Electronic Supplementary Material (ESI) for Materials Horizons.

Electronic Supplementary Information

Interfacial Floating Tumbler with Penetrable Structure and Janus Wettability Inspired by Pistia stratiotes

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Experimental section:

Materials and Characterization:

Commercial melamine sponge (150 mm × 50 mm × 20 mm). Degussa hydrophobic silica (R-972) was purchased from Evonic Co. Ltd. Sygard 184 polydimethylsiloxane (PDMS) was purchased from the Dow Co. Ltd. Hexane, glucose and other chemicals are purchased from Tianjin Yuanli Chemical Co. Ltd. and used without further treatment.

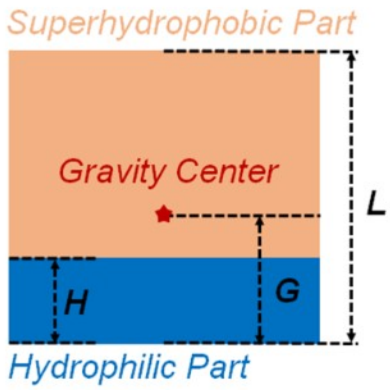
The Scanning Electron Microscope (Apreo S LoVac, FEI Co. Ltd., America) was used to observe the surface morphology of the sponge structures of floaters. The water contact angles of surfaces were measured by a SDC-200 geometer (SFMIT Co., China) with a 4 µL droplet. The movements of sponge floating processes and water penetration were recorded by Huawei ANA-AN00.

Preparation of Pistia-inspired Janus interfacial floater (PIJIF):

To produce superhydrophobic coating solution, PDMS pre-polymer with 10% w/w curing agent was mixed with r-972 in n-hexane with a concentration of 25 mg/ml and 50 mg/ml, respectively. The melamine sponge was cut into 20 mm × 20 mm × 10 mm cube, and rinsed in ethanol with ultrasonic cleaner for 15 min and then dried in the oven for standby. The glucose was mixed with equal amount of water and heated to 60^{o}C, and the viscous glucose solution was used as template to tailor the wettability of sponge. After the glucose layer is cooled and solidified, the patterned sponge was immersed in superhydrophobic solution for one hour. Then the hexane in the sponge was evaporated at ambient temperature, and the sponge was finally solidified at 80°C for 3 h. At last, the glucose template on the sponge was dissolved into enough quantity of water at room temperature for one hour.

The measurement method and the analysis of gravity center of PIJIF:

We assume that the reason why Janus sponge has floating stability is that its center of gravity is lower than that of ordinary superhydrophobic sponge. Therefore, we measured the center of gravity of sponges with different hydrophilic heights to verify our hypothesis. We theoretically analyze the center of gravity of each sponge to compare with the actual sponge center of gravity to verify our hypothesis. Because of the hydrophilic layer of Janus sponge might not be completely uniform, the actual thickness of hydrophilic layer (H) is difficult to accurately measure by the apparent thickness of hydrophilic layer. Therefore, the thickness of hydrophilic layer was set as an unknown factor during the calculation. In order to simplify the model, we only consider the height of gravity center of sponge (G), and use the total mass of Janus sponge (m) to calculate the position of gravity center in vertical direction.



The density of hydrophilic layer (ρ_w) can be measured by ordinary sponge after being wetted, and the density of hydrophobic layer (ρ_{SHPS}) can be directly measured of superhydrophobic sponge. It is assumed that the average height of hydrophilic layer is h, the bottom area of sponge is S= 4 cm^2, and the total height of sponge is L = 2 cm. The mass m of Janus sponge is the sum of the mass of hydrophilic layer and hydrophobic layer.

$$m = \rho_W HS + \rho_{SHPS}(L - H)S$$

According to the equation X, we can calculate actual thickness of hydrophilic layer as follows.

$$H = \frac{\frac{m}{S} - \rho_{SHPS}L}{\rho_W - \rho_{SHPS}}$$

If the center of gravity is assumed to be located at the hydrophobic layer, as shown in the figure, the moment formula for reaching the equilibrium is showed.

