Apex structures enhance water drainage on leaves

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The rapid removal of rain droplets at the leaf apex is critical for leaves to avoid damage under rainfall conditions, but the general water drainage principle remains unclear. We demonstrate that the apex structure enhances water drainage on the leaf by employing a curvature-controlled mechanism that is based on shaping a balance between reduced capillarity and enhanced gravity components. The leaf apex shape changes from round to triangle to acuminate, and the leaf surface changes from flat to bent, resulting in the increase of the water drainage rate, high-dripping frequencies, and the reduction of retention volumes. For wet tropical plants, such as \textit{Alocasia macrorrhiza}, Gaussian curvature reconfiguration at the drip tip leads to the capillarity transition from resistance to actuation, further enhancing water drainage to the largest degree possible. The phenomenon is distinct from the widely researched liquid motion control mechanisms, and it offers a specific parametric approach that can be applied to achieve the desired fluidic behavior in a well-controlled way.

\textbf{Water} drops interacting with substrate are omnipresent in our lives, and shedding is relevant to numerous fields, including microfluidics (1), printing (2), spraying (3), transfer (4, 5), and water collection (6), as well as for the survival of natural species (7–11). Many natural species utilize their surface structures, such as bumps, spines, or irregular structures with varying curvature outlines, to directional transport water and achieve water conservation and drainage. For instance, the periodic spindled-knots and joints of spider silk and hierarchical curvatures of pitcher plants transport water to the desired destination (7, 8), and the oriented microstructures of butterfly’s wing and clusters of wet fibers on dog shed undesired water for stable movement and to keep warm (9, 10). Although these delicate structures perform well, they only influence small volumes of water, in droplet sizes, over limited transport distances. In heavy rain events, it remains a challenge to achieve fast water drainage in bulk volumes, especially for wet tropical plants that typically have broad leaves.

The drip tip is the most famous evolution of rainforest leaf with curving apex shapes and orientations for quick drainage (\textit{SI Appendix, Table S1}). Although biologists found the fast drainage ability of the drip tip since the 1980s (12–18), the detailed mechanism of how the apex improves the water drainage remains unknown. Besides, it is still not clear whether the curving structures of leaf apex affect the drainage process. Hence, insight into the behavior of droplets interacting with the curvature-varying surface at the apex is needed.

Here, we demonstrate the water drainage behavior of leaf is controlled by the leaf apex structure and the leaf surface curvature. The surface curvature variation of the leaf apex reduces the capillary resistance force, and the bending down of the leaf surface enhances the water gravity component, leading to a high dripping frequency and low water retention. Gaussian curvature reconfiguration at the leaf drip tip leads to the capillarity change from resistance to actuation, which forces droplet detaching at the transition point and enhancing drainage to the highest degree possible. Measurements of leaf apexes and water drainage across the plant leaves from the temperate zone to the wet tropics support this finding. The leaf of rainforest plant \textit{Alocasia macrorrhiza}, which integrates multiple structures and curvature advantages at the leaf apex, has a high drainage efficiency. Learning from \textit{A. macrorrhiza}, we optimize an artificial drainage device to acquire superior drainage ability than most natural species.

\textbf{Results and Discussion}

\textbf{Water Drainage Efficiency of Different Leaf Apices.} Plant leaves in shape and size vary with temperature and precipitation (19). The leaf apex is a protruding part of a leaf where water droplets accumulate, and droplet separation occurs during drainage. To determine the abilities of different leaf apex morphologies on water drainage control, 44 different species (36 families) of leaves with various apex angles (20), $\alpha$, were investigated and classified (Fig. 1A and SI Appendix, Tables S2 and S3). These leaves were collected from the botanical garden in the subtropical zone with less precipitation in Beijing, China, and tropical zone with rich precipitation in Guangzhou, China. Based on the values of apex angles, leaf apices can be roughly classified into two categories: acute ($0^\circ < \alpha < 90^\circ$) and obtuse ($90^\circ < \alpha < 180^\circ$) (diagram in Fig. 1A) (20). Triangular leaf apices with the acute apex, marked with green dots in Fig. 1A, commonly exist in areas with high precipitation (\textit{SI Appendix, Table S2}).

