Efficient Fog Harvesting with Self-Pump Bio-Inspired Multilayer Interface

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SUMMARY

Effectively harvesting fog water can offer a significant water supply. Fog meets the World Health Organization's drinking water standards, and harvesting fog is cheaper than building conventional water supply systems. It is highly adoptable in many regions with water inaccessibility, such as Chile and Spain, since fog is abundant in coastal dry lands. Nevertheless, its application is greatly limited, because most current fog collectors cannot achieve high efficiency and low cost simultaneously, making it hard for less developed regions to support this project. Inspired by cacti, butterfly proboscides, and Namib beetles, this research presents a fog collector with a hydrophobic-superhydrophilic Janus interface to address these challenges. When experimenting with other structures, this sample with a superhydrophilic interlayer demonstrated the highest efficiency under various fog concentrations. The best-performing parameters of this design are stem width 0.5 mm, spine length 1 mm, spine width 0.4 mm, and spine gap 0.5 mm. This structure effectively prevents evaporation, thus helps it capture water at ~5752 $mg \cdot cm^{-2} \cdot h^{-1}$, which exceeds the efficiency of single-layer hydrophobic models in this research by 28.6%. Simplified to a 2D structure, it is also highly cost-effective as its fabrication merely requires a laser cutter, and the PET material only costs \$0.5 per m^2. This design could alleviate the global drinking water crisis by encouraging more communities to adopt fog harvesting since it reduces the difficulties in maintenance, its low cost addresses their financial burden, and its efficiency can potentially support more industries with water demand to facilitate local development.

Key words: Fog harvesting, bio-inspiration, sustainability, freshwater shortage, self-pumped

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INTRODUCTION

Accessing freshwater is a fundamental need for lives. In 2022, the 6th sustainable development goal of the United Nations is to provide universal access to water and sanitation (1). However, our current progress is far from achieving that goal. Over 40% global population do not have adequate supply of water (2). By May 2022, 2 billion people still lack access to safely managed drinking water at home (3). Modern human activities exacerbated water shortage by bearing a rapid population growth, demanding high industrial and agricultural water input, while contaminating ground water. Most cases of drinking water inaccessibility also centralize in less developed areas. According to the United Nations, 8 out of 10 people who lack access to even the most basic drinking water services are from rural areas, with roughly half of them living in least developed regions (1). These people are usually forced to fetch water from open water sources with no safety guarantee. Their fetched water is barely sufficient to sustain their living, leaving minimal amount for personal hygiene. While conventional water supply systems brought these regions technological and financial difficulties, fog harvesting pointed out a new affordable method to replenish the inadequacy of water provision.

Fog harvesting has two major advantages: simple and sustainable (4). Operating a collection site only requires setting up meshes to intercept liquid and installing pipelines to transport them to homes (5). In areas without severe pollution, fog meets international drinking water standards; therefore, people don’t need complex procedures to purify it before usage (6). This simplicity lowers the cost of water supply and the difficulty of maintenance. Fog is also an abundant but unexploited freshwater source (7). It is highly favored for thick advection fog to be formed when warmer moisture impacts cooler dry air (8). Because of this, it is usually a significant hydrological input in arid or semi-arid coastal dry highlands, where water shortage prevails (9). In northwestern Chile, fog is present almost every day; in Columbia, Peru, and Spain, the annual coverage days of fog averaged 188 days (10). Developing a method to harvest fog efficiently and cost-effectively is a potential method to sooth the water stress in these regions.

Raschel mesh, a polyethylene black net co-knitted into triangles, has been widely applied in fog harvesting projects (11). However, recent studies have suggested it unsatisfactory, because (i) there is lack of studies into the most efficient parameters of each fiber; (ii) droplets cling on the mesh; (iii) droplets must travel over a long distance before they are collected (12). To improve the performance of fog collectors, some scientists mimicked the water collection mechanisms of some creatures in nature. For example, the wettability difference on Namib beetles’ back enables intercepted droplets to roll from their hydrophilic peaks along the hydrophobic surfaces, all the way to their mouths (13). Cactus developed conical spines to utilize Laplace pressure gradient to achieve directional transport to the stem and to minimize the evaporation on the surface (14). Although recent studies endeavored to improve the efficiency of their models by using bio-inspiration, the production cost was elevated, making fog collectors still unrealistic to be employed in regions that lack budget and technical support (15).

