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Bioinspired materials for water collection, water purification and oil-water separation

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Bioinspired Water Collection Methods to Supplement Water Supply

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An Ominous Forecast

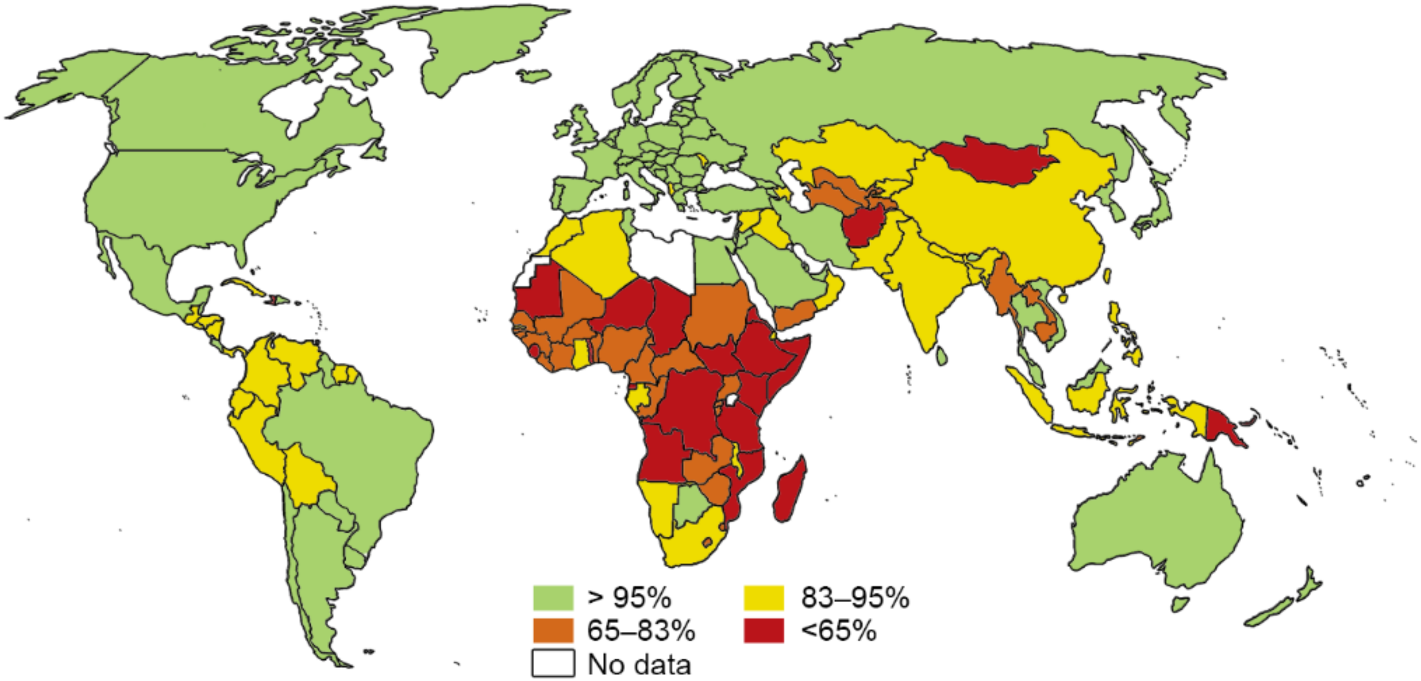
By 2021, more people will be using mobile phones than running water.

11th Annual Cisco Visual Networking Index (VNI) Global Mobile Data Traffic Forecast for 2016-21

Mobile phones are great for connectivity,
but fraction of those with mobile phones will not have access to running water!