Besides the category of apex angles, apex shapes, i.e., rounded, acuminate, and drip tip, are also used for classifying the leaf apices (20). The acuminate apex indicates the margin between the apex and the lamina is convex proximally and concave distally, or concave only. The drip tip is one special kind of acuminate, where the distal portion of the apex abruptly narrows. Four representative leaves with distinct apex shapes are shown in

\textbf{Significance}

Liquid manipulation is of significance not only for industrial spraying and drainage facilities, but also for the survival of creatures. Plant leaves perform excellently in rainwater drainage and leaf drying at the apex to avoid damage. Here we demonstrate that apex structure enhances water shedding with high dripping frequencies and low retention volumes. Based on the understanding of the tiny apex structure in controlling water delivery at the plant leaf, the evolutionary law of leaf apex shape could be further revealed. The shape-controlled liquid manipulation mechanism would improve the microfluidic and drainage systems.

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drying (12–16) of leaf, which decreases the need for leaf support, reduces organism colonization (17), and facilitates transpiration (21). The underlying mechanism of apex morphology and structure in determining the drainage efficiency, therefore, is needed to be demonstrated.

Fig. 1 reveals the water drainage ability of the above three apex shapes. The water weight per square centimeter, \( \omega \), on three selected leaf surfaces with rounded, acuminate, and drip tip was measured in real time by microbalance under a constant leaf inclination angle (the angle between the leaf surface and the vertical), \( \beta \), of 30° and the same heavy mist of 90% relative humidity. The average values of the threshold droplet weight, \( \omega_{\text{threshold}} \), and water retention weight, \( \omega_{\text{Retention}} \), for different leaf apices are shown on the right side. Notably, the drip tip of A. macrorrhiza performs excellent water drainage with dripping frequency, dripping volume, and water retention values \( \sim 1.8 \), \( \sim 1/6 \), and \( \sim 1/10 \) than those of R. pseudoacacia with rounded leaf apex, respectively.

**Shortened Drainage Time of an Inclined Artificial Triangular Apex.** To determine the underlying drainage mechanism, we create artificial leaf apices that are simplified into three geometrical models, including circle, triangle, and pendulous triangle (curved acuminate) models, through 3D printing (22) and laser-cutting techniques (SI Appendix, Table S4). X-radiation and high-speed cameras are used to record the profile of dripping droplets at the leaf apices. We investigate the effect of apex angle and apex shape on drainage based on the 2D and 3D leaf morphologies. Apices changing from the circular, elliptical, large triangle, to small triangle, have shown different drainage ability with distinct threshold drop volume, \( \Omega_{\text{c}} \), and drainage time, \( \tau_{\text{d}} \). The smallest triangular apex (\( \alpha = 30° \)) has the lowest threshold drop volume \( \Omega_{\text{c}} \) compared to those of R. pseudoacacia and A. macrorrhiza with rounded leaf apex.

**Fig. 1.** Water drainage on leaves with different leaf apices. (A) The statistical plot of the leaf apex angles, \( \alpha \), among different species of leaves in alphabetical order. According to the leaf apex angle, leaf apex can be classified into obtuse and acute. SI Appendix, Table S1 shows 44 species and 36 families of these leaves in alphabetical order. (B–I) Four representative leaves have various apex shapes: rounded (B), acuminate (C and D), and drip tip (E). Moreover, the corresponding optical images of the magnified apices are shown as round (F), elliptical (G), triangular (H), and triangular with curvature transition (I), respectively. (J) Water weight per area, \( \omega \), for various shapes of leaf apices versus time under a heavy mist of 90% relative humidity (Left) and the corresponding average threshold droplet weight, \( \omega_{\text{threshold}} \), and water-retention weight, \( \omega_{\text{Retention}} \) (Right). The measurement tests are conducted in the same leaf apex area of 2.0 cm² and the same inclination angle with \( \beta = 30° \). The drip tip has a high dripping frequency, low threshold droplet weight, and low water retention. (Scale bar, 1 mm.)

**Fig. 2.** Sharp triangular apex shortens threshold drainage time under a steep inclination. (A–D) Profiles of water droplets in the threshold state at various apex margins from the top view, round \( \alpha = 180° \) (A), ellipse (B), large triangle \( \alpha = 90° \) (C), and small triangle \( \alpha = 30° \) (D). (E–G) Mechanism of water drainage around a sharp apex in a quasistatic state. An accumulating droplet is pinned by the TCL, as marked with a red dashed line. The drop contact width, \( W \), changes from threshold state ① to state ④ under the balance between the front resistance force of capillarity and the driving force of the gravity component. The front resistance force decreases with contact drop width, \( W \), and apex angle \( \alpha \). (H) Threshold drainage time, \( \tau_{\text{d}} \), decreases with the apex angle, \( \alpha \), and inclination angle, \( \beta \). A sharp triangular apex shortens the \( \tau_{\text{d}} \) value of the accumulating droplet to only 1/4 of that for a circular apex. (Scale bar, 2 mm.)
to other shapes of apex models under the same inclination angle \((\beta = 30^\circ)\) (Fig. 2 A–D).