Subsequent studies into bio-inspired fog collectors suggested that cost-effective models with extremely fine wettability structure coupled with pumps can improve applications of fog harvesting in community use (16). Other researchers mentioned that a higher efficiency of fog collectors could be achieved by combining the characteristics of multiple creatures with superior fog collection capability (10). In a recent study, it is proven that simplifying 3-dimensional cactus spines to a 2-dimensional structure has no impact on fog collectors' water interception ability, which is a new approach to reduce their cost (17). Following the instructions above, we designed a model that can be fabricated by laser-cutting PET (polyethylene terephthalate) sheets, treating the central stem with hydrophilic coating, and overlapping the fibers. This design is based on the following principles: Cacti's conical spines are simplified into 2-D short rectangular fibers and arranged on both sides of a central stem, similar to that of a fish bone structure (17). Nano-particle hydrophilic coating is applied on the central stem to construct wettability difference from the PET spines, like the Namib beetles (13). The overlapping central stem mimicked the capillary channel inside the butterfly proboscis (18). We combined the simplified characteristics of these three creatures to achieve a self-pump fog harvesting system.

We hypothesize that this model will increase the effectiveness of droplet collision and largely boost the speed of water delivery and perseveration, thus finding the highest-performing parameters will makes it an ideal design due to its satisfactory cost-efficiency ratio. We used COSMOL Multiphysics simulation to test the ideal shape of the collector, tested several combinations of parameters, and compared the efficiency of the designed model with other models without the self-pump ability. We found that the self-pump structure largely shortens the duration of water exposure in the open air and is the most efficient in lower fog concentration. Its efficiency is 5752.2 $mg \cdot h^{-1} \cdot cm^{-2}$; neglecting the cost of laser cutting, 1 square meter of this model only costs \$0.50. Compared to 5 recent designs, the low cost and high efficiency gives this design a high potential of communal application. We hope to reduce the water burden of lower-income communities and bring future studies closer attention to multiple bio-inspirations.

RESULTS

Simulation

Abandoning horizontal structures was considered a good solution to water clogging on fog collectors (19). However, this decision has a detrimental effect on fog collision, because less area is exposed for droplet attachment (20). We would like to test the advantage of having *horizontal spines on non-clogging fog collectors, as compared to fog harps. To directly visualize the results, we used COSMOL Multiphysics to simulate wind flow behaviors on the surfaces of fog harps and this work. Under equal impacting wind speeds, in every direction, the model with horizontal fibers had significant color changes around its surface, which indicates a drastic velocity change; by contrast, the change of wind speed around the fog harp sample was very subtle in any direction* ***(Figure 1, Figure 2).***

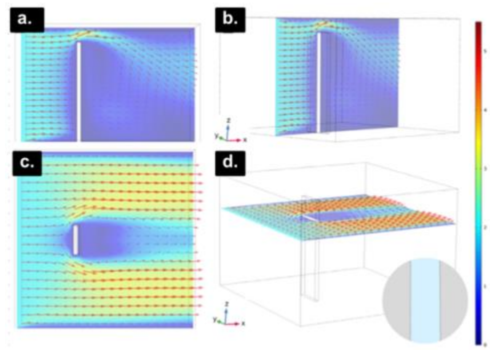

Figure 1. Simulation of the wind flow behavior around a fog harp fiber. Wind speed was set at 2 m/s. The wind speed's velocity vector around the fog collector surface was illustrated by the color difference, from purple (v_{wind} = 0) to red (v_{wind} > 5 m/s).

