Small Structure, Large Effect: Functional Surfaces Inspired by *Salvinia* Leaves

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Nature-inspired superhydrophobic surfaces have attracted significant attention because of their remarkable properties. In particular, recent findings about the aquatic plant *Salvinia* provide novel approaches for the application of superhydrophobic surfaces. The unique heterogeneous eggbeater structures endow *Salvinia* leaves with superhydrophobicity and strong adhesion, which ensures that the leaves show durable air-retainability in underwater environments. However, the complex eggbeater structures present a difficult manufacturing challenge. Therefore, this review first introduces the air-retention mechanism, which may benefit the design of *Salvinia*-inspired structures. Moreover, advanced techniques including photolithography, direct laser lithography, chemical vapor deposition, electrodeposition, electrostatic flocking, 3D printing, chemical etching, and plasma etching recently have been developed for fabricating *Salvinia*-inspired structures. This review focuses on the advantages, disadvantages, and application prospects of such techniques. In addition, the excellent air-retainability of *Salvinia* structures has inspired many engineering applications, including drag reduction; water harvesting, evaporation, and repellence; oil/water separation; and thermal insulation. This review discusses the performance and challenges of artificial structures to such applications. Finally, methods of evaluating air-retainability are discussed. It is expected that this review will not only satisfy scientific curiosity but also contribute to the design and application of *Salvinia*-inspired functional surfaces.

1. Introduction

Hydrophobic surface is a surface that has the ability to repel water. Usually, a surface with a water contact angle (WCA) of above 90° is considered as a hydrophobic surface. If the WCA is above 150°, the surface is superhydrophobic.[1,2] Because of their remarkable properties, nature-inspired superhydrophobic surfaces show great promise for application to engineering fields and a diverse range of devices.[3,4] Over the long course of evolution, many animals and plants such as water striders, lotus leaves, and rice leaves have evolved superhydrophobic surfaces to counter survival threats, including microbial infections, foulant adhesion, and flow resistance.[5,6] Nature-inspired superhydrophobic surfaces exhibit a diverse range of fascinating antibiofouling,[5,7] drag reduction,[8] oil/water separation,[9,10] anticorrosion,[11] antifrosting,[12] and anticorrosion properties,[13] which endow such surfaces with excellent application potential. Moreover, the considerable economic and environmental benefits mean that such superhydrophobic surfaces can contribute to the sustainable development of humanity.

When a liquid spread on superhydrophobic surfaces, there are three possible contact states, i.e., Cassie–Baxter state,[14] Wenzel state,[15] and intermediate state (coexistent state).[16] In the Cassie–Baxter state, air is trapped within the voids of the superhydrophobic surface and generates an air mattress between the liquid and surface. Because the silver reflection at the interface between a liquid and lotus provides evidence of such an air mattress, the “Lotus effect” occurs in the Cassie–Baxter state. In the Wenzel state, the interaction between the liquid and surface is strong, and the liquid completely fills the surface voids. Rose petals provide evidence of the Wenzel state, which is not only superhydrophobic but also strongly adheres to droplets; this helps keep the rose fresh. This feature is called the “Petal effect.”[17] In addition, an intermediate state exists wherein voids are filled with both air and liquid. Sometimes, one state can transform into another. For example, the Cassie–Baxter state transforms into the Wenzel state when the liquid pressure is high because the trapped air escapes from the voids.[18,19] Trapped air is important for drag reduction, antibiofouling, and liquid repellence. Thus, the maintenance of an air mattress at the interface between the liquid and the superhydrophobic
surface is crucial for engineering applications. Conventional bio-inspired superhydrophobic surfaces cannot maintain an air mattress because of various external disturbances. Therefore, superhydrophobic surfaces exhibiting stable air-retainability have important scientific and engineering applications.

Several plants and animals have evolved surfaces exhibiting long-term (i.e., days to months) air-retainability to prevent wetting and submersion. One example is Salvinia, a plant that floats on water. Salvinia has complex multicellular hairs on the upper side of its leaves, and each group of four hairs is connected at the terminal ends, forming an eggbeater structure (Figure 1a–d). The hairs are coated with hydrophobic wax crystals, while the patches at the terminal ends of the hairs lack wax crystals and are, therefore, hydrophilic (Figure 1e). The unique combination of hydrophilic patches on superhydrophobic surfaces is called the Salvinia effect, which enhances the stability of the Cassie–Baxter state by pinning the air–water interface, thus promoting the air-retainability. Air retention also causes the leaves to exhibit superhydrophobicity (Figure 1f).

In the last decade, the excellent air-retainability of Salvinia leaves has inspired many applications, including oil/water separation, drag reduction, thermal insulation, and water repellence. However, the eggbeater structure of Salvinia leaves is complex and, therefore, difficult to replicate in fabricated structures. Recently, several advanced, efficient, low-cost prospective techniques including photolithography, direct laser lithography, chemical vapor deposition (CVD), and 3D-printing have been developed to imitate complex structures. This review introduces the air-retention mechanism of Salvinia leaves and subsequently focuses on advanced fabrication techniques and various engineering applications of recently developed Salvinia-inspired surfaces. Finally, recently developed methods of evaluating air-retainability, which may benefit the design of Salvinia-inspired surfaces, are discussed. We expect that this review will not only satisfy scientific curiosity but also contribute to the design and application of Salvinia-inspired functional surfaces.

2. Air-Retention Mechanism

The air-retention mechanism, which is called the “Salvinia effect,” is attributed to the unique structure of the Salvinia leaves (Figure 2). In the last decade, researchers have proposed several factors influencing the Salvinia effect. 1) Structural support: the eggbeater structures act as a tent supporting the air-water interface and preventing it from approaching the leaf base. 2) Maximizing penetration energy: the hydrophobic hairs increase the energy required for water to approach the leaf base; thus, the four enclosed arms increase the penetration energy owing to the increase of surface per height difference. 3) Pinning effect: water can be pinned to hydrophilic patches. When the air–water interface is pulled away from (F1 in Figure 2) or closer to (F2 in Figure 2) the leaf base, the water strongly adheres to the hydrophilic patches, which can effectively reduce the disturbance because the movement of the air–water interface requires extra energy. Thus, the combination of hydrophilic patches and superhydrophobic hairs increases the energy required to move air–water interface. In other words, the air–water interface is fixed at a predefined level, and any deviation from the level will require extra energy. Hydrophilic patches, on the contrary, can slow or completely stop the flow of liquid in the wetted area, and the reduced water velocity minimizes the risk of losing the air layer. 4) Elastic buffer: the elasticity of the eggbeater structures provides a buffer against the slight deformation of the air–water interface, which helps reduce the

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**Figure 1.** a,b) Images of Salvinia leaves. Reproduced with permission. Copyright 2020, National Academy of Sciences. c) Scanning electron microscopy (SEM) image of eggbeater structures. d) Four hairs are connected at terminal ends. e) Top part is hydrophilic patch, and bottom part is hydrophobic wax crystals. f) Spherical droplet sits on top of Salvinia leaf, indicating that leaf is superhydrophobic. c–f) Reproduced with permission. Copyright 2010, Wiley-VCH.
interfacial disturbance. Undercuts or simple inclinations are preconditions for elasticity.