Introduction

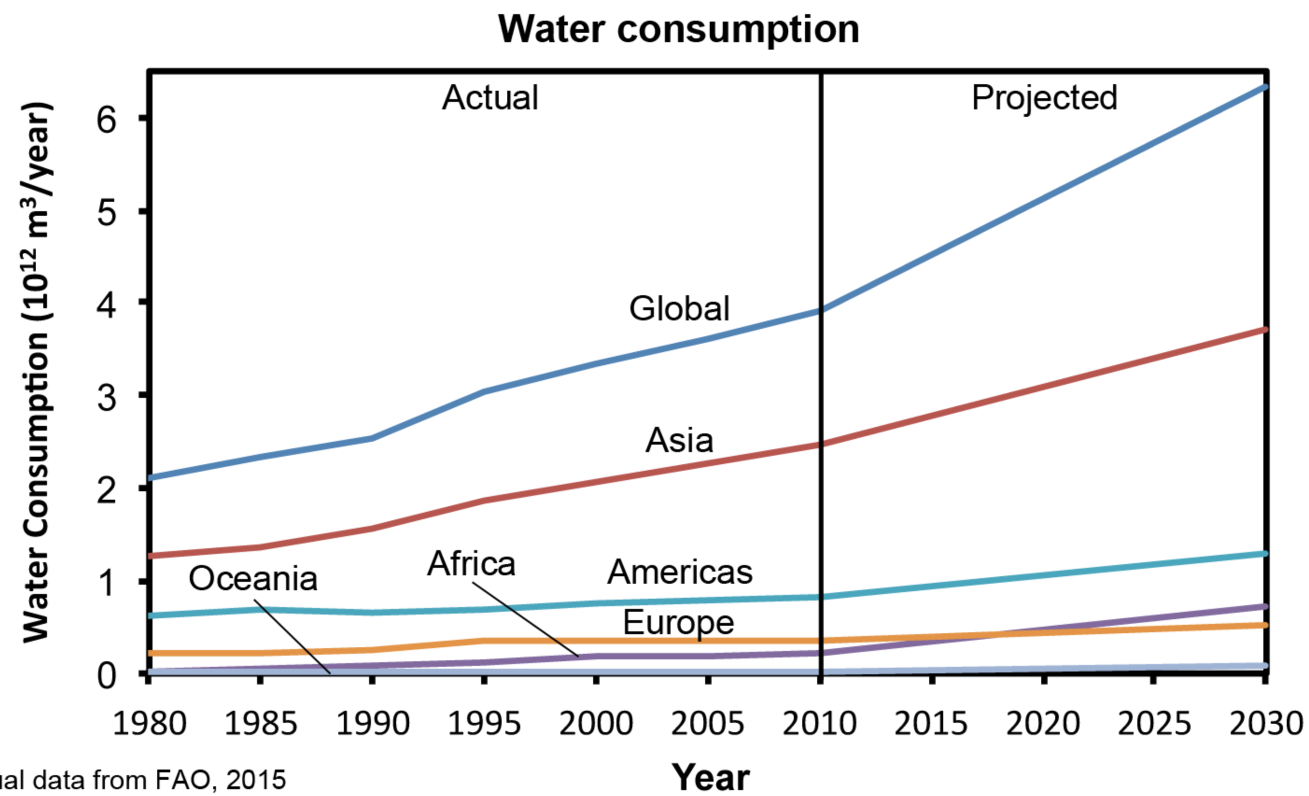
- Access to a safe water supply is vital for human health.



Percent population with access to water source in 2015 (WHO/UNICEF)

- Some of the arid regions of the world lack adequate water supply.
- Water scarcity affects more than 40% of the global population and is projected to rise.
- It is estimated that about 30% of the global population does not have access to safe and easily accessible drinking water (UNESCO, 2019).