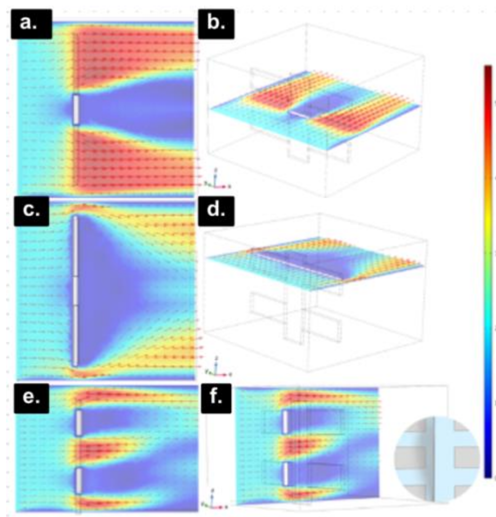

Figure 2. Simulation of the wind flow behavior around a fog collector fiber with horizontal structures. Wind speed was set at 2 m/s. The wind speed's velocity vector around the fog collector surface was illustrated by the color difference, from purple (v_{wind} = 0) to red (v_{wind} > 5 m/s).

Studying the hydrophilic surface properties

*Applying superhydrophilic coating on the central stem can be an affordable approach to construct a Janus surface. To examine the effectiveness of the superhydrophilic coating purchased online, we applied it on a PET surface to observe its nano-properties under a scanning electron microscope (SEM). An effective superhydrophilic material can significantly reduce the contact angle between a droplet and the surface to below 10º (21). More roughness can contribute to a higher hydrophobicity; therefore, for a surface to be more hydrophilic, a material must fill it its rough parts (22). The silica-based hydrophilic coating formed a thin, porous nano-particle layer on top of the highly hydrophobic PET sheet to fill in the rough gaps, which suggests a good hydrophilic modification result **(Figure 3).***

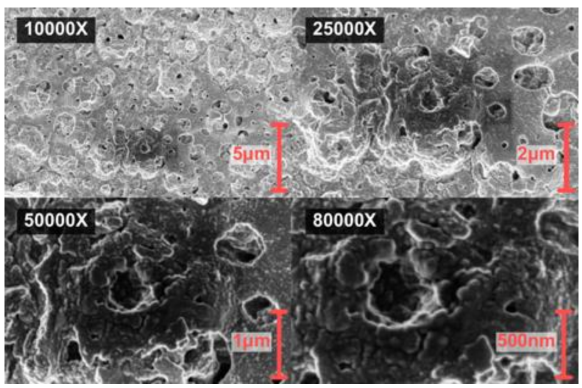

Figure 3. PET surface after the hydrophilic treatment. These images show the surface properties of the PET sheets when silica-based hydrophilic treatment is applied. Scaling is noted on each picture. They were taken with OptiPlan SEM, mode A+B, at Tianjin University in July 2022.

Quantitative Analysis: The optimal parameter combinations (spine length, gap width)

The specific value of each parameter can significantly affect the efficiency of the fog collector (23). It is important to investigate the best set of parameters, with which the droplets can be harvested the fastest, the droplets on each fiber do not touch, and they do not locate too far from each other. In this model, the spine length, spine width, gap width, and stem width can be altered. We first keep the stem width constant to not make water delivery a part of the factor. With 1 mm stem width and 0.4 mm spine width, the parameter combination with spine length 1 mm and gap width 0.5 mm collects the most water within an hour, which was 6143 mg•h^{-1}•cm^{-2} ***(Figure 4).***

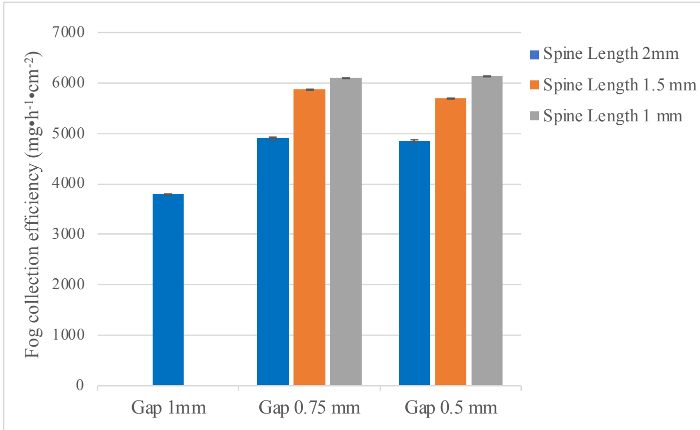

Figure 4. Fog collection efficiency with varying spine parameters. Bar graph shows how the amount of fog water in an hour altered with the change of spine parameters. Fog collector samples with 1 mm stem length and different spine parameters (as indicated in the graph) were tested with a humidifier set 5 cm apart. (n=6)