3. Fabrication Techniques

On the basis of the air-retention mechanism, Barthlott et al. proposed five criteria for achieving the *Salvinia* effect in artificial structures: hydrophobic chemistry, high-aspect-ratio hair structures, undercut/simple inclinations, elastic hairs, and chemically heterogeneous anchor cells. These criteria provide a reference for fabricating artificial *Salvinia* leaves. In 2011, lithography was first applied to fabricate simplified eggbeater structures. Since then, several techniques including direct laser lithography, low-temperature chemical vapor deposition (LTCVD), atmosphere pressure plasma chemical vapor deposition (APPCVD), water-assisted chemical vapor deposition (WACVD), electro-deposition, electrospinning, electrostatic flocking, 3D printing, plasma etching and chemical etching have been developed to imitate the fine structures of *Salvinia* leaves (Figure 3). These techniques have been used to replicate simple artificial eggbeater structures (Table 1). In addition, the development of these techniques has massively increased the production of diverse engineering applications and materials. In this section, we summarize the details, advantages, and disadvantages of these techniques.

3.1. Photolithography

Photolithography is a popular technique for synthesizing and preparing bioinspired surfaces using photosensitive materials called “photosists” to form patterns on target plates. After the negatives have been exposed to light, the photoresist hardens and becomes insoluble, while the area protected from light can be washed out (i.e., negative resist), and the bare metal can be etched to form a relief pattern on a substrate surface. The advantage of photolithography is that it can accurately control the shape and size

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**Figure 2.** Schematic illustration of the special structures of *Salvinia* leaves.

**Figure 3.** Eggbeater structure fabrication techniques developed in the past decade. Photolithography: Reproduced with permission. Copyright 2011, Elsevier. LTCVD: Reproduced with permission. Copyright 2013, Wiley-VCH. APPCDV: Reproduced with permission. Copyright 2013, The Japan Society of Applied Physics. Direct laser lithography: Reproduced with permission. Copyright 2015, American Chemical Society. WACVD: Reproduced with permission. Copyright 2017, Wiley-VCH. Electro-deposition: Reproduced with permission. Copyright 2017, American Chemical Society. Plasma-etching: Reproduced with permission. Copyright 2017, Elsevier. Electrospinning: Reproduced with permission. Copyright 2018, Royal Society of Chemistry. Electrostatic flocking: Reproduced with permission. Copyright 2018, Wiley-VCH. 3D Printing: Reproduced under the terms of the Creative Commons CC-BY license. Copyright 2017, The Authors. Published by MDPI. Chemical Etching: Reproduced with permission. Copyright 2020, Elsevier.
of the patterns. Therefore, photolithography has recently been applied to manufacturing artificial *Salvinia* blades because it provides an important method of bionically preparing the *Salvinia* blade structure and a technical foundation for bionic manufacturing. However, different photolithography-based manufacturing processes are implemented differently. Therefore, in this section, the details, differences, advantages, and disadvantages of these photolithography techniques are discussed.

| Techniques            | Eggbeater structures | Hair properties | Static WCA [°] | Adhesion strength [μN] | Air-retaining ability | Advantages                                                                                           | Disadvantages or limitations                                                                 | Ref. |
|-----------------------|----------------------|----------------|---------------|------------------------|-----------------------|------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|------|
| Photolithography      | None                 | None           | 136           | 0.2                    | None                  | This is a mature technique and can accurately control the shape and size of the patterns.           | Replicating the fine structures of *Salvinia* leaves is difficult. The realization of heterogeneous structures is inefficient. | [31] |
|                       | None                 | ≈36            | 150           | ≈2.5                   | None                  | Pressure resistance (940 Pa)                                                                         |                                                                                              | [92] |
|                       | Achieved             | ≈555           | 151.7         | None                   | None                  |                                                                                                     |                                                                                              | [46] |
| Direct laser lithography | Achieved             | 7              | 122           | None                   | Air-retaining for several hours | This technique can replicate the fine structures of *Salvinia* leaves.                            | Only a few materials can be used to fabricate the artificial eggbeater structures.            | [32] |
|                       | Achieved             | 10             | 120           | None                   | Air-retaining for 100 h |                                                                                                     |                                                                                              | [52] |
| Electrodeposition     | None                 | 47             | 148           | 45 000                 | Good stability        | The heterogeneous tips can be achieved.                                                              | Many steps are required and the eggbeater structures cannot be replicated.                  | [39] |
| LTCVD                 | None                 | None           | 170           | Strong                 | Air-retaining for 7 days | It can be applied to many types of substrates, using simple equipment. The heterogeneous tips can be achieved. | Many steps are required and the eggbeater structures cannot be replicated.                  | [36] |
| APPCVD                | None                 | 30             | >140          | 0.08                   | Better than Lotus effect | It can be operated without a vacuum system, using more coating materials. The heterogeneous tips can be achieved. |                                                                                              | [37] |
| WACVD                 | None                 | None           | 162           | Strong                 | Good stability        | Simple preparation method.                                                                            | It cannot replicate the eggbeater structures. The available materials are limited in carbon nanotubes. The superhydrophobic samples show nonheterogeneous tips. | [38] |
| Electrospinning       | None                 | 50             | 139.8         | None                   | None                  | Simple preparation method, and adjustability of the wetted surfaces.                                | It cannot replicate the eggbeater structures. The mechanical stability of the prepared surfaces is unknown. | [40] |
| Electrostatic flocking | None                 | 900            | 140.3         | None                   | None                  | Air-retaining for 530–610 h This is a mature technique, producing soft artificial hairs. The prepared surface has a tunable wettability. | The available fibers are limited. The fine eggbeater structures cannot be achieved.          | [41] |
| 3D printing           | Achieved             | 950            | 152–170       | 23–55                  | None                  | This technique can replicate the fine eggbeater structures. The wettability and adhesive force are controllable. | The eggbeater structures are not soft and elastic, and the production efficiency is low. The heterogeneous tips cannot be achieved. | [26] |
| Plasma etching        | Similar              | 5.5            | >160          | None                   | Good                  | Simple preparation method with no coatings required. The hairs can be adjusted in shape and size. | The heterogeneous tips cannot be achieved. The eggbeater structures may be fragile.           | [42] |
| Chemical etching      | None                 | None           | None          | >90                    | Strong                | The preparation method is simple, and the heterogeneous tips can be achieved.                      | The etching rate is difficult to control. The fine eggbeater structures cannot be achieved. | [43] |