Population Growth



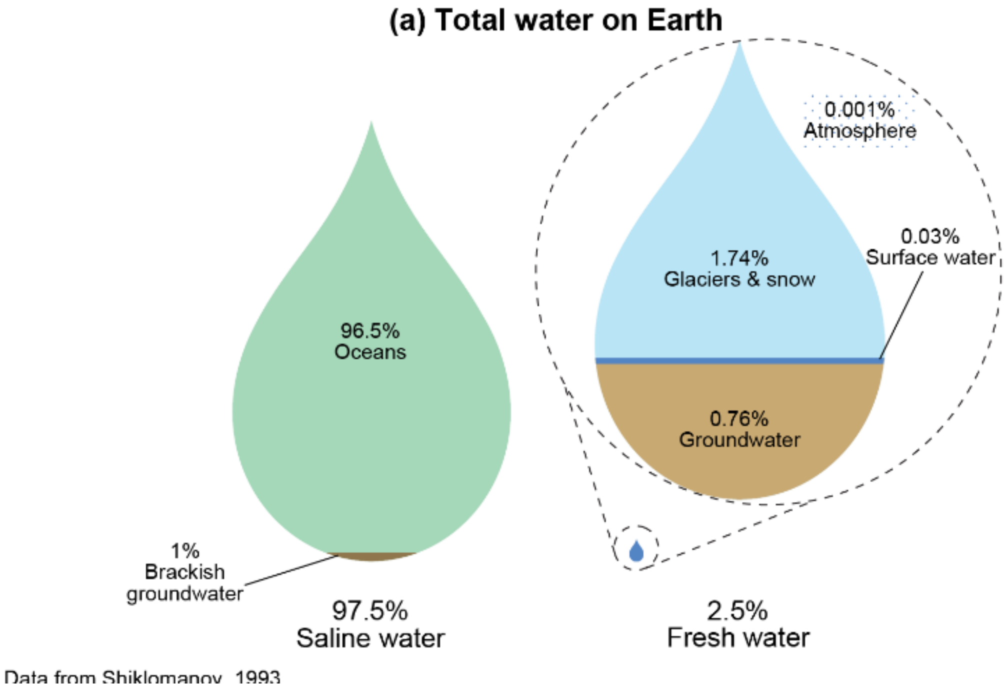
Actual data from FAO, 2015
Projected data from 2030 Water Resources Group, 2009

- Water consumption continues to grow because of growing population, projected to be ~8.2 billion in 2030.

- This will further result in shortage of water supply.

Brown, P. S. and Bhushan, B., "Bioinspired Materials for Water Supply and Management: Water Collection, Water Purification, and Separation of Water from Oil," *Phil. Trans. R. Soc. A* **374**, 20160135 (2016).

Water Source on Earth



- Water covers 70% of the Earth's surface.
- However, ~96.5% of water is saline water, contained in the oceans. For consumption, it needs to be desalinated, which is an energy-intensive process.
- Fresh water accounts for ~2.5% of all water supply.
- Of this, only about 0.79% exists as ground and surface water.
- Furthermore, the distribution of fresh water is not uniform across the globe, e. g. ~20% world's fresh water is found in Great Lakes in MI in the US.

Brown, P. S. and Bhushan, B., "Bioinspired Materials for Water Supply and Management: Water Collection, Water Purification, and Separation of Water from Oil," *Phil. Trans. R. Soc. A* **374**, 20160135 (2016).

- In addition to lack of availability of surface water, *clean water supply* is becoming scarce because of contamination.