Quantitative Analysis: The optimal stem design (stem width, stem layering)

We have hypothesized that the capillary channel can preserve water and avoid evaporation, so we should assess that idea with some supporting data. It is also important to test the highest-performing stem width, because a larger stem area may allow big droplets to accumulate on its surface, which will increase the risk of evaporation (23). We have performed this test under various fog efficiencies and selected the group of data when the humidifier is set 10 cm from the sample, with 2 m/s flow speed, because the data will be closer to reality when there is less fog present. The stem width value exhibits negative correlations with the amount of fog harvested in an hour, with the samples with 0.5 mm stem width having the highest efficiency ***(Figure 5).*** *Amongst the three wettability structures, the best-performing structure was the one with an overlapped stem structure, within which two hydrophilically coated surfaces face each other* ***(Figure 5).*** *Compared to the worst-performing group with untreated PET surface and 1 mm stem width, the best-performing group elevated the amount of water collected within an hour by 28.6% (Superhydrophilic interlayer: 5752 mg•h^{-1}•cm^{-2}; untreated PET: 4475 mg•h^{-1}•cm^{-2})* ***(Figure 5).***

Figure 5. Fog collection efficiency with varying stem structures. Bar graph shows how the amount of fog water in an hour altered with the change of stem width and wettability. Samples with 1 mm stem length, 0.5 mm gap width and varying stem structures (as indicated in the graph) were tested with a humidifier set 10 cm apart. (n=6)

Qualitative Analysis

In this qualitative analysis, we took pictures of fog collector surfaces during the quantitative collection experiments to better interpret the results. We aim to understand why the double-layer model with a superhydrophilic interlayer performed the best in the experiment and how fog concentration affected the results. On the hydrophobic PET sheet, droplets were first intercepted by both the stem and the spines; then, they coalesce into a big droplet that continued to grow under the incoming fog's impact ***(Figure 6a).*** *It clogged on its surface, and it took 59 seconds for it to roll down Sample A. Water on Sample B's spines was quickly induced to the central stem. The droplets formed a very small contact angle with the surface, and they were evenly spread throughout the stem surface in 10 seconds* ***(Figure 6b).*** *On Sample C, fog collision made individual droplets form both on the spines and on the outer hydrophobic stem surface under 10 seconds. At t = 17s, when droplets grew big enough to contact the edge of the central stem, they were all readily drawn into the inner channel* ***(Figure 6c).*** *The maximum size of the droplets accumulated on the spines was the biggest on Sample A, where they were in obvious contact with the stem but stayed still; on Sample B and Sample C, the largest droplets on the spines were in significantly smaller sizes.*

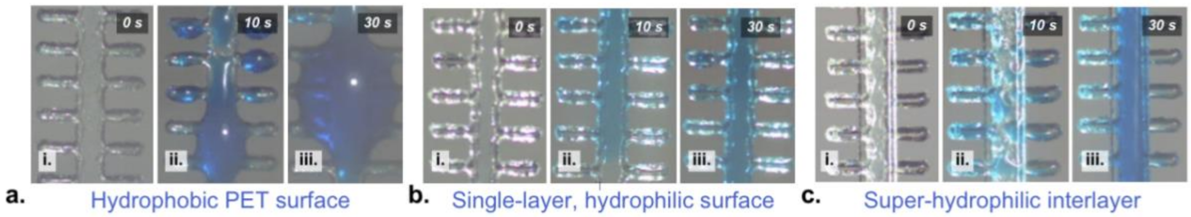

Figure 6. Water dynamics on surfaces with different wettability structures. Pictures showing water harvesting process of each wettability structure in the results, Sample A to Sample C refer to single-layer hydrophobic, single-layer hydrophilic, and super-hydrophilic interlayer respectively. High-speed camera was set in front of the samples to capture videos. Water in humidifier was colored in blue for better visualization. (n=6)

DISCUSSION

We hypothesized how simplifying and combining bio-characteristics are valuable approaches to design an ideal fog collector. From the experimental results, we can conclude that this design improved the feasibility of fog harvesting by lowering its cost and elevating its efficiency in multiple aspects.