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3.1.1 Tape Stripping

This technique was an early attempt to mimic the function of Salvinia leaves. First, the negative Si model was prepared by photolithography and then filled with liquid epoxy resin (Figure 4a(i)). After curing, positive micropatterns were removed from the mold (Figure 4a(ii)). The micropatterns were then coated with a hydrophobic layer (Figure 4a(iii)). To obtain hydrophilic tips, double-sided tapes were then used to strip away the hydrophobic coating at the end of the micropatterns (Figure 4a(iv)). Two micropatterns (diameter: 14 μm, height: 30 μm, and pitches: 26 and 210 μm) were fabricated using this technique and were subsequently investigated. The 26 μm-pitch micropatterns exhibited a WCA of 136°/C14, which was higher than that of the 210 μm-pitch micropatterns (115°/C14). The results also revealed that the former exhibited air trappability while the latter did not, indicating that appropriate spacing is important for air trappability. However, tape stripping cannot be used to completely mimic the complex structures of Salvinia leaves and is, therefore, unsuitable for industrial application. Therefore, more efforts are required to improve this technique.

3.1.2 Mechanical Forming

Although the Salvinia structure is extremely complex and difficult to fabricate (especially its eggbeater hairs), Zheng et al. developed a relatively simple method of preparing complex structures.[46] First, the fibers were placed on paper in a cross pattern (Figure 4b(i)), and the pattern was immersed in SU-8 liquid and irradiated with 365 nm UV light to produce fibers coated with a hydrophobic surface. Then, a micropore-patterned paper was prepared using standard photolithography (Figure 4b(ii)). Finally, the eggbeater structures were formed by fibers passing through the micropores (Figure 4b(iii)). The resulting structures replicated natural Salvinia structures more accurately than the other surfaces fabricated using photolithography, and the contact angles of the structures shown in Figure 4b(iv) can reach 151.7°. However, the scale and tips of the eggbeater structures were several millimeters and hydrophobic, features that are different from the natural structures. In addition, eggbeater structures cannot maintain long-term air retention because of their rough handmade structures. Therefore, this technique can be further improved.

3.2 Direct Laser Lithography

Direct laser lithography is a mature technology involving local curing by tightly focusing laser beams against etchants to directly write any 3D microstructures.[47,48] The resolution makes this method versatile for fabricating structures, ranging from micro-optical elements and 3D templates[49] to microbranches for cell research.[50] Direct laser lithography shows great potential for fabricating micro/nanoscale structures, is highly flexible for fabricating artificial structures inspired by nature creatures, and can replicate the functional characteristics of target structures.[51]

Recently, direct laser lithography was used to fabricate artificial eggbeater structures 100 times smaller than natural ones to obtain microcharacteristics and tunable hydrophobicity.[32] The artificial stalk was 7 μm high and 1.5 μm in diameter (Figure 5a(i)). The head of the structure was obtained by rotating three 6 μm-diameter × 1 μm-thick rings at 60°. The eggbeater structures were hexagonally arranged and spaced at 9 μm. Figure 5a(ii) shows the details of artificial eggbeater structures fabricated using a hydrophilic IP-DiLL photoresist and direct laser lithography. Although the IP-DiLL photoresist was hydrophilic (WCA = 53°), the eggbeater structures showed a WCA...
These results suggest that the hydrophobicity of a material can be tuned by adjusting the surface microstructure. The 3D reconstruction from the images obtained using a confocal microscope confirmed the air-retainability of the artificial eggbeater structures (Figure 5a(iv)).

To investigate the correlation between air-retainability and the number of eggbeater arms or head radius, artificial eggbeater structures were fabricated using a similar technique.[32] The structures exhibited different eggbeater arm and head radii (Figure 5b(i,ii)), which were 8–25 times smaller than their natural counterparts. Figure 5b(iii,iv) show that more eggbeater arms and a larger head radius helped the structures trap more air. Further investigation, the artificial structures demonstrated excellent air-retainability for up to 100 h. Although this technique fabricated complex structures highly accurately, a heterogeneous hydrophobic surface exhibiting hydrophilic tips was not achieved.

3.3. Deposition Techniques

3.3.1. Electrodeposition

Electrodeposition, or electroplating, is a deposition method driven by an electric current and can coat nanomaterials, nanoparticles, and so on onto target surfaces.[53] Owing to these advantages, this technique was used to deposit hydrophilic materials on artificial tips and fabricate heterogeneous hydrophilic–hydrophobic surfaces.[39] As shown in Figure 6a, the microstructures were first fabricated with silicon by photolithography and deep reactive ion etching (DRIE). The surface was then coated with hydrophobic materials. Because the electrolyte cannot penetrate the cavity of the microstructures, the electrochemical reaction between the electrolyte and solid only occurs at the tips. The heterogeneous surface exhibited a static angle of 148 ± 2° and strong adhesion such as natural Salvinia leaves. This simple method may be applied in many gas-retaining applications, including drag reduction, antifouling, and anticorrosion. However, the microstructures were fabricated on silicon wafers, which are rigid materials, and therefore lack elastic properties, which negatively affects the elastic buffer of the eggbeater structures. As discussed in Section 2, the elastic buffer can reduce interfacial disturbance; thus, rigid materials will reduce gas-retainability.