$$\rho_{SHPS}(L-G)S\frac{(L-G)}{2}=\rho_{SHPS}(G-H)S\frac{(G-H)}{2}+\rho_W HS\left(G-\frac{1}{2}H\right)$$

The relationship between center of gravity and mass is obtained by combining the above two formulas.

$$G=\frac{\left(\frac{m}{S}-L\rho_{SHPS}\right)^2+\rho_{SHPS}L^2(\rho_W-\rho_{SHPS})}{2\left(\frac{m}{S}-\rho_S L\right)(\rho_W-\rho_{SHPS})+2\rho_{SHPS}L(\rho_W-\rho_{SHPS})}$$

In contrast, when the center of gravity is in the hydrophilic layer, the expression of the center of gravity remains unchanged, and the lowest value of the center of gravity is at the junction of the hydrophilic layer and the hydrophobic layer.

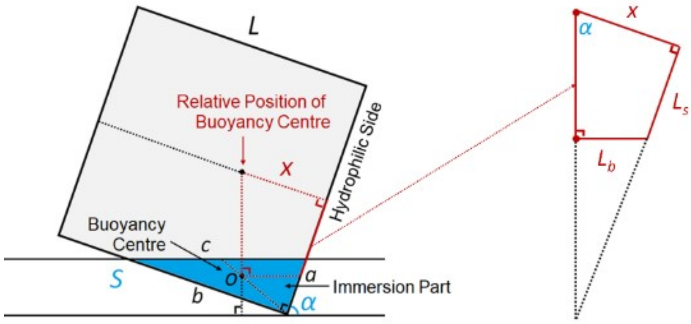
The measured density of wetted sponge (ρ_W) is 0.999 g/cm^3, and the density of superhydrophobic sponge (ρ_{SHPS}) is about 0.083 g/cm^3. Therefore, when S= 4 cm^2 and L = 2 cm, we can obtain the following results:

$$G=\frac{\left(\frac{m}{4}-0.165\right)^2+0.303}{1.834\left(\frac{m}{4}-0.165\right)+0.303}cm$$

It can be calculated that the lowest center of gravity is 0.447 cm, i.e., the position value G/L is 22.35%. Compared with the theoretical value, the experimental value is basically consistent with the theoretical value. In the article, we have showed the data by using the percentage of the relative position. Therefore, the position of gravity center is noted as G/L, and the thickness of hydrophilic layer is denoted as H/L. The G/L is plotted as a function of H/L in Figure 3a.

The calculation of buoyancy center of PIJIF during rotation:

As an example, the buoyancy centre of the cubic PIJIF can be calculated according to the geometric analysis. The parameters of PIJIF are showed in the following figure.



Considering the projected area of immersion part of PIJIF (S_i) and length of cubic PIJIF (L) as constant, and the inclined angle (α) as variable. The side lengths of the immersed triangle are showed.

$$a = \sqrt{\frac{2S_i}{\tan \alpha}}$$

$$b = \sqrt{2S_i \tan \alpha}$$

$$c = \sqrt{\frac{2S_i}{\sin \alpha \cos \alpha}}$$

The buoyancy centre is located at the barycentre of the immersed triangle (*o*), and the relative position of buoyancy centre is the vertical point of intersection with the axis of symmetry of PIJIF. Therefore, considering the quadrilateral including relative position of buoyancy centre, the relatively position of buoyancy centre (*B*) can be calculated.

$$L_b = \frac{c}{3} = \frac{1}{3}\sqrt{\frac{2S_i}{\sin \alpha \cos \alpha}}$$

$$L_s = \frac{L}{2} - \frac{2a}{3} = \frac{L}{2} - \frac{2}{3}\sqrt{\frac{2S_i}{\tan \alpha}}$$

$$B = \frac{L_s + L_b/\cos \alpha}{\cos \alpha} = \frac{\frac{L}{2} - \frac{2}{3}\sqrt{\frac{2S_i \cos \alpha}{\sin \alpha}} + \frac{1}{3}\sqrt{\frac{2S_i}{\sin \alpha (\cos \alpha)^3}}}{\frac{\sin \alpha}{\cos \alpha}}$$

The *B* is varying with the inclined angle of PIJIF during rotation. To achieve a self-regulated rotation of PIJIF, the height of gravity centre should be lower than that of minimal buoyancy centre during rotation.