From the simulation, we took note of how the wind speed changed much more dramatically after we added the horizontal components. When a non-viscous liquid flow impacts a surface, the region where the flow decelerate due to the surface's presence is known as the boundary layer. A thinner boundary layer will make it more likely for the non-viscous liquid to attach to the surface. From our observation, horizontal spines, having thinner edges and smaller areas compared to the stem, contributed to a more intense change in speed. Therefore, it has a thinner boundary layer, and can be very beneficial in enhancing the effectiveness of fog collision on a given surface. It also tells us how spines with smaller radius can be more helpful in reducing the effects of the boundary layer. As a result, in the subsequent experiments, 0.4 mm (the thinnest parameter for the laser cutter to fabricate) was used as the spine width.

From the feedback of the SEM images, the super-hydrophilic coating constructed a very thin and porous layer of nanoparticles, which indicates its capability to modify the wettability of a highly hydrophobic surface. When water collides with the PET sheet, this characteristic will avoid the intercepted water to form big droplets with large contact angles; instead, it makes a thin film of water. Therefore, by coating the stem with the hydrophilic coating while keeping the hydrophobic spines untreated, we can form a Janus surface, where water accumulated on the spines can be drawn to the center without external force. More importantly, due to the low cost of the coating, directional transportation is financially achievable.

In the quantitative experiments, we found that the sample with the most refined wettability system performed the best. The physical properties of this system demonstrated their advantages in the images from the qualitative analysis too. (i.) Droplets that grew big enough to contact the stem can be delivered much faster. The timely transportation can avoid the loss of the intercepted water by the force of gravity or by evaporation. (ii.) The edges of the double-layer sample facilitated this process: droplets in contact with the edges are instantaneously drawn inside the channel due to their release of surface energy. (iii.) Capillary forces spread the water inside the channel to avoid clogging and kept the layers compact. (iv.) The water preservation ability of the super-hydrophilic interlayer made minimal amount of water on the sample expose in the air during harvesting, and largely shortened the traveling distance for the droplets to arrive at a closed structure.

The unpredictable nature of environmental conditions is a source of inaccuracy. Though this research endeavored to model the typical situations of realistic application, it is challenging to take every possible detail into account, such as the change in wind direction and wind speed. Therefore, until we fabricate a large test mesh and set it in locations where fog harvesting is feasible, we cannot directly compare this model's capability with that of the Raschel mesh. Instead, we can only compare the laboratory results with other proposed models tested in similar conditions in the laboratory.

Aside from the factors of inaccuracy, this research marked a significant improvement in designing bio-inspired fog collectors. As discussed above, all individual advancements in this design worked well in improving its efficiency without requiring external energy. These met expectation from the directions from earlier literature, which suggested researchers to investigate micro-structure parameters and the combination of multiple bio-inspirations (12). This work's remarkable efficiency is also remarked in data. Compared to 5 other recent fog collector designs tested in laboratory, this work achieved a rate of collection at 5752 $mg \cdot h^{-1} \cdot cm^{-2}$, which is outstanding among the other designs **(Table 1).** While most other designs relied on comparably costly materials, such as steel needles, copper wires, and PFDT, the only major material of this design is PET sheet (24, 25, 26, 27, 28). At the same time, the 3-step fabrication of this work can be done with minimal advanced technology and time. The affordability and simplicity of this work will make it much easier for communal adoption and maintenance. Therefore, this work has a high potential to be applied in fog harvesting projects in communities in freshwater around the world. To further improve this model, there is a need for cost-effective methods to enhance the antibiotic performance of the surface and enhance the robustness and durability of this model, so that it can be more reliable for long-term usage. For future investigations in the fog harvesting field, researchers may continue to explore the possibility of simplifying and combining more bio-characteristics.