3.3.2. CVD

The working principle of chemical vapor deposition is that the gaseous substances formed by thermal activation near the coating assembly produce chemical reactions on the solid surface and transport reactions to form solid sediments.[54] The greatest advantage of CVD is that it can form high-purity products exhibiting good microstructures and produce high-quality, high-performance solids under vacuum.[55] CVD can grow uniform coatings on many substrates, including metals, ceramics, and plastics, and the raw materials for growing films are usually easily obtained. Moreover, the same film can be prepared by choosing different highly flexible chemical reactions. Because of these characteristics, CVD has recently been used by researchers to grow artificial hair on target surfaces. This section focuses on three CVD techniques used to fabricate artificial structures to achieve the Salvinia effect.

LTCVD: LTCVD has many desirable features, including good plating performance, uniform coating, and excellent growth of carbon fibers.[56] In addition, LTCVD has been performed using copper as catalysts on different substrates, including flexible polyimide, rigid glass, and silicon wafers.[36] Using this technique, hairy carbonaceous fibers (HCFs) can be fabricated on target surfaces. The deposition temperature is controlled between 230 and 300°C, which is lower than traditional CVD temperatures. First, copper is deposited on a substrate by electroless plating. Then, acetylene gas is introduced to grow HCFs. This process grows high-density HCFs on substrates (Figure 6b(i)), and the HCF hydrophobicity can be enhanced by fabricating hierarchical structures. The process involved is shown in Figure 6b(ii). First, the desired pattern is electroplated on the substrate surface. Next, the entire surface is electroplated. Finally, hierarchical structures are formed on the surface (Figure 6b(iv)). To obtain hydrophilic HCFs...
tips, an aqueous tetraethyl orthosilicate (TEOS) solution is gently cast on the HCFs. Because TEOS cannot reach the substrate, it only attaches to the HCF tips. Finally, a thin silica layer is formed by consolidating on the tips (Figure 6b(v)). This heterogeneous hydrophobic–hydrophilic surface strongly adhered to the droplet (Figure 6b(vi)). Moreover, this technique is simple and suitable for fabricating HCFs on many substrates. The silica-coated layer on the tips opens a door for fabricating a wide range of such surfaces.

**APPCVD:** APPCVD can provide high-quality coatings using low-surface-energy materials such as fluoroalkyl-silane (FAS). APPCVD exhibits a very high deposition rate and a high-density free-radical atmospheric pressure plasma that can be used to fabricate functional films. As shown in Figure 6c, the pattern is first designed using standard photolithography and anisotropic inductively coupled plasma (ICP) etching. A hydrophobic coating is obtained using 1 H,2 H,2 H-perfluoroctyltriethoxysilane (a type of FAS). Then, the hydrophobic tops are lifted off to obtain hydrophilic tips. The adhesion force of the tips can reach an average of 80 nN compared with 30 nN in other parts of the eggbeater structures. In addition, the surface WCA is higher than 150°, indicating that the structures are superhydrophobic. Although the *Salvinia* effect can be achieved using this technique, silicon is a rigid material and lacks elastic properties; therefore, the structures cannot act as an elastic buffer to dampen external disturbances.

**WACVD:** In WACVD, the properties of carbon nanotubes (CNTs) (e.g., length, diameter, and distance) typically are determined by the type and size of the catalyst particles. However, introducing a small (controlled) amount of water can enhance and maintain the catalyst-particle activity and lifetime. Therefore, WACVD is a good method of preparing hydrophobic vertically aligned carbon nanotubes (VACNTs). The robust mechanical properties and chemical stability of VACNTs can be attributed to the natural *Salvinia* effect. During actual VACNT fabrication, 13–15 nm of aluminum is deposited onto a B-doped silicon wafer (initially coated with 600 nm of SiO₂). Then 1.2 nm of iron is sputter deposited onto the silicon wafer. The as-prepared VACNTs are grown for 15 min at 850 °C, using ethene as the carbon source. The hydrophobic VACNTs (Figure 6d) are detached from the substrate, and cleaned and dried. Then, the VACNTs are regrown on the as-prepared VACNTs to obtain a higher surface roughness and WCA (142°). Because of the hydrophilic hydroxyl groups (–OH), the regrown VACNTs exhibit a high-contact-angle hysteresis (the droplet pinned to the inverted surface). Finally, the regrown VACNTs are treated with polydimethylsiloxane (PDMS) to obtain superhydrophobic VACNTs exhibiting a low-contact-angle hysteresis (<5°) and a high advancing contact angle (162°). This technique is simple and suitable for large-area fabrication. In addition, the excellent mechanical properties and chemical stability of carbon materials make them compatible with harsh environments. However, the hydrophilic hydroxyl groups of VACNTs were lost after the hydrophobic treatment with PDMS. This factor may bring a barrier to achieve the *Salvinia* effect.

### 3.4. Electrospinning

Electrospinning is a relatively new fabrication technique developed in recent decades. During electrospinning, fibers and particles from solutions are driven by voltage, and a charged jet is ejected toward a collector on which fibers are formed. Electrospinning is a versatile and feasible technique for producing fiber-based materials and has recently become a popular method of fabricating bioinspired surfaces. As shown in Figure 7a, electrospinning has also been applied to fabricate *Salvinia*-like
structures. The fabrication begins using standard photolithography to form micropillars on a substrate, and the micropillars are subsequently electrospun. WCA measurements reveal that shorter spacing between the micropillars increases WCA and that the 50 μm spacing surface shows the maximum WCA of 139°. These results suggest that micropatterns affect not only fiber arrangement but also surface wettability. This simple technique is low cost, flexible, and suitable for mass production. However, micro/nanostructures usually exhibit poor mechanical strength; thus, the durability of electrospun surfaces should be fully evaluated.

3.5. Electrostatic Flocking

Electrostatic flocking is based on the physical characteristics arising from same-charge repulsion to perpendicularly orient fibers into negatively charged fluff. Electrostatic flocking is simple, low cost, and highly adaptable. Under zero potential or grounding conditions, fibers are attracted to a substrate and are vertically fixed to the surface with adhesive (Figure 7b). The flocked fluff is then treated with a water repellent (TG-5601) to achieve a hydrophobic surface. By adjusting the flocking parameters (e.g., fiber height/diameter and flocking voltage/time), surfaces exhibiting different WCAs, roll-off angles (RAs), and air-retainabilities are obtained. Air-retainability increases with increasing fiber density, reaching the maximum when the flocking time is 30 s. In addition, hybrid flocking with a mixture of both long and short fibers (SEM image in Figure 7b) shows better air-retainability than single-size fibers because of the hierarchical structure. The optimized sample (i.e., height: 0.9 mm; diameter: 22 mm; flocking voltage: 30 kV; flocking time: 30 s) shows the longest air-retainability of 530–610 h. As a relatively mature technique, electrostatic flocking has a promising future for fabricating artificial Salvinia leaves. Currently, the key problems are the effects of fiber properties (e.g., wettability and elasticity) on air-retainability. In addition, because hydrophilic fiber tips and the original complex structures have not been fabricated using this method, more effort is required.