In the experiment, water continuously accumulated on the surface of the leaf apex at a speed of 1.0 mL/min and shed off at the apex. The shedding of a sessile drop starts on an inclined surface with a tilt angle of \(\beta\), when the gravitational force component \(\gamma g \cos \beta\) is greater than the capillary force of the droplet at the front of apex – \(\gamma W \cos \theta\) (23–25), where \(\rho\) is the liquid density, \(\gamma\) is gravity, \(\Omega\) is the droplet volume, \(\gamma\) is the liquid surface tension, \(\theta\) is the apparent contact angle, and \(W\) is the contact width of the drop at the front of apex, respectively (Fig. 2 E–G and SI Appendix, Fig. S2A–C). A critical depinning drop with a threshold drop volume \(\Omega_t\) and a threshold contact width \(W_c\) exists such that \(W_c/\Omega_t \propto \cos \beta / (\cos \theta)^{0.5}\), where \(\cos \theta = (\gamma/g)^{0.5}\) is the capillary length. Hence, for a surface with a constant contact angle and inclination angle, a critical shedding droplet has a threshold drop contact width of \(W_c\) and a threshold volume \(\Omega_t\). \(\Omega_t\) is proportional to \(W_c\). As \(\alpha\) has a positive relationship with \(W_c\), \(\alpha\) has a positive relationship with \(\Omega_t\). Besides, a steeply inclined leaf surface with a small \(\beta\) increases the component of gravity, which induces a low threshold drop volume \(\Omega_t\). Therefore, a leaf with a triangular apex under specific inclined orientation provides a practical design for reducing the threshold drop volume.

The threshold droplet drainage time, \(\tau_{th}\), is proportional to the threshold drop volume \(\Omega_t\) and inversely proportional to the dripping frequency. For a dripping droplet with constant flow velocity and a sharp apex angle, a small \(\Omega_t\) reflects a reduced threshold dripping time \(\tau_{th}\). Then, we investigate the effect of the apex angle on water drainage time under the inclination angle of the leaf surface between \(0^\circ\) and \(85^\circ\) at a velocity of 1.0 mL/min (Fig. 2H). Through mimicking the apex structures of natural leaves, we design two-dimension artificial 3D printing leaf apices with apex angles in a range between \(0^\circ\) and \(180^\circ\). \(\tau_{th}\) decreases with \(\alpha\) around the apex under the same inclination angle. For instance, the \(\tau_{th}\) value of a flat circular apex is 53.52 ± 1.52 s when \(\beta\) equals \(80^\circ\), whereas the \(\tau_{th}\) value of a flat triangular apex (FTA, \(\alpha = 30^\circ\)) is only 13.86 ± 0.33 s under the same \(\beta\). A nearly 75% reduction occurs when the leaf apex changes from circular to acute. Besides, a small \(\alpha\) leads to a low apex sticking force and little water retention, thus enhancing the drainage efficiency (SI Appendix, Fig. S3). A narrow acute apex or a steeply inclined orientation leads to a small threshold drop volume and a short dripping time. Notably, more than 80% of the leaves in Fig. 2H have triangular apices.

**Reduced Water Drainage Retention on Pendulous Triangular Grooved Apices.** Based on the analysis in Fig. 2H, a steeply inclined triangular leaf apex is the best state for drainage. However, the natural leaves give another answer. We observe and record the inclination angles of four species of leaves, Alocasia macrorrhiza (Lour.) Scott, M. denudate desr., Sophora japonica Linn., and Comus controversa at different times of the day under sunshine and rainfall, respectively (SI Appendix, Fig. S4). The leaves of subtropical zone possess a relatively large inclination angle, \(\beta\), in a range of \(50^\circ–70^\circ\) under sunshine for better photosynthesis and a relatively small inclination angle, \(\beta\), in a range of \(20^\circ–40^\circ\) for better drainage and avoiding damage (26, 27). In the rainforest with frequent heavy rainfall, the leaf of A. locuasia macrorrhiza (Lour.) tilts a large \(\beta\) in the base to guarantee maximum sunlight exposure, and a small \(\beta\) in the apex to satisfy the need for fast drainage (28, 29). The leaf surface curves from a 2D shape to a 3D shape (the pendulous shape) at the leaf apex, which could impose an instability force on the threshold droplet.