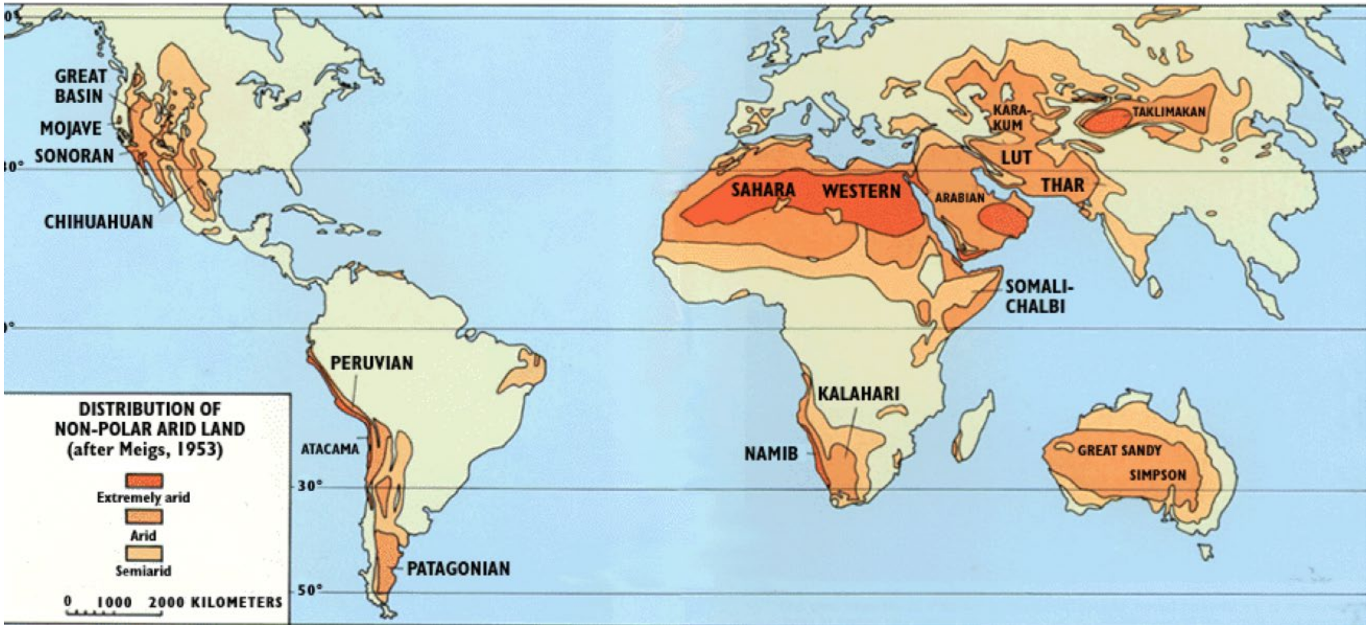
- It is apparent that current supply of water needs to be supplemented to meet future needs.

Lessons from Nature

To find new source of water supply, we may look to Living Nature.

- All living things require water.
- After some 3 billion years of evolution, various flora and fauna can survive in arid desert environments.
- Water supply in arid desert is supplemented by collection from fog and condensation.

World map of desert with relative degrees of aridness



Sahara desert is hot and very arid. It covers 1/3 of African continent.

Deserts have living species. Water is supplemented by fog and condensation.