3.6. 3D Printing

3D printing, also known as additive manufacturing, is an efficient technology that enables rapid prototyping and flexible design. It is an advanced manufacturing technology that can rapidly print 3D objects with the help of computers and has been widely used to prepare bionic structures. In addition, 3D printing can effectively simulate the microstructure of the Salvinia blade and accurately replicate the original natural structure.

Recently, Salvinia structures have been manufactured using immersed surface accumulation-based 3D printing (ISA-3D) (Figure 7c(i)). The key component of which is a light guide tool, which has a resolution of 2.5 μm and can be submerged in liquid photocurable resin. Unlike common 3D printing, ISA-3D can be used to modify the surface of an inserted object. Based on the 3D model designed by SOLIDWORKS, high-precision structures were fabricated and tested. Different structures were fabricated by adjusting the number of eggbeater arms and the stack spacing. The structures showed superhydrophobic surfaces (WCA = 152–170°, Figure 7c(iv)) and controllable adhesive force (23–50 μN, Figure 7c(v)). In addition, this technique exhibits good extensibility. Even when hydrophilic materials are used, the structures can macroscopically show hydrophobicity. Nanomaterials such as multilayered carbon nanotubes (MWCNTs) can be incorporated into photocurable resins to enhance their mechanical properties and roughness. In view of these advantages, we believe that this technique has a promising future. However, several 3D-printing limitations should be...
overcome. For example, natural *Salvinia* leaves are elastic, whereas photocured resins are usually rigid. Currently, the use of soft/elastic materials for 3D printing remains challenging. The inefficient high-cost production of 3D printing also poses a barrier to industrial production.

3.7. Plasma Etching

Size-tunable ripples and nanoripples have been produced on several plastic materials using plasma etching,[68] *Salvinia*-like micro/nanopillars (which height and spacing are 5.5 ± 1.2 and 1.5 ± 0.5 μm, respectively) have been prepared (SEM image in Figure 7d) by applying plasma etching to Teflon (polytetrafluoroethylene, PTFE) in a reactor (Figure 7d).[42] Moreover, the SEM image clearly shows that the structure sizes, positions, and shapes are random. In addition, the WCA of the plasma-etched Teflon considerably increases and then decreases, indicating the excellent hydrophobicity of the *Salvinia*-like micro/nanostructures. This technique is simple and low cost and does not require a coating. However, it cannot be controlled well during fabrication.[69]

3.8. Chemical Etching

Chemical etching is a high-precision method wherein etchants selectively remove materials from the substrate to produce the desired surfaces. It is widely used to fabricate superhydrophobic surfaces owing to its low cost and flexibility.[70,71] As shown in Figure 7e, the Al sheet is first treated with HCl to roughen the surface. Then, the hydrophobic material 1H,1H,2H,2H-perfluorodecyltrichlorosilane (FTCS) is used to reduce the free energy of the rough surface. The obtained surface shows WCAs of 155.5 ± 0.7° and sliding angles (SAs) of 6.0 ± 1.4°. Subsequently, the surface is immersed in a hydrophilic dopamine (DA) solution to obtain hydrophilic nanotips. The correlation between the immersion time and the WCA/sliding angle is shown in Figure 7e. With increasing immersion time, the WCA changes negligibly. However, the SA reaches 90° when the immersion time is 9 min, and the droplet remains pinned on the surface even when the surface has been completely turned over. The results suggest that this technique produces a superhydrophobic surface exhibiting high adhesion strength. However, the air-retainability of the prepared surface was not evaluated. Thus, such investigations must be completed. Because this technique is simple, low cost, and scalable, it will attract more attention for practical applications. It should be noted that the etching rate of this technique is hard to control, as it requires a large amount of etchant to maintain initial etching rate. In addition, chemical etching is incompatible with several inert materials.

4. Applications of Artificial *Salvinia* Surfaces

The excellent air-retainability and high adhesion strength of natural *Salvinia* leaves have inspired many artificial surfaces. In the past decade, such surfaces have been extensively investigated to demonstrate their potential in many fields, including drag reduction,[27,42] water harvesting,[32] water evaporation,[19,63] water repellence,[60] oil/water separation,[56,72] and thermal insulation.[29] This section focuses on the different applications of artificial *Salvinia* surfaces (Figure 8). In addition, the performance and current problems associated with the application of such surfaces are discussed.

4.1. Drag Reduction

Drag refers to the force a fluid exerts when resisting a body’s motion. A body experiencing drag will slow if no extra energy is provided to counteract the drag. For example, pipeline drag increases energy consumption and pumping costs.[71] In the marine shipping industry, “skin drag” arises from vessels carrying extra heavy loads of fuel or marine-gas oil. Techniques for reducing drag have been proved effectively to reduce the fuel consumption and CO₂/SOₓ emission. In the past decades, several active (e.g., injecting bubbles[74]) and passive (e.g., shark skin ribs[75]) strategies have been developed to reduce drag.

A useful and interesting method of reducing drag is to maintain an air layer around ship hulls. In 1995, a study revealed that water streaming over an air layer could reduce drag by up to 80% compared with that of water streaming over a smooth surface because of the low viscosity of air.[76] Figure 9a,b shows the flow profiles generated for a conventional ship hull and an air layer surface, respectively. The water velocity at the boundary layer of the conventional ship surface is zero, while that at the air layer interface is larger than zero, and the lower viscosity reduces the transmission of friction forces.[27]

The excellent air-retainability of *Salvinia* structures suggests they could be used long term in drag-reduction applications.[34]

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**Figure 8.** Applications of artificial *Salvinia* structures. Water harvesting: Reproduced with permission.[32] Copyright 2015, American Chemical Society. Water repellence: Reproduced with permission.[32] Copyright 2020, image was reproduced with permission.[19] Copyright 2020, National Academy of Sciences. Oil/water separation: Reproduced with permission.[24] Copyright 2018, Wiley-VCH.
In addition, several recent studies have confirmed that *Salvinia* structures reduced drag. For example, natural “eggbeater hairs” reduced drag by up to 30%,[77] and similar positive results have been obtained in qualitative studies on artificial *Salvinia* structures. For example, Teflon was plasma-etched to fabricate *Salvinia*-like structures (Figure 9c),[42] and the nanofilaments on the treated surface enhanced the air-retainability. In addition, the motions of pristine and etched Teflon spheres in liquids showed that the plasma-etched spheres moved faster than the pristine ones (Figures 9d, e, respectively). In other words, the etched spheres encountered less drag resistance because the highly stable air layer had helped reduce it.