The artificial leaf apex model is designed to be a version of the pendulous triangular shape or pendulous grooved triangular shape (Fig. 3). Threshold droplets form a stable triple contact line (TCL) at a given threshold drop contact width \(W\) on a flat triangular apex (FTA) (Fig. 3A). When the bending position of the pendulous triangular apex (PTA) is located at the threshold contact line, the drop remains stable (Fig. 3B). If the bending position is located above the threshold contact line, the droplet would experience a sudden instability induced by the increased gravitational force component and decreased resistant capillarity at the bending point. The reconstructed balance forces the water droplet to drip off with a smaller volume than for other flat apex shapes (Fig. 3C and SI Appendix, Fig. S2E).

In addition to a lower threshold dripping volume, the PTA also reduces water retention on the leaf surface compared with flat triangular apex. The water retention on the surface per square meter, \(w_{Re}\), at flat triangular apex and PTA were measured under the same apex angle range and the inclination angle range \((15^\circ < \alpha < 180^\circ, 30^\circ < \beta < 60^\circ)\) at a water injection velocity of 1.0 mL/min (Fig. 3D). The \(w_{Re}\) on a pendulous circular apex \((\alpha = 180^\circ, \beta_1 = 60^\circ, \beta_2 = 0^\circ)\) is only 3/5 of that on a flat circular apex \((\alpha = 180^\circ, \beta = 60^\circ)\). A PTA \((\alpha = 15^\circ, \beta_1 = 60^\circ, \beta_2 = 0^\circ)\) further reduces \(w_{Re}\) to 1/21 of that on the flat circular apex \((\alpha = 180^\circ, \beta = 60^\circ)\).

The use of PTA in design was common in Eastern Asia ancient architectures, including tile art, especially for the drip tiles on the edges of eaves (30, 31). Drip tile shows a similar function with the pendulous triangular leaf apex. The upper surface of the drip tile possesses a slight inclination of the tile surface in base with a large \(\beta_1\) to converge and transport water. The downward triangular apex possesses a steep inclination with a small \(\beta_2\) to achieve a fast rainwater runoff, decrease the requirements for roof support, and reduce the erosion of the architecture base (Fig. 3E).

Significantly, leaf veins in plants form the gradient of groove, further promoting water shedding under capillary force (32, 33). The large gradient of the groove reduces the threshold drainage time (Fig. 3F). The gradient of the conical groove is controlled by the ratio of the large side of radius \(R\) and a small side of radius \(r (r = 5 \text{ mm})\), the radius ratio \((R/r)\) of which changes from 1 to 4 (SI Appendix, Fig. S5A). We design the PTA with a groove structure by folding along the artificial apex axis with a folding
Gaussian curvature inversion at the drip tip promotes threshold droplet shedding. (A) The integration of the drainage structure of the pendulous grooved triangular apex and the spatial curvature inversion at the drip-tip apex of the rainforest leaf A. macrorhiza. (C) The drip-tip apex with curvature inversion at the outlet of the groove structure promotes the detachment of the threshold droplet. (B and D) Magnified scanning electron microscope (SEM) images of the structure of the drip-tip apex from the front and top views. The surface of drip tip changes from the concave shape to the convex shape along the groove outlet at the apex. (E and F) X-ray slices of the structure of the drip tip from the cross-sectional view. A Gaussian curvature transition from negative of the concave shape to the positive of the convex shape occurs. (G) Force mapping of the threshold droplet under curvature inversion at the outlet of the groove. Minimum resistance of the threshold droplet with a characteristic length of W at the concave-convex curvatures transition point. (H and I) Threshold droplet detaches at the outlet of the groove with a separation point at concave-convex curvatures inversion point from top and side views under pressure-driven process. (Scale bar, 300 μm.)