The COSMOL Multiphysics simulation of floating process:

We used Phase Field Method in COMSOL Multiphysics to stimulate floating process of Janus sponge released in water. The software uses following equations to calculate the processes.

In the Phase Field interface the two-phase flow dynamics is governed by a Cahn-Hilliard equation. The equation tracks a diffuse interface separating the immiscible phases. The diffuse interface is defined as the region where the dimensionless phase field variable ϕ goes from -1 to 1. When solved in COMSOL. Multiphysics, the Cahn-Hilliard equation is split up into two equations

$$\frac{\partial \phi}{\partial t} + u \cdot \nabla \phi = \nabla \cdot \frac{\gamma \lambda}{\varepsilon^2} \nabla \Psi$$

$$\Psi = - \nabla \cdot \varepsilon^2 \nabla \phi + (\phi^2 - 1)\phi$$

where $\boldsymbol{u}$ is the fluid velocity (m/s), γ is the mobility $m^3 \cdot s/kg$, λ is the mixing energy density (N) and ε is the interface thickness parameter. The Ψ variable is referred to as the phase field help variable. The following equation relates the mixing energy density and the interface thickness to the surface tension coefficient:

$$\sigma = \frac{2\sqrt{2}\lambda}{3 \ \ \varepsilon}$$

We set interface thickness parameter (ε) as 1.08 [mm] to fit the size of grid. In the Phase Field interface, the volume fraction of the individual fluids is

$$V_{f1} = \frac{1 - \phi}{2}, \quad V_{f2} = \frac{1 + \phi}{2}$$

In the present model air is defined as Fluid 1 and water as Fluid 2. The Multiphysics coupling feature defines the density (kg/m^3) and the viscosity (Pa·s). The mixture is varying smoothly over the interface by defining as follows.

$$\rho = \rho_w + (\rho_{air} - \rho_w)V_{f1}$$

$$\mu = \mu_w + (\mu_{air} - \mu_w)V_{fi}$$

where the single phase water properties are denoted w and the air properties air.

The Navier-Stoke equations describe the transport of mass and momentum for fluids of constant density. In order to account foe capillary effects, it is crucial to include surface tension in the model. The Navier-Stokes equations are then

$$\rho\frac{\partial u}{\partial t}+\rho(u\cdot\nabla)u=\nabla\cdot\left[-pI+\mu\left(\nabla u+(\nabla u)^T\right)\right]+F_{st}+\rho g$$

$$\nabla\cdot u=0$$

Here, ρ denotes the density (kg/m^3), μ equals the dynamic viscosity ($N{\cdot}s/m^2$), **u** represents the velocity (m/s), *p* denotes the pressure (Pa), and **g** is the gravity vector (m/s^2). $\mathbf{F}_{st}$ is the surface force acting at the air/water interface.

In the Phase Field Interface, the diffuse interface representation makes it possible to compute the surface tension by

$$F_{st}=G\nabla\phi$$

where φ is the phase field parameter, and *G* is the chemical potential (J/m^3).

$$G=\lambda\left[-\nabla^2\phi+\frac{\phi(\phi^2-1)}{\varepsilon^2}\right]=\frac{\lambda}{\varepsilon^2}\Psi$$

As seen above, the phase field surface tension is computed as a distributed force over the interface using only *Ψ* and the gradient of the phase field variable. This computation avoids using the surface normal and the surface curvature, which are troublesome to represent numerically.

The acceleration that resulted from buoyant force of Janus sponge is defined as $a_f=-g$.