Because shark skin ripples can reduce drag resistance, a surface combining the properties of shark skin and *Salvinia* leaves is appealing. Figure 9f shows the SEM image of shark skin pattern (type I riblet).[73] Only the bottom and side walls of the trenches are covered with micro/nanostructures. Furthermore, the superhydrophobic *Salvinia* leaves are fabricated on the type I riblet. As shown in Figure 9g, the surface of the SH riblet is entirely covered with micro/nanostructures. The pressure-drop measurements are shown in Figure 9f,g. In the graphs, the dashed line represents the pressure drop measured for a flat PTFE sample. The results show that the pressure drop measured for the type I riblet was considerably lower than that measured for the flat PTFE sample. However, combining the shark skin ripples and *Salvinia* structures did not synergistically affect the pressure drop, and movement along the flow and cross-flow translation of vortices might actually increase the drag on the SH riblet sample. These results suggest that combining drag-reduction strategies should be fully evaluated prior to their practical application.

### 4.2. Water Harvesting

*Salvinia*-inspired patterns have been tested for their water-vapor condensability.[32] As shown in Figure 10a, the test was performed using an environmental scanning electron microscope (eSEM). According to the macro-Wenzel regime, the droplets first nucleated around the eggbeater heads and then grew larger around the stalks. Finally, the droplet filled the entire space and reached the substrate (Figure 10a). Nucleation is a crucial stage of water-vapor condensation.[78] In *Salvinia* structures, the eggbeater head is much rougher than its surroundings. Consequently, water easily condenses around it. The results also reveal that artificial *Salvinia* structures fabricated with smaller crown-like heads show better water condensability possibly owing to the increased capillary force and Laplace pressure.[79] Furthermore, this method provides a novel strategy for collecting water vapor, which will undoubtedly mitigate water shortages. However, this strategy is different from traditional fog collectors, which can promote water transportation.[80]
4.3. Water Evaporation

The evolution and kinetics of droplet evaporating are affected by the wettability of tips of the *Salvinia* structures. In droplet evaporation tests, droplets become increasingly smaller over time. Furthermore, the comparison of the stacked-droplet contours provides additional evidence of the effect of the hydrophilic tips on the superhydrophobic surfaces (Figure 10b). The graph of the droplet-volume evolution in Figure 10b shows that the droplet on the surface fabricated with hydrophilic tips is slightly larger than the one on the surface fabricated without any hydrophilic tips. However, the differences between both surfaces were negligible. The contact diameter of the droplet on the surface fabricated with hydrophilic tips was constant during the first 14 min, while that of the other droplet decreased with time. The sticky hydrophilic tips provide a strong pinning effect and solid–liquid retention on the surface, which is of great importance in droplet evaporation applications. However, the effects of the *Salvinia* characteristics (e.g., height, diameter, and size) on the droplet-evaporation behavior were not studied; therefore, further study will deepen the understanding of *Salvinia* functions.

4.4. Water Repellence

Owing to their air-trappability (e.g., Cassie state), superhydrophobic surfaces have many advantages in underwater applications. Furthermore, recent studies have revealed that *Salvinia* leaves exhibit not only strong water repellency but also continuous air-layer recoverability occurring through the formation of seed air and the spread of air within *Salvinia* structures. The micro-grooves at the base of *Salvinia* leaves provide air-spraying canals (Figure 10c). Artificial 3D-printed *Salvinia* structures also show air recoverability (see 3D confocal microscopy images in Figure 10). In addition, strongly pinned hydrophilic tips ensure the stability of the air–liquid interface, thereby promoting robust air-layer recovery on *Salvinia* structures. Because of their robustness, these structures can be applied to harsh environments, including high pressure, fast flows, and violent waves. These findings not only reveal the air-recovery mechanism but also promote the development of water-repellent materials.

4.5. Oil/Water Separation

Owing to increasing oily industrial wastewater discharge and frequent crude oil leaks and spills, oil/water separation has become an urgent worldwide subject. Although crude oil is a well-known valuable commodity, oil exploration, transportation, processing, and use are all plagued by oil spills. Therefore, the treatment and cleanup of oil spills and oily industrial wastewater have attracted the attention of many researchers, and many methods have been proposed. However, traditional methods
treating oil/water mixtures often lead to many problems such as generating toxic substances and secondary pollution. Thus, environmentally friendly oil/water separation strategies are attractive. Toward that goal, the hydrophobic and oleophilic properties of *Salvinia* leaves have sparked intense interest among researchers. Figure 11a shows evidence of the oil/water separability of natural *Salvinia* leaves. The *Salvinia* leaves absorb the crude oil in just 20 s, while the superhydrophobic structures repel water. The oil absorbabilities of *Salvinia* leaves, *Pistia stratiotes*, and *Nelumbo nucifera* were tested using artificial oil sorbents as the control. The results reveal that the oil absorbability of *Salvinia* is superior to that of the others and is equivalent to that of the artificial oil sorbent. Moreover, oil absorbability is affected by structural characteristics, that is, tall hairs and bent/fused tips can promote oil absorbability. The results suggest that well-designed *Salvinia* structures have the potential for application to oil/water separation.

Owing to the hydrophobicity, oil affinity, and high adhesion strength of natural *Salvinia* structures, artificial ones have been 3D-printed for application to oil/water separation. An oil/water mixture was dropped onto an artificial eggbeater structure, and the oil (dyed red) was completely adsorbed by it (Figure 11b). Furthermore, the oil/water separation tests conducted on inverted and inclined artificial *Salvinia* structures yielded the same results. In addition, the *Salvinia* structures displayed oil absorbabilities for many different oils (see graphs in Figure 11b). After cycle tests, the structures exhibited high absorbability and recycling efficiency.