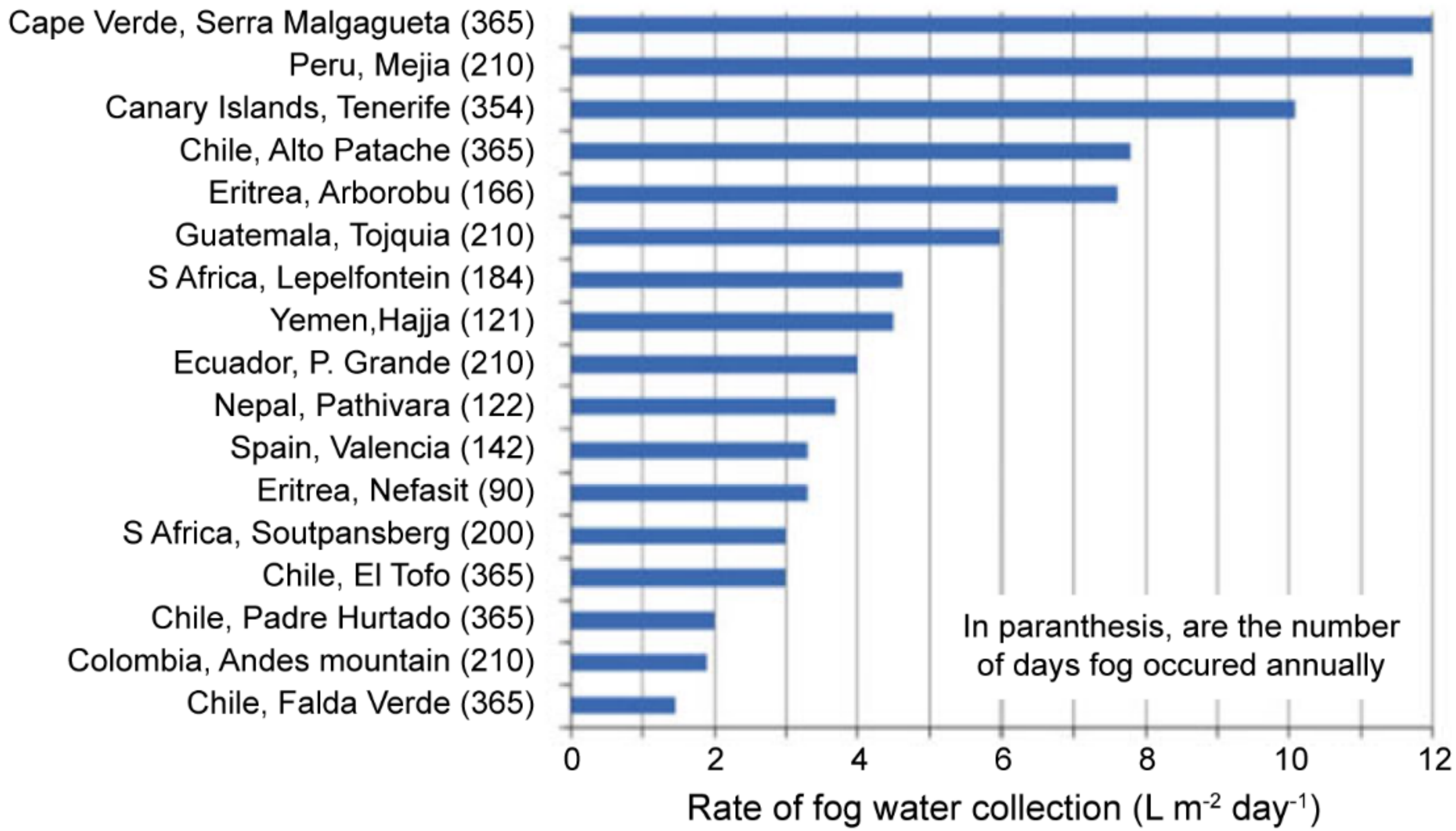
Fog

- Water droplets are deposited from micro-sized water droplets in air.

Condensation

- Water droplets are formed on a surface by condensation of water vapor in air, if the surface is colder than dew point.

Rate of fog water collection and number of days fog occurs annually at various locations (Fessehaye et al., 2014)



Number of foggy days ranging from 121 to 365.

Rate of fog water collection on desert surface ranges from 2 to 10 L m^{-2} day^{-1}.

Desert nights are cold, as low as 0 - 4ºC, and condensation also occurs.

- Collected water evaporates as soon as sun comes out in early mornings. Before it evaporates, species have mechanisms to *transport water to a location where, either it is stored* or *consumed*.

- These species possess unique chemistry and structures on or within their body for collection and transport of water.

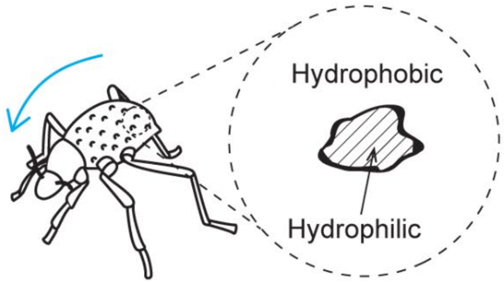
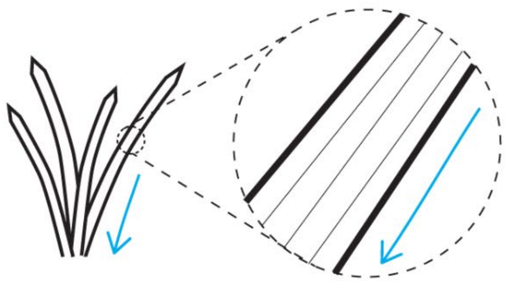
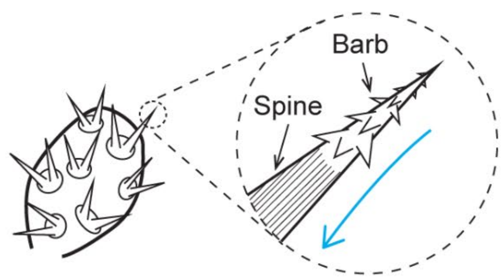
- We need to understand the mechanisms used in nature.