Supplementary Figures:

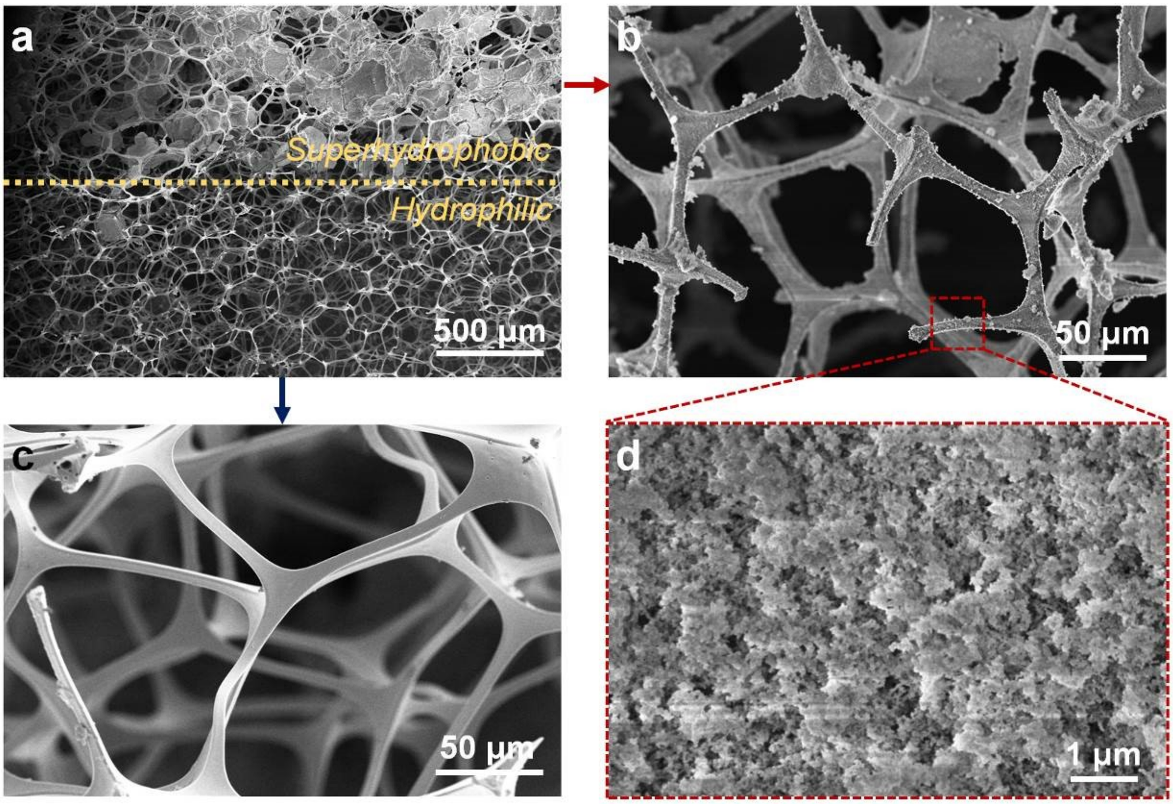


Figure S1. The images of scanning electronic microscope of Pistia-inspired Janus interfacial floater (PIJIF). (a) The wettability boundary between the superhydrophobic and hydrophilic parts. (b) Superhydrophobic porous structure. (c) Pristine hydrophilic porous structure. (d) The micro-structure of silica/silicone coating that is deposited on superhydrophobic structure.