Because *Salvinia*-inspired structures perform well in oil/water separation applications, they can provide a more convenient method of cleaning up oil pollution in various fields. However, 3D printing is inefficient and costly for industrial scalability. Therefore, simple low-cost strategies are attractive. A recent study has revealed that commercial flock and textiles treated with a hydrophobic agent (TEGOTOP 210) show excellent self-driven oil absorption that does not require an external driving force. This finding lays a foundation for developing oil–water separation technologies and materials. Moreover, the natural *Salvinia* blade provides a theoretical basis for bionics and a more environmentally friendly, efficient, feasible, and thorough method of cleaning up oil pollution.

### 4.6. Thermal Insulation

Heating and cooling systems are important components of energy consumption. Excessive energy loss due to poor thermal insulation results in massive fuel consumption and greenhouse gas emissions. The world’s fuel resources are shrinking, and
greenhouse and other harmful gases are threatening environmental security. Therefore, the development of renewable energy is a priority. In addition to developing alternative environmentally friendly energy sources, improving energy efficiency is critical \cite{86} and thermal insulation plays an important role in the technological changes required to mitigate climate change. However, many renewable materials exhibit poor thermal insulating properties compared with their commercial counterparts. Therefore, toward the development of next-generation environmentally friendly thermal insulation materials, enhancing thermal insulating properties is a priority. \cite{87}

Because nature’s creatures have developed excellent thermal insulating features, learning from/mimicking nature is an effective strategy for solving engineering problems. Because of their heterogeneous structures, natural Salvinia leaves can maintain a stable air layer in water, and the unique Salvinia structures have attracted considerable attention from researchers and are expected to be used as thermal insulation materials. In life-saving medical appliances, thermal insulation materials can play a vital role in maintaining a constant body temperature or losing as little heat as possible at low temperatures. Therefore, to mimic Salvinia structures and properties, four terrycloths were hydrophobically treated. As shown in Figure 11c, the fabric structures were either an arch \((F_1, F_2)\) or a whole circle \((F_3, F_4)\). The changes in air volume and thermal insulation tests revealed that \(F_1\) and \(F_2\) exhibited the highest thermal insulation. On the basis of the results, the study authors proposed the following criteria for designing Salvinia-inspired thermal insulation materials: 1) the loop yarns should enhance the surface roughness, which is important for air retention. 2) Higher loops benefit from the retained air volume. 3) A vertically standing loop structure is better than a sideways-leaning one for optimizing water repellency. 4) A tight loop arrangement should be avoided because the groove between the loop lines can increase the air loss.

Although these textiles have excellent application prospects, previous studies have revealed that pinning is important for the air-retainability of natural Salvinia leaves. \cite{19,20} Thus, it is necessary to improve the thermal insulation because the hydrophilic tips were not pinned.

Traditional water evaporators consist of light absorbers, thermal insulators, and water-transport channels, and the separable structure decreases evaporator durability and portability. Owing to their thermal-insulating feature, Salvinia structures show potential for application to all-in-one integrated solar-driven interfacial water evaporators (AEs). \cite{64} As shown in Figure 11d, the hydrophilic and hydrophobic fibers vertically planted at the top and bottom promoted photothermal conversion and enhanced the thermal insulating property, respectively. An infrared (IR) camera and temperature sensors were used to evaluate the insulating performance of the AE (see IR images in Figure 11d). Because of air retention, \(F/N\) \((55.9 °C)\) exhibited a much higher temperature than the pristine fabric \((30.8 °C)\) (sensor A data), and the bulk water below \(F/N\) \((32.9°C)\) was lower than that of the pristine fabric \((33.5 °C)\). In total, the hydrophobic flocks reduced the heat loss by 17.1%. The AE is low cost and scalable compared with traditional water evaporators; thus, it has broad application prospects.

5. Protocol for Conducting Air-Retainability Measurements

Since the discovery of the excellent air-retainability of Salvinia leaves, evaluating their air retention has become an important issue because rational scientific methods of evaluating air retention will benefit the design and application of replica Salvinia leaves. Toward that goal, the development of a standard protocol for qualitatively and quantitatively measuring air-retainability in accordance with the scientific method is essential. Therefore, in this section, such air-retainability measurement methods are introduced and discussed.

5.1. Qualitative Analysis

5.1.1. Liquid-Barrier Grid Method

The underlying principle of this method is that if Salvinia-like structures could retain air even when surrounded by water, a grid of Salvinia-like structures could act as a barrier generating pockets of liquid. \cite{18} First, a copper grid was formed on a substrate using photolithography. Fluffy Salvinia structures were then grown on the grid using CVD. Subsequently, a droplet containing mobile microalgae cells was cast onto the surface. Finally, a soft PDMS cap was placed on the grid to flatten the cell droplet to the height of the chamber. The movement of microalgae cells was observed using a fluorescence microscope (red spots in Figure 12a). Clearly, the microalgae cells could not pass through the grid walls, indicating the air-retainability of the Salvinia structures. The structures shown in Figure 12a can trap air for 7 days. Although this method is effective, it has many practical limitations. For example, Salvinia structures must be fabricated on a grid, which is complex and time-consuming. Live microalgae cells require an appropriate growth temperature and medium, and the survival of microalgae cells affects the fluorescent optical image; thus, the results of the experiment will be affected by the microalgae-cell culture.

5.1.2. Microscopic Observation

When Salvinia leaves are submerged in water, silver reflections can be observed by the naked eye or microscopy (Figure 10c). This phenomenon is due to the transition of visible light through air–water interfaces, and the different refractive indices of air and water lead to specular reflectance. Owing to this phenomenon, optical microscopy was used to observe the air-retainability of the Salvinia structures. \cite{10,21} Although this method is straightforward, the reflective level is difficult to define. Therefore, the method only gives an approximation/estimation with errors.

Confocal laser scanning microscopy (CLSM) scans objects pointwise using a laser beam to reconstruct the 3D morphology. \cite{88} In addition, CLSM resolution can reach hundreds of nm depending on the wavelength of the focused light and exhibits its higher resolution and more functionality compared with common optical microscopy. This is a popular method for evaluating the air-retainability of Salvinia leaves. \cite{10,21,50} Figure 12b shows a schematic and confocal microscope images of the air-retention tests. The boundary lines of the air–water interfaces in Figure 12b are very clear compared with the optical microscope...
Although CLSM is a powerful tool for qualitative analysis, the lack of qualitative analyses may limit its application.