- Then, these can be used to fabricate bioinspired surfaces to supplement safe drinking water supply.

- This would be of particular interest in arid regions to develop means to harvest fog and condensation.

Lessons from Nature

Inspirations for water-collecting device

Species	Mechanism	Comments
 *Stenocara gracilipes* (Beetle)		Water droplets grow on wax-free hydrophilic bumps before being transported towards the mouth by the waxy hydrophobic surround (Hamilton III and Seely, 1976; Parker and Lawrence, 2001).
 a (Grass)		Water droplets are channelled down the hydrophilic leaves towards the base of the plant and eventually reaching the roots (Ebner et al., 2011; Roth-Nebelsick et al., 2012).
 (Cactus)		Water droplets grow on tips of small barbs before moving down onto spine and travelling towards base, due to Laplace pressure gradient and grooves, where they are absorbed (Ju et al., 2012).

spired Materials for Water Supply and Management: Water Collection, Water Purification and
R. *Soc. A* **374**, 20160135.

Structures and Chemistries for Bioinspired Surfaces

- Heterogeneous wettability inspired by desert beetles
- Longitudinal grooves inspired by desert grass
- Conical geometry inspired by cactus
- Can also use triangular geometry on flat surfaces

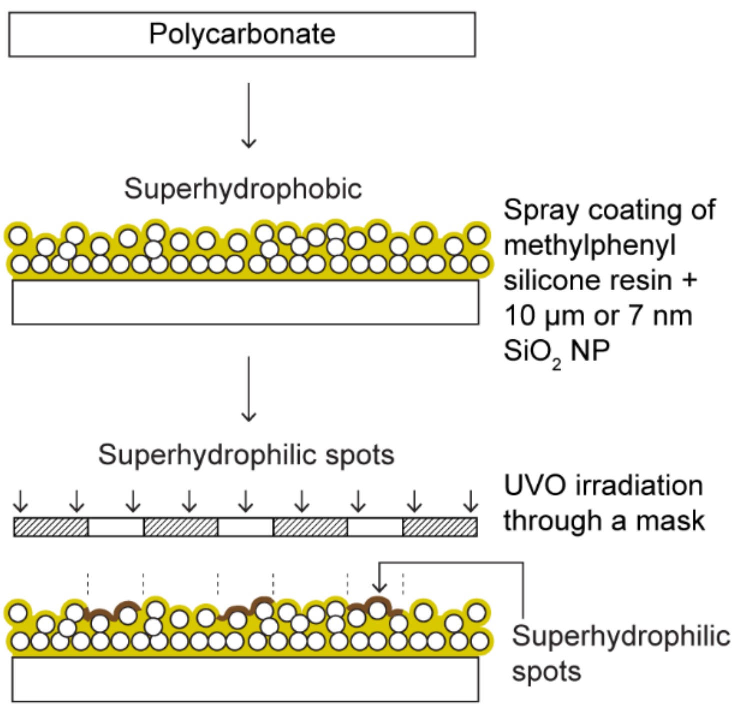
- Measure water collection from Fog and Condensation for both conical and triangular geometries.