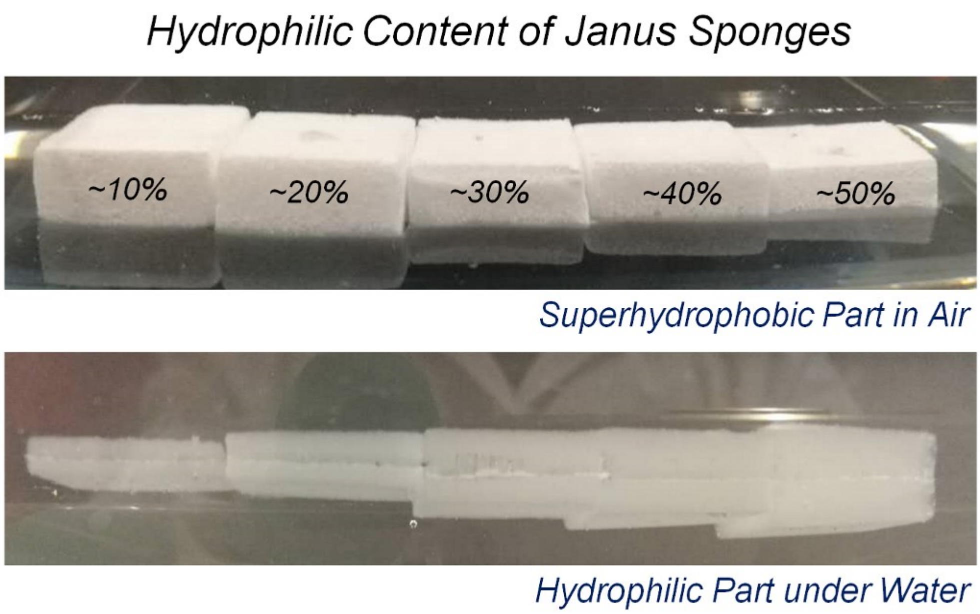


Figure S2. The controllable floating position of PIJIF. The on-water and in-water ratio can be easily tuned by the hydrophilic contents.