5.1.3. Atomic Force Microscopy Imaging

When a large volume of air is trapped in structures, the total reflection at the air–water interface will be strong. Figure 12c shows a confocal image of a superhydrophobic surface covering the total reflection (air is represented in green). Under these conditions, the air–water interfaces become fuzzy because of the CLSM resolution and light-scattering limitations. This method provides a solution for measuring the air-retainability of superhydrophobic surfaces. The wide applicability and high-precision measurements will attract more attention and inspire new applications.

5.2. Quantitative Analysis

5.2.1. Buoyancy Measurement

When an object is immersed in a fluid, the fluid exerts a vertical upward force called buoyancy or buoyant force on the object. Therefore, measuring the buoyancy differences of Salvinia structures with and without an air layer can be used to estimate the trapped-air volume. Figure 12d shows a schematic of the measurement setup. In the measurement, a sample with an air layer was first attached to the needle and stabilized for 10 s. The buoyancy was then recorded as $F_1$. After this measurement, the sample was removed from the water and covered with ethanol to wet the surface. Subsequently, the sample was washed for 20 s in water and reattached to the needle for another measurement. The buoyancy of the second measurement was recorded as $F_2$. According to Archimedes’ principle $F = \rho g V$, the trapped air volume ($V$) can be calculated as follows:

$$ V = \frac{F_1 - F_2}{\rho g} \tag{1} $$

where $\rho$ is the density of the liquid and $g$ is the acceleration due to gravity. Although buoyancy is a good quantitative measurement, completely removing the air layer in the second measurement is crucial for computational accuracy according to Equation (1). In practice, however, this may require several tests and much training.

5.2.2. Air Bubble Loss Measurement

Figure 12e shows a schematic of the apparatus used to measure air bubble loss. A sample was placed on a glass slide and then placed at the bottom of an aquarium filled with distilled water. The sample was covered with an inverted funnel connected to an upside-down burette. The burette was filled with 8 mL of distilled water and sealed at the top. When air escapes from the sample, it enters the burette through the funnel and pushes out the same volume of water from the burette. Then, the volume can be read from the scale of the burette, and this value can be recorded as $V_0$. To calculate the total air layer ($V_{\text{total}}$), the air in the sample can be manually squeezed out and remeasured, obtaining a value ($V'$). Then, the total air layer can be calculated as

$$ V_{\text{total}} = V_0 - V' \tag{2} $$

Then, the volume of air bubble loss ($V_{\text{loss}}$) after several hours can be calculated as
where $V_t$ is the air volume measured at time $t$. When the test ended ($t = x h$), the burette scale read $V_c$. After the air was manually squeezed into the burette, the burette scale was recorded as $V_e$. Therefore, the air left on the sample ($V_{left}$) is calculated as

$$V_{left} = V_x - V_e$$ (4)

Based on these measurements, the volume of air dissolved in water during the test is

$$V_{dissolved} = V_{total} - V_{loss} - V_{left}$$ (5)

Although this method can be used to obtain numerous measurement data, manually eliminating air from the sample may introduce experimental errors.

5.2.3. Laplace Pressure Measurement

The stability of the Cassie–Baxter surface wetting can indicate air-retainability.\textsuperscript{[92]} Therefore, to investigate the stability of the Cassie–Baxter surface state, drops were evaporated at a higher Laplace pressure and the evaporation was recorded using high-speed cameras. Figure 12f shows the results of drop evaporation tests on SSS (Salvinia-like slippery surface) and control (common superhydrophobic surface) samples. The top graph in Figure 12f shows the change in the contact base diameter of the droplet with time. The stability of the Cassie–Baxter state against impalement can be calculated based on the shape of the droplet as determined by the Laplace pressure ($p$), which can be calculated by\textsuperscript{[93]}

$$p = \frac{2\gamma}{r}$$ (6)

where $\gamma$ is the surface tension, and $r$ is the radius of the droplet. The results showed that the SSS could withstand pressures up to 940 Pa, which is 35% higher than that of the control sample.

This technique provides a new method of measuring air-retainability. However, the Laplace pressure is determined using Equation (5), whose results highly rely on measurements of $\gamma$ and $r$. Because reliably measuring and estimating $\gamma$ is difficult for a surface, the calculation may lead to some errors.\textsuperscript{[94]} In addition, $r$ is obtained from the droplet profile; thus, the precision depends on the measurement tool and operator, which requires good operational skills.

6. Conclusion and Outlook

Salvinia-inspired superhydrophobic surfaces are of great interest because of their remarkable properties. Heterogeneous eggbeater structures endow Salvinia leaves with excellent and durable air-retainability. Based on the air-retention mechanisms and design criteria, advanced techniques have been developed to replicate the structures and functions of natural Salvinia leaves. The artificial replicas fabricated using these techniques range from simple to complex and are increasingly approximating complex natural structures. These advanced techniques provide possibilities for producing and engineering artificial Salvinia structure-based applications. However, several issues should be addressed before applying these techniques: 1) several fabrication techniques such as photolithography, deposition, electrostatic flocking, and chemical/plasma etching cannot copy the complex and precise eggbeater structures. Because the eggbeater structures are crucial to air-retainability, the properties of these replicas are somewhat decreased. 2) Direct laser lithography and 3D printing can be used to fabricate complex structures of Salvinia leaves. However, heterogeneous hydrophobic–hydrophilic structures were not fabricated. The adhesion of hydrophilic tips is crucial in several applications, thus fabricating heterogeneous structures will be necessary. 3) Fabrication techniques such as photolithography and 3D printing are inefficient and expensive, which may restrict their applications. In addition, the structures are usually fabricated with rigid materials, whereas soft/elastic structures are helpful for promoting air-retainability. The fabrication of soft/elastic materials is still an issue in the 3D-printing industry. We believe that this issue will be well resolved with the development of 3D-printing techniques.

The excellent air-retainability and adhesion of Salvinia structures have inspired many attractive applications, including drag reduction, water harvesting, water evaporation, water repellence, oil/water separation, and thermal insulation. Satisfactory experimental results have demonstrated their application potential to relevant fields. However, these experiments are feasible only in principle, and thus, more tests in practical or harsh environments are necessary. Several methods of evaluating the air-retainability of Salvinia structures may result in large experimental errors, which may affect the design and application of artificial Salvinia structures. It is expected that more feasible evaluation methods will be developed in the future. Because of their excellent properties, Salvinia structures can be applied to many fields.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

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