the fronted micro-tips, which reduce the water collection rate. In order to mimic the cactus with a continuous fog collection function, a cotton fabric was assembled to the bottom of

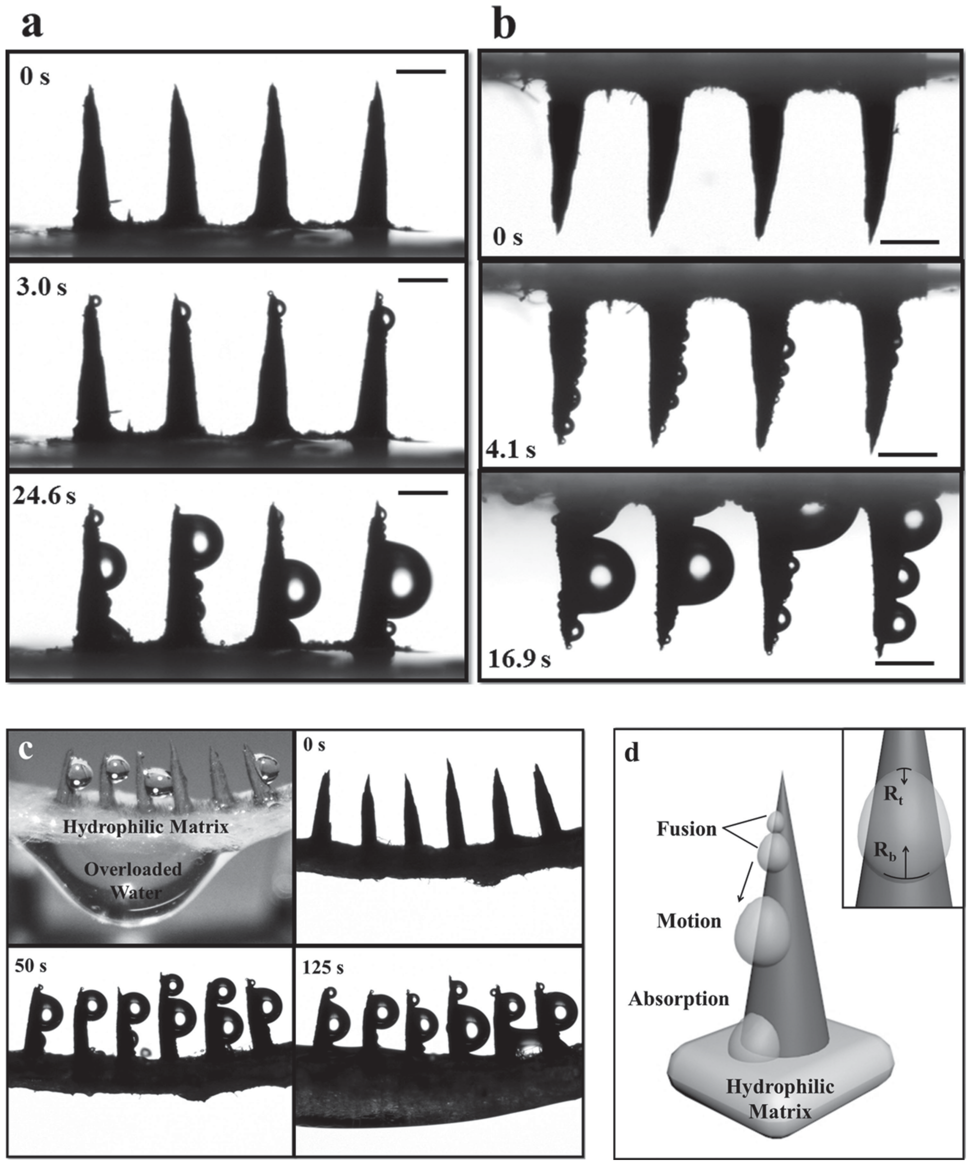

Figure 3. Test of fog collection behavior of the micro-tip array. The micro-tip array placed a) upwards and b) downwards, respectively. The hydrophobic/hydrophilic integrated system and its behavior of fog collection were shown in c). All scale bars in Figure 3 were 500 μm, and the time intervals of the fog collection were marked in the figure. d) The illustration of the "fusion" and "motion" process, and the difference of the inner radius of a water droplet placed on a conical tip.

the micro-tip array as shown in Figure 3c. Analog to the composition and function of cactus' trichomes, the cotton fabric was hydrophilic and water-absorbable. Once the water droplet contacted the hydrophilic matrix, it will be rapidly absorbed and transported due to the wettability difference. The spontaneous transportation of the water droplet made it possible to for the continuous fog collection through releasing the fresh hydrophobic conical surface. The hydrophilic cotton matrix acted as a water "pipeline" in terms of the wettability preference,[14] and released the water when it was overloaded during the water collection. It is worth to mention that, without the hydrophilic matrix, the water droplet would gradually cover the micro-tips (Figure S3), which is not desirable in the application of fog collection.