Fig. 4. Gaussian curvature inversion at the drip tip promotes threshold droplet shedding. (A) The integration of the drainage structure of the pendulous grooved triangular apex and the spatial curvature inversion at the drip-tip apex of the rainforest leaf A. macrorhiza. (C) The drip-tip apex with curvature inversion at the outlet of the groove structure promotes the detachment of the threshold droplet. (B and D) Magnified scanning electron microscope (SEM) images of the structure of the drip-tip apex from the front and top views. The surface of drip tip changes from the concave shape to the convex shape along the groove outlet at the apex. (E and F) X-ray slices of the structure of the drip tip from the cross-sectional view. A Gaussian curvature transition from negative of the concave shape to the positive of the convex shape occurs. (G) Force mapping of the threshold droplet under curvature inversion at the outlet of the groove. Minimum resistance of the threshold droplet with a characteristic length of W at the concave-convex curvatures transition point. (H and I) Threshold droplet detaches at the outlet of the groove with a separation point at concave-convex curvatures inversion point from top and side views under pressure-driven process. (Scale bar, 300 μm.)

Gaussian Curvature Inversion at the Drip-Tip Apex Promotes Threshold Droplet Shedding. The leaf drip tip of A. macrorhiza in rainforest areas has a long and curvy acuminate apex with a PTGA structure (Fig. 4A). Water drains at the leaf drip tip and detaches at the groove outlet (Fig. 4C). Detailed observations of the drip tip apex are shown in Fig. 4 B and D–F and Movie S1. For the drip tip of A. macrorhiza, the microchannel curves outward in a concave open state, and the end of the apex curves inward in a convex closed state (Fig. 4B). At the closing outlet of the groove, the concave groove transforms into a convex apex from the front and top view (Fig. 4 B and D), with the curvature changing from negative to positive along with the groove outlet angle of 120° (SI Appendix, Fig. S5B). Pendulous triangular grooved apex (PTGA) can significantly increase the drainage efficiency by reducing water retention and decreasing threshold drainage time. The pendulous triangular grooved apex (α = 15°, β0 = 60°, β1 = 0°) reduces the water retention, W20, to 0.250 ± 0.100 kg/m2, and with only 4% the retention of the flat circular apex (Fig. 3G). Therefore, the PTGA improves drainage efficiency by reducing water retention and threshold drainage time. The understanding of this drainage mechanism from leaf apex and architecture drip tile can be used to design drainage facilities and solve problems in printing and open-air fluidic systems (34–36) that are currently faced.

As water drains along the surface of the drip tip, the gradually closing groove with outward concave shape forces water to the distal end of the apex (blue arrow in Fig. 4G). The structure transition from the concave surface to the convex surface at the outlet of the groove rapidly reverses its curvature, resulting in the entrapment of an air wedge with a minimum drop contact width W (Fig. 4G). The reduced air–water–solid contact line promotes droplet shedding (SI Appendix, Fig. S2F). Besides, local pressure caused by surface curvature makes a difference in water shedding from the cross-sectional view (Fig. 4H). The upward pressure difference drives water from the neck to the upper site, ΔPupper = P2 − P1 = γ (1/R2 − 1/R1), and the downward pressure difference drives water from the neck to the lower site, ΔPdown = P1 − P3 = γ (1/R3 − 1/R1), where P1 is the local pressure, R1 is the local radius of the droplet perpendicular to the plane. Gaussian curvature transition changes from negative at the concave groove to positive at the convex apex along the drip tip. The inversion of Gaussian curvature at the drip tip leads to the reverse of the Laplace pressure direction, promoting the necking, separation, and shedding of threshold droplets at the curvature transition point (Fig. 4 F–I). Significantly, the inversion of Gaussian curvature results in the local pressure difference (or the inversion of Laplace pressure difference) and droplet necking and detaching off, which is different from the liquid spontaneously breaking up into droplets. These two processes are similar in the result but different in origin.

Fast Water Drainage of the Bioinspired Drip-Tip Apex. X-ray scan can measure the drip-tip apex morphologies in detail and reconstruct the drip-tip morphologies for the biomimetic 3D printed model (Fig. 5A and SI Appendix, Fig. S3C). Considering the curvature from the radial cross-sectional view (Fig. 4E). The curve outline of the drip tip shows a positive curvature from the axial cross-sectional view (Fig. 4F). The Gaussian curvature along with drip tip changes from negative to positive correspondingly (SI Appendix, Fig. S6).