P. S. Brown and B. Bhushan (2016), " Bioinspired Materials for Water Supply and Management: Water Collection, Water Purification and Separation of Oil from Water," *Phil. Trans. R. Soc. A* **374**, 20160135*;* B. Bhushan (2019), *"Bio*inspired Water Collection Methods to Supplement Water Supply," *Phil.Trans. R. Soc. A* **377**, 20190119; B. Bhushan, *Biomimetics: Bioinspired Hierarchical-Structured Surfaces for Green Science and Technology*, third ed., Springer (2018)

Fabrication of Bioinspired Surfaces (w/ Dev Gurera)

Beetle-inspired water collectors

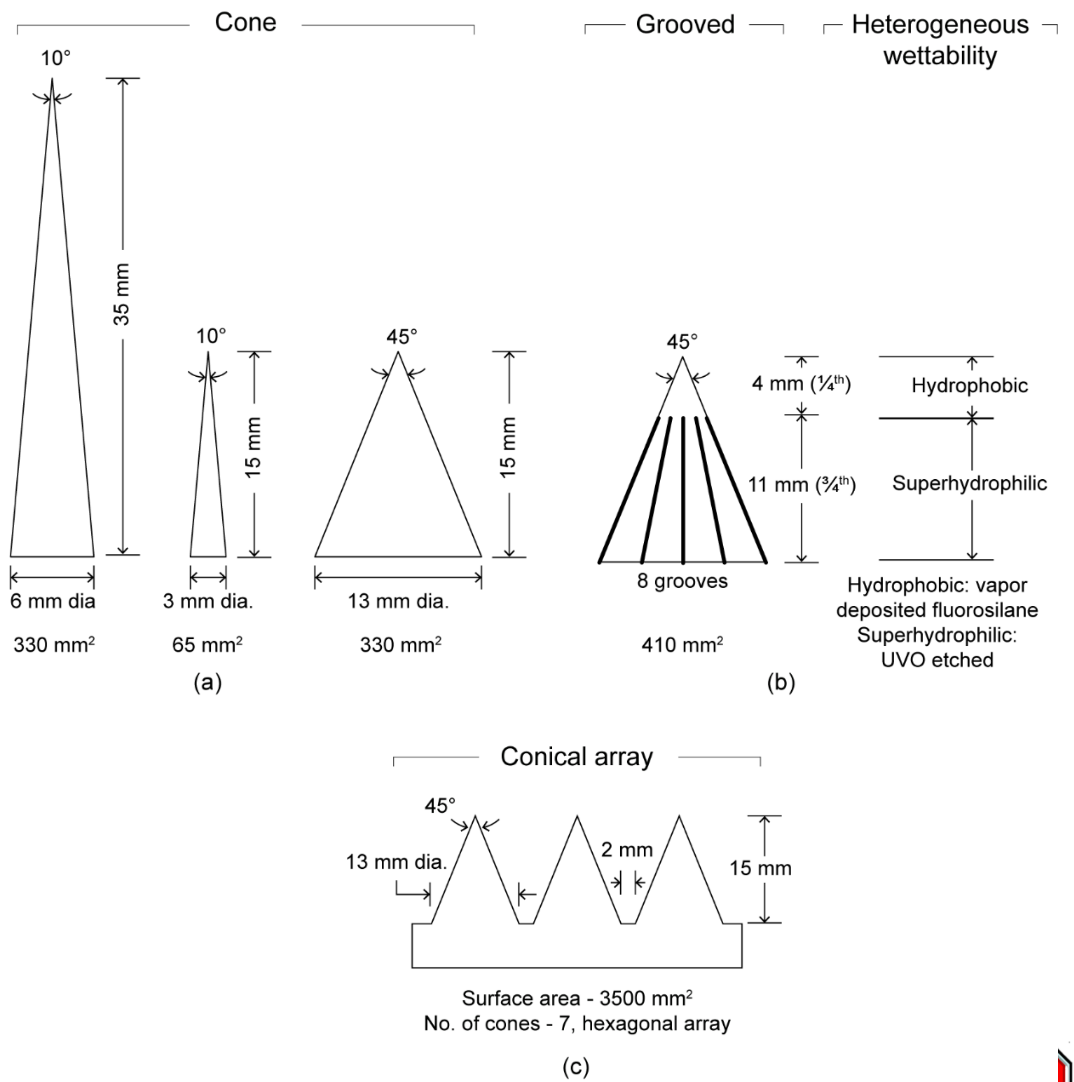