2.3. Design and Fabrication of Cactus-Inspired Continuous Fog Collector

Although a series of functional materials with fog collection have been fabricated in recent years, the construction of an effective fog collector in large scale is a particularly interesting challenge for its practical application in the regions lacking drinking water. In the present work, through integrating hydrophobic conical micro-tip arrays with the hydrophilic cotton matrix, a cactus-like spherical fog collector in large scale was successfully constructed for the first time (**Figure 4**). This cactus-like fog collector could spontaneously and continuously achieve the collection, transportation, and preservation of fog water. Firstly, the fog water can be continuously collected by

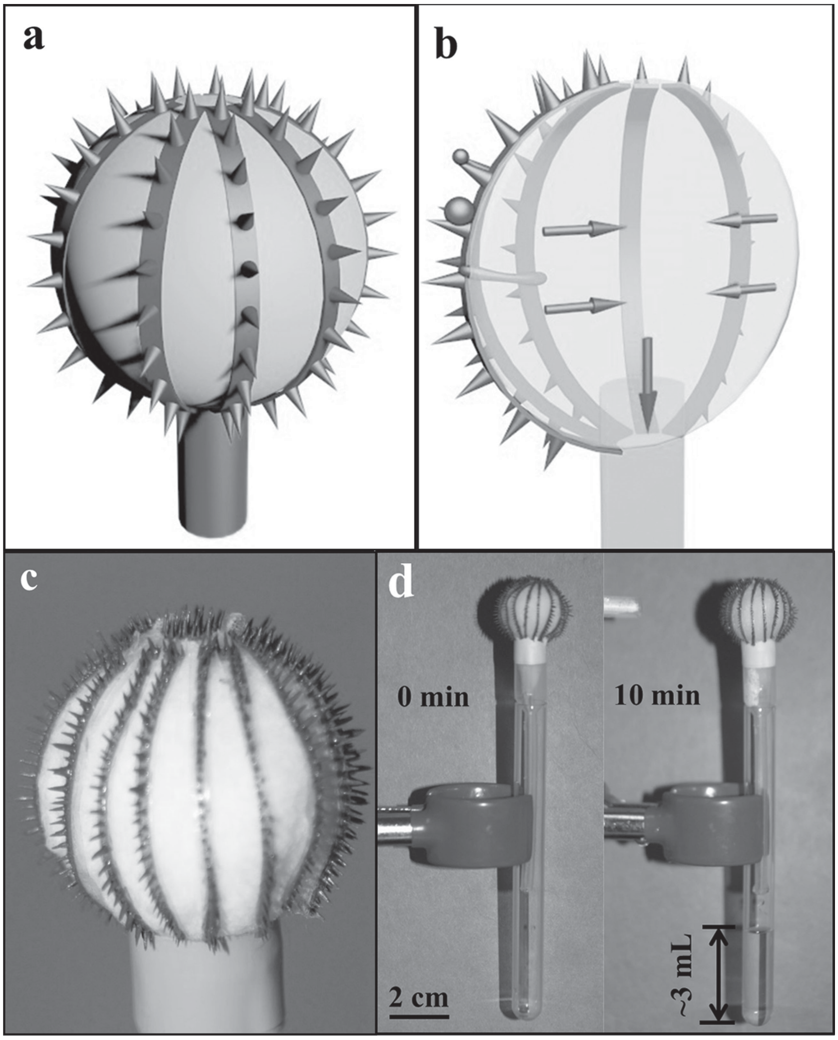

Figure 4. a) The illustration of the cactus-inspired device and b) The water transportation pathway in the device. c) The photographs of the cactus-inspired continuous fog collector fabricated by integrating the as-prepared hydrophobic conical micro-tips array with a spherical cotton matrix. Approximately 30~40 micro-tips were located at each redge of the artificial cactus, and the max distance between two ridges was 4~5 mm. d) The fog collection process of the device. The cactus-like fog collector was fixed, and the fog flow was generated with a initial velocity of 45~50 cm/s, which could harvest about 3 milliliters water in 10 min. The distance between the fogging jet and the collector was 3 cm.