Fig. 5. Fast water drainage efficiency of the bioinspired drip tip. (A) Illustration of bioinspired drip-tip model. (B) Fast water drainage at the artificial tip with curvature transition from concave shape to convex shape. Tip with curvature transition performs better droplet shedding than the tip with one curvature, with a fixed separation point and a nearly ~56% reduction of the drainage time under an injection liquid speed of 1200 mL/h. (C) Water weight per area, w, of artificial leaf apices versus time under a heavy mist of approximately ~90% relative humidity (Left) and the corresponding average threshold droplet weight and water-retention weight (Right). The bioinspired drip-tip apex (BDTA) yields a high dripping frequency, small dripping volume, and low water retention. LTA, large triangular apex; STA, small triangular apex. (Scale bar, 3 mm.)
inversion from concave shape to convex shape is the unique part of the drip tip, we demonstrate the effect of the curvature in inversion structure on enhancing water drainage by a control experiment (Fig. 5B). Comparing the leaf tip with only one convex curvature, the artificial tip with concave–convex curvatures can reduce nearly 56% of the drainage time. Besides, the lower the convex shape of the drip tip than the concave shape can enhance the water drainage with a much shorter drainage time (SI Appendix, Fig. S7).

To better evaluate the drainage performance, we compare the drainage efficiency of the bioinspired drip tip and other artificial tips (Fig. 5C). The experiment was performed under a heavy mist of ~90% relative humidity and a large inclination angle β = 30° to mimic the real-leaf apex dripping process. The sample surface has the same area of 2.0 cm². The water weight per square centimeter, ω, of the PTGA reflects excellent drainage ability, with a dripping frequency that is ~6 times greater than that for a large triangular apex and water retention that is ~1/4 that for a large triangular apex. The bioinspired drip tip apex (BDTA) performs even better on drainage, with a dripping frequency ~12 times greater than that for a large triangular apex and with water retention ~1/6 than that for a large triangular apex. The average values of the threshold droplet weight and water retention weight for different artificial leaf apices are shown in Fig. 5 C, Right. The bioinspired drip tip apex has the least amount of accumulated water at the leaf apex over the longest time, which shows the best drainage efficiency among all of the artificial apices studied. Following the movement of the raindrops at plant leaves, the special posture and unique structure of the leaf apex inspire us to perform biomimetic researches that optimize artificial leaf apex structures with superior drainage abilities.

Conclusions

Water drainage is enhanced by the apex under the instability force. The enhanced instability is caused by the reduced capillary resistance of droplet at acuminated apex shape and the increased gravity component of a droplet under steep apex orientation.

The multiple steric curvature structures and efficient drainage modes of leaf apices can be studied to understand the roles of “tiny” structures in plant survival control and provide inspiration for upgrading the drainage facilities and anticorrosion corrosion. Such information may offer insights into the field of water collection with rapid water shedding or transport. Moreover, a different perspective for solving scientific and technological problems, such as those related to printing and liquid fluidic applications, may be developed to achieve high-speed spatial water delivery. Besides, the relevant results can be used to developing cutting-edge commercial drop and fiber fabrication processes, such as fog/drain nano/microdroplet fabrication via spraying and fiber construction via electrosprining.

Materials and Methods

Different species of plant leaves were collected from the subtropical zone of Beijing and the tropical zone of Guangzhou. The leaf surfaces were cleaned by water and 50% ethanol concentration in sequences and dried by N2 (SI Appendix, Fig. 5B). Flat artificial apices and bioinspired drip tip were made by a 3D printer (formlabs 2), and the artificial PTA and PTGA were made by laser cutting (LSC30 CO2 laser). Fog-shedding experiment was conducted under the dense fog mist with ~90% relative humidity, and water weight was measured on the microbalance in real time. The selected surface area of the artificial leaf apex is 2 cm². The water-shedding experiment was captured by a high-speed camera (SPEED-3, Olympus). Water flowed from a nozzle perpendicular to the leaf surface at a constant injection speed. The water-flow velocity was controlled by a microinjection gear pump (Harvard). The effect of incoming drop on the dripping drop at the drip-tip leaf (SI Appendix, Fig. S9) and the influence of leaf wettability (37, 38) on drainage at the apex (SI Appendix, Table S3 and Fig. S10) were illustrated. Other detailed experimental procedures are illustrated in SI Appendix, SI Materials and Methods.

Data Availability Statement. All data discussed in the paper is available within the SI Appendix and Dataset S1.

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