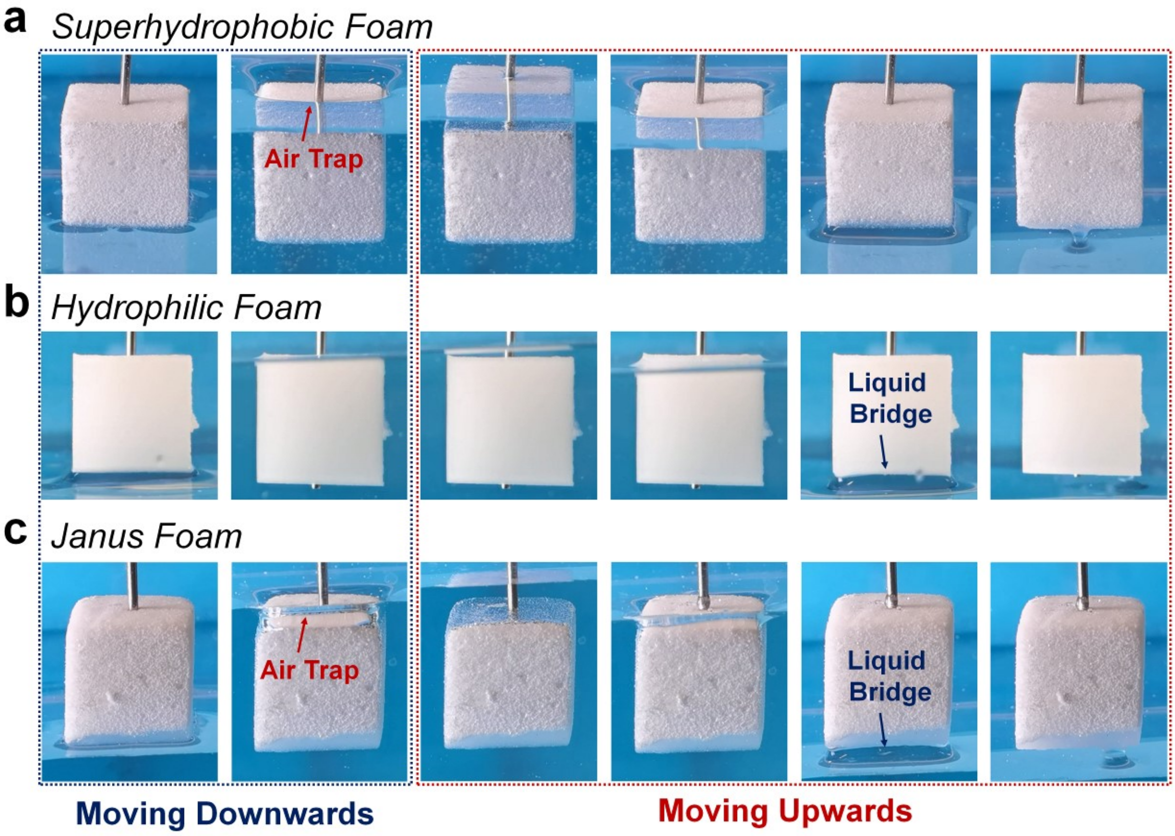


Figure S3. The interacting process between the samples and the water surface. (a) Superhydrophobic sponge, (b) hydrophilic sponge, and (c) Janus sponge. The corresponding air trap and liquid bridge can be clearly observed.

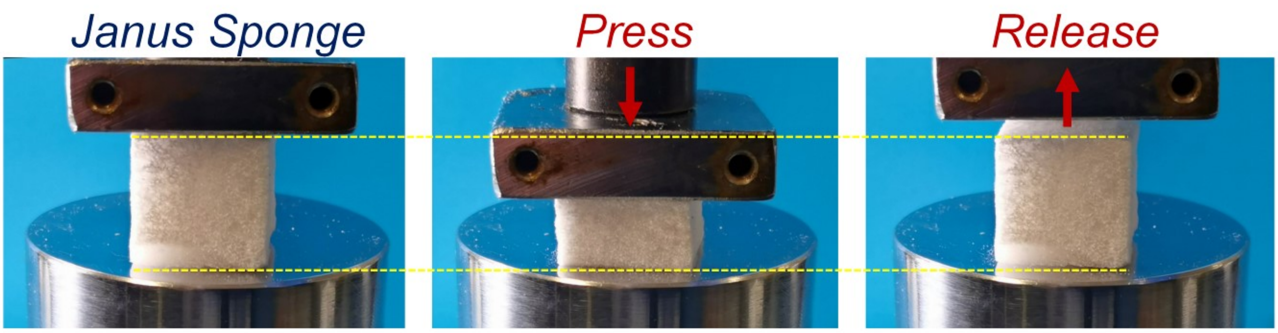


Figure S4. The compressibility of PIJIF is attributed to the open porous structure of sponge.