the hydrophobic micro-tip array located on the surface of the device. Then, the collected water could be transported and absorbed by the hydrophilic cotton matrix. Finally, the overloaded water will be overflowed downwards and preserved in the container. As compared to the orthodox macroscopic canvas based fog collector, this smart device can rapidly transfer the collected water and continuously release the fresh surface for fog collection. More importantly, this fog collector shown here may offer a new idea for fog collector design that integrated collection, transportation and preservation in one device. In this work, the fog collection efficiency of the integrated fog collector was also quantitatively studied for the first time. In order to evaluate the the effect of the fog velocity on the water collection performance of the cactus-inspired fog collector, three different fog velocities, 20~30, 45~50, and ~70 cm/s were chosen. For the cactus-inspired fog collector, in 10 min, about 2 mL, 3 mL, and 5 mL water can be collected under the fog velocities at 20~30, 45~50, and ~70 cm/s, respectively (Figure S4). The bare cotton sphere can only collect about 0.3 mL, 0.7 mL, and 2 mL under the same condition, arising from the lack of hydrophobic micro-tips and a high water evaporation rate. With the increase of the fog velocity, the collected water was increased owing to the enhanced water content per min and increased droplet-surface collision probability. Previous reports for fog collection substrates and devices have revealed that hydrophobic substrates were more efficient than hydrophilic ones;[9b,15] therefore, it is important that the surface of the fog collector should be covered by hydrophobic structure, which can reduce the water re-evaporation rate at the collector surface. Analog to the cactus' trichome, the hydrophilic substrates exhibited preferential high water transportation rate and water absorption ability. Considering those factors mentioned above, in this contribution, the hydrophilic/hydrophobic integrated device was designed and fabricated. It could be an ideal design that the outer surface of the collector was fully covered by the hydrophobic conical micro-tips; however, the water absorption and transportation process might not be efficient in this hypothesis. Therefore, there are also some unsolved problems for the cactus-inspired fog collectors in the future.

According to the World Health Organization, the minimum water requirement to sustain life is about 2.5 liters per person per day under moderate climatic conditions.[16] In this work, the cactus-inspired fog collector can harvest about 3 mL water in 10 min under a normal fog velocity at 45~50 cm/s (Figure 4d). This indicated that the basic water requirement for maintaining human survival can be solved by using 100 cactus-like fog collectors to collect drinking water from fog-laden wind for only 1.5 hours. Moreover, the present cactus-like fog collector could be produced in larger scale, which will reduce the amount of fog collections and the time for fog harvesting, showing a promising application potential in the foggy region lacking drinking water.

3. Conclusion

In this contribution, a novel cactus-inspired continuous fog collector was designed and fabricated, demonstrating high fog collection efficiency. Cactus spine-like conical micro-tip arrays were fabricated through a modified MPAM method using PDMS and MPs under the external magnetic field. The structure morphology of the micro-tips can be controlled by tuning the weight ratio of PDMS to MPs. It was found, in order to obtain cactus spines-like hydrophobic conical micro-tips, the optimal weight ratio of PDMS to MPs was 2:1. Driven by the Laplace pressure difference, the water droplet tends to move towards the base of the conical micro-tip through a "fusion" and "motion" process. By integrating hydrophobic conical micro-tip arrays with the hydrophilic cotton matrix, a novel cactus-inspired fog collector in large scale was first fabricated, which can spontaneously and continuously collect, transport, and preserve the fog water. Furthermore, the present approach proved to be a simple, time-saving, and cost-effective strategy for the design of conical micro-tip arrays with fog collection in large scale. This cactus-inspired fog collector demonstrates promising applications in the regions with drinking water scarcity, which provides a potential avenue to solve the growing global water crisis.

4. Experimental Section

Preparation of Cactus Spine-like Ordered Micro-tip Arrays: In our case, cactus-inspired ordered conical micro-tip arrays were fabricated using a modified MPAM approach. In a typical synthesis, a mixture was firstly prepared containing PDMS pre-polymer (contained 0.1 equivalent curing agents; purchased from Dow Corning, SYLGARD 184) and Co MPs (purchased from Sigma-Aldrich; average diameter of 2 μm) with the weight ratio of 2:1. Then, the well-distributed mixture was coated on the geometric patterned polystyrene plate with the size of 0.5 mm (length) ×0.5 mm (width) ×0.13 mm (depth) through a spin coating process. Driven by the external magnetic field using a neodymium magnet with a superficial magnetic field intensity of about 0.5 Tesla, uniform and ordered cactus spine-like micro-tip arrays were produced along the magnetic field direction, which can be solidified by the IR irradiation. Slightly vibration will accelerate the arrangement of the MPs arrays. In order to investigate the effect of compositions on the micro-tip morphology, a variety of samples were fabricated by adjusting the weight ratio of PDMS to MPs. Alternatively, disordered micro-tip arrays can be prepared on the flat polystyrene plate under the same experimental condition.

Test of Fog Collection: The micro-tip arrays were carefully fixed upwards or downwards. An ultrasonic humidifier (YC-E350, China) was set to generate the fog flow vertically, and the saturated fog was flowing with a velocity of 45–50 cm/s at room temperature. The distance between the fogging jet and the collector was 5 cm. The whole processes were recorded by a contact angle goniometer contained optical microscopy and its CCD components (OCA 20, Data-physics, Germany).

Characterization of the Micro-tip and its Array: The images of Environmental Scanning Electronic Microscopy were obtained by a Phenom G2-Pro Microscopy (Phenom-World, Netherlands). The optical images were captured by Nikon DS-Ril camera and Sony α-230 single-lens reflex camera with a macro lens. The statistic of the micro-tip properties were obtained by analyzing 20 micro-tips randomly.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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