#	Names of biomimic fog collectors	Year	Major materials and estimated cost per square meter	Laboratory conditions	Rate (mg•cm-2•h-1)	Reference
1	Hybrid wettability surface with spraying nanoparticles on SSM substrate	2020	Stainless steel mesh; aluminum hydroxide ~6 USD	Fog flow rate: ~50 cm/s Distance: 5 cm 85-90% RH	~1700	24
2	Hierarchical surface with hydrophilic foam, hydrophobic stripes, and needles	2018	Silica stripe; melamine foam; steel needles ~13 USD	Fog flow rate: ~120 cm/s Distance: 5 cm	~1900	25
3	Artificial periodic roughness-gradient conical copper wire	2016	Copper wire ~79 USD	Fog flow rate: ~180 cm/s 90% RH	~618	26
4	Incorporating superhydrophobic metal gauze onto PS flat sheet	2015	PFDT; polysterene plane sheet; copper gauzes ~10 USD	Fog flow rate: ~12 cm/s Distance: 7 cm 90-95% RH	~159	27
5	Magnetic field-relied, cactus-inspired conical spines collector	2014	PDMS pre-polymer; Neodymium magnet ~6 USD	Fog flow rate: ~50 cm/s Distance: 3 cm	~1900	28
6	Laser-cut PET multilayer self-pump bio-inspired fog harvesting surface	2023	0.075 mm PET film ~0.5 USD	Fog flow rate: ~200 cm/s Distance: 10 cm	~5752	this work

Table 1: Comparing this design with other recent designs. This table compared the cost and the efficiency of this work with 5 other recent designs. The major materials considered for the cost estimation have also been included. Since the results were collected in different laboratory conditions, interpretations of the values should also take this factor into account. The material costs are based on the results from Taobao.com.

MATERIALS AND METHODS

Simulation

Using the 2D work-plane feature of COSMOL Multiphysics, we sketched basic models for the fog harp (only having a vertical fiber) and this work (have both the vertical fiber and thin horizontal spines symmetrically arranged on both sides) ***(Figure 1, Figure 2).*** *Then, with the laminar flow analysis feature of COSMOL Multiphysics, we set the wind speed at 2 m/s, coming from a uniform direction normal to the fog harvesting surfaces. We take pictures of the reflected results on the simulation three seconds after the simulation started.*

Fabrication

PET films with 0.075 mm thickness were laser cut three times at 70% power into the basic shape of this work, with 1 mm spine length, 0.4 mm spine width, 0.5 mm spine gap, and 0.5 mm stem width ***(Figure 7a).*** *The length of the sample does not impact the results, because the efficiency is calculated per area. The hydrophilic coating is diluted with water at 1:15. On each sample, the stem is brushed with diluted silica-based hydrophilic coating* ***(Figure 7b).*** *To make a fiber, the ends of two samples are joined together with the hydrophilic side facing each other* ***(Figure 7c).*** *To make an entire mesh, individual fibers are joined together in parallel* ***(Figure 7d).*** *For the simplicity to copy the methodology, we used tape to join the fibers. However, other methods are feasible too. In this study, we tested the efficiency of different parameters and structures. We should fabricate untreated single-layer samples and hydrophilic single-layer samples to compare too* ***(Figure 7 alt. a, Figure 7 alt. b).***

SEM image study

Single-layer, hydrophilic samples are placed under SEM for surface property investigation after the hydrophilic coating has dried ***(Figure 7 alt. b).*** *The microscope is focused on the hydrophilically-coated stem, and zoomed into four scales: 10,000x, 25,000x, 50,000x, and 80,000x* ***(Figure 3).*** *Screenshots were taken for analysis.*