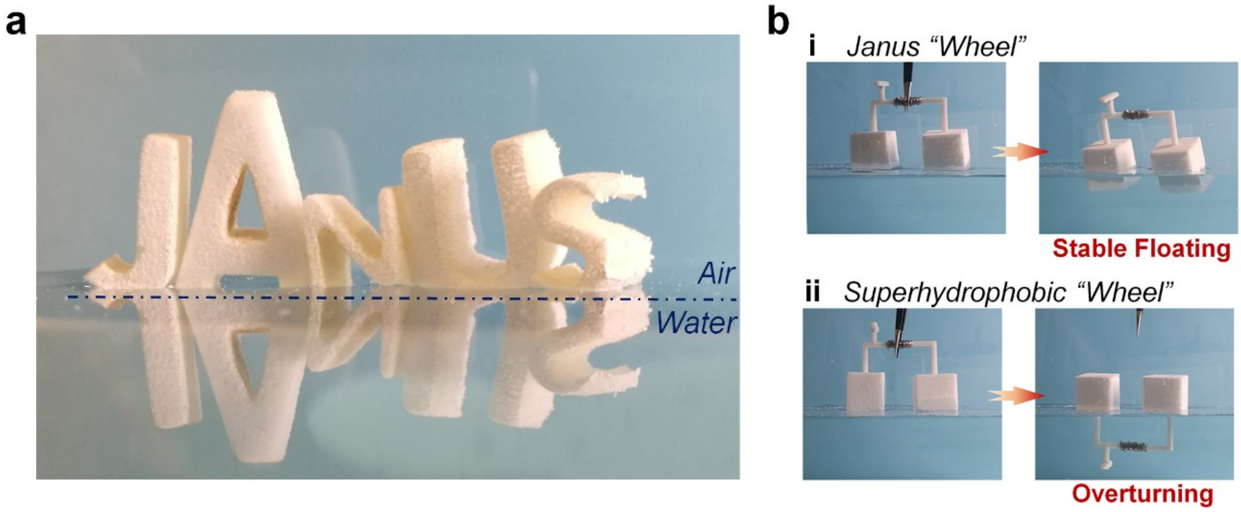


Figure S5. The PIJIF with complicated and integrated structure. (a) The letter "Janus" was floating on water surface based on the logic of PIJIF. (b) The mini-bicycle with (i) Janus wheel shows a better interfacial stability as compared with that with (ii) superhydrophobic wheel.

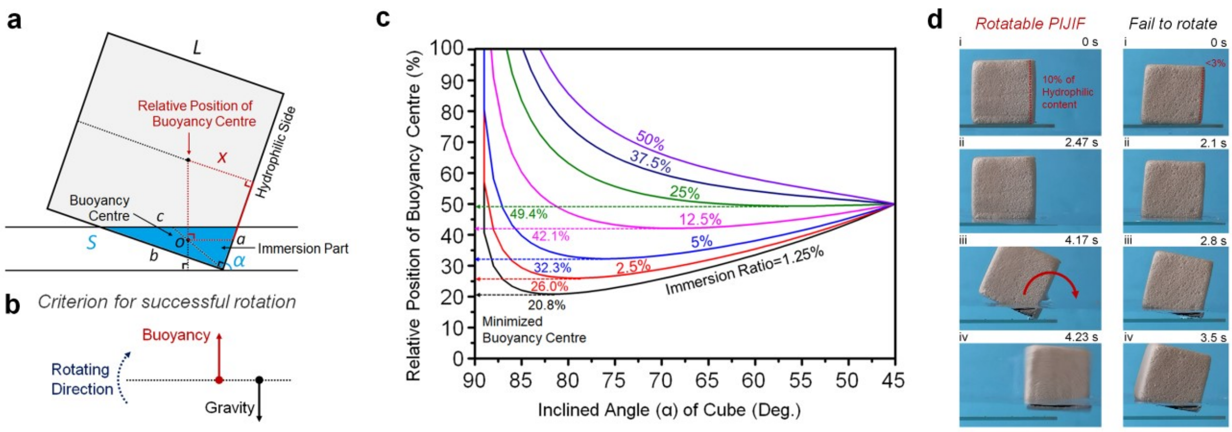


Figure S6. The analysis of the availability of self-regulated rotation of cubic PIJIF in a quasi-static condition. (a) The geometry analysis of cubic PIJIF and the parameters of calculation. The right side of cube is defined as hydrophilic side, and the rotation direction is from left to right. (b) The criterion of the successful rotation is depended on the suitable positions of buoyancy centre and gravity centre which can generate sufficient torque. (c) The simulation of the relative position of buoyancy centre as a function of inclined angle of cubic PIJIF. The different immersion ratios were considered. (d) The availability of the self-regulated rotation of PIJIF. With an ultralow hydrophilic content, the PIJIF fails to rotate due to the mismatch of buoyancy centre and gravity centre.

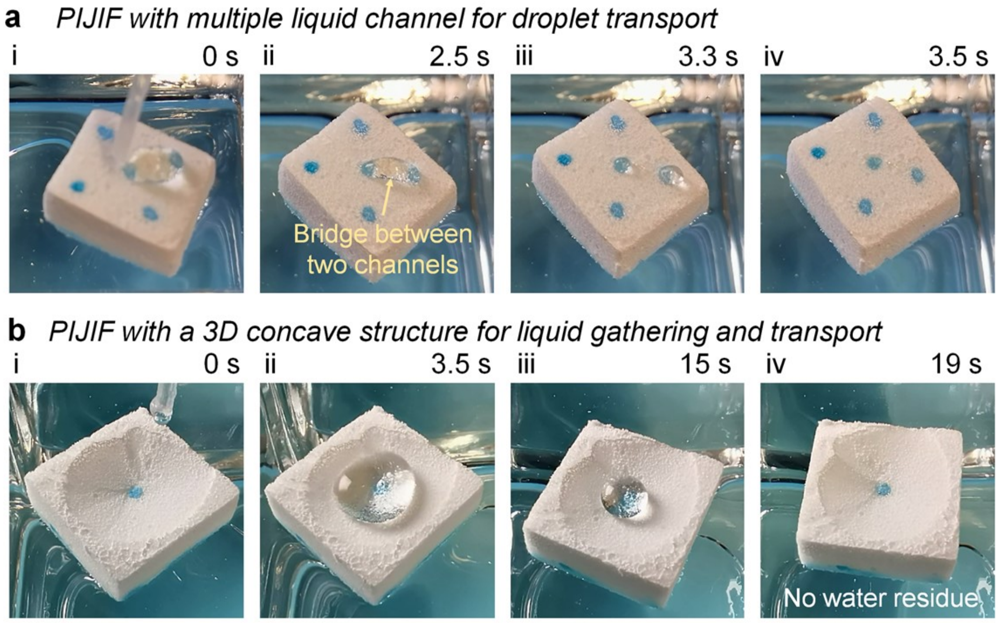


Figure S7. (a) PIJIF with multiple liquid channel for droplet transport can be facilely achieved via the glucose template. (b) The 3D concave shape of upper surface of PIJIF can realize a liquid gathering process for complete liquid drainage.

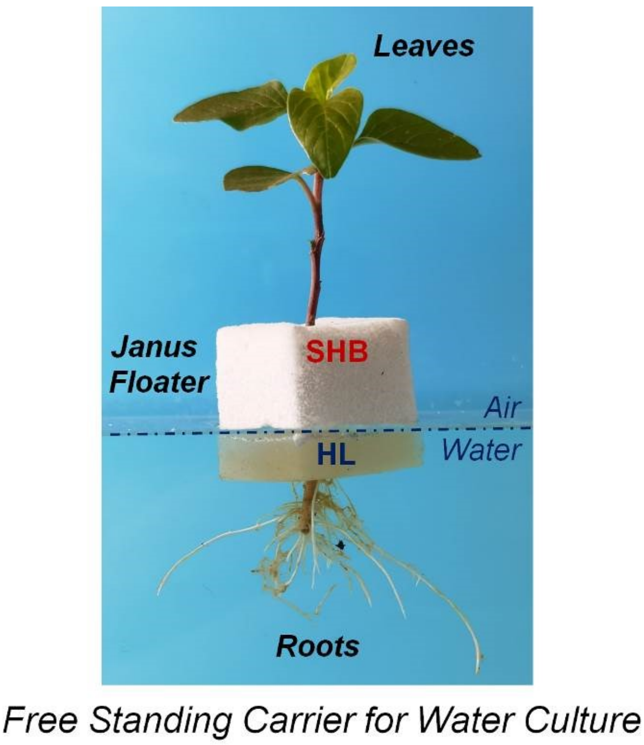


Figure S8. The illustration of applying PIJIF in hydroponics. The plant can be inserted into PIJIF and then freely float on water surface.

Supplementary Movie:

Movie S1. The self-regulated floating process of *Pistia stratiotes*

Movie S2. The rapid water drainage from the center of *Pistia stratiotes*

Movie S3. The stability of PIJIF on water under shaking (2x speed)

Movie S4. The stability of superhydrophobic floater on water under shaking (2x speed)

Movie S5. The self-regulated floating process of PIJIF (0.125 x speed)

Movie S6. The COMSOL Multiphysics simulation of the floating process of PIJIF in different initial states

Movie S7. The directional water penetration through the channel of PIJIF

Movie S8. The effective water drainage of PIJIF on water surface

Movie S9. The PIJIF based micro-light-buoy for on-water signal (4x speed)