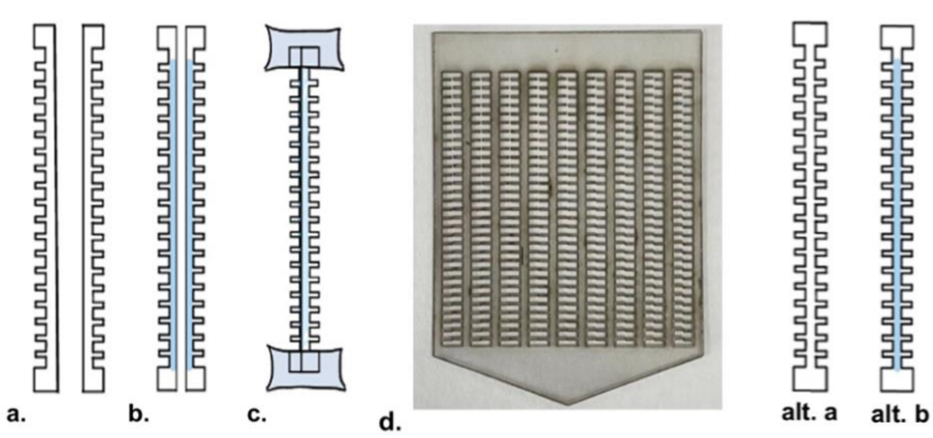

Figure 7: Fabrication steps and the product. The three basic steps to fabricate this work (double-layer sample with super-hydrophilic channel) has been presented by the illustration 7a-7c. After laboratory fabrication, the product is present by 7d. Alt. a and alt. b are illustrations of the single-layer, untreated sample and the single-layer sample with a hydrophilically modified stem (control groups).

Fog collection quantitative and qualitative experiments

At a time, one fabricated fog collector sample was fixed on a clamp stand, with a container set underneath to collect the captured water. The mass of the container was measured by an electronic scale before the placement. A pipe was connected to the mist lid of the humidifier, and a flat opening of the pipe was fixed on another clamp stand at the same height and was set 10 cm apart from the sample. Before each experiment, a high-speed camera was set in front of the fog sample to take videos of the process. Fog harvesting experiments were run over a 60-minute duration. After each duration, reweigh the container, and repeat the experiment 6 times. The average collection efficiency of the six trials were calculated in $mg \cdot cm^{-2} \cdot h^{-1}$ *for direct comparison. During the investigation of the best spine parameters, the stem width was held constant at 1 mm, while the parameters on the spines varied. A bar graph with error bars as the standard deviation was generated, with gap width as the horizontal axis and collection efficiency as the vertical axis. Data was grouped by spine lengths. During the investigation of the best stem structures, the best-performing spine parameters from the last experiment were held constant, while the wettability and layering varied. On the bar graph, stem width was on the horizontal axis, and the collection efficiency was on the vertical axis.*

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Commitments on Academic Honesty and Integrity

We hereby declare that we

1. are fully committed to the principle of honesty, integrity and fair play throughout the competition.
2. actually perform the research work ourselves and thus truly understand the content of the work.
3. observe the common standard of academic integrity adopted by most journals and degree theses.
4. have declared all the assistance and contribution we have received from any personnel, agency, institution, etc. for the research work.
5. undertake to avoid getting in touch with assessment panel members in a way that may lead to direct or indirect conflict of interest.
6. undertake to avoid any interaction with assessment panel members that would undermine the neutrality of the panel member and fairness of the assessment process.
7. observe the safety regulations of the laboratory(ies) where we conduct the experiment(s), if applicable.
8. observe all rules and regulations of the competition.
9. agree that the decision of YHSA is final in all matters related to the competition.

We understand and agree that failure to honour the above commitments may lead to disqualification from the competition and/or removal of reward, if applicable; that any unethical deeds, if found, will be disclosed to the school principal of team member(s) and relevant parties if deemed necessary; and that the decision of YHSA is final and no appeal will be accepted.

(Signatures of full team below)

X Huiyi Wen ________________________
Name of team member: Huiyi Wen

X____
Name of team member:

X____
Name of team member:

X Moyuan Cao ______________________________
Name of supervising teacher: Moyuan Cao

Declaration of Academic Integrity

The participating team declares that the paper submitted is comprised of original research and results obtained under the guidance of the instructor. To the team’s best knowledge, the paper does not contain research results, published or not, from a person who is not a team member, except for the content listed in the references and the acknowledgment. If there is any misinformation, we are willing to take all the related responsibilities.

Names of team members

Huiyi Wen

Signature of team members

Name of the instructor

Moyuan Cao

Signature of the instructor

Date: Aug 20, 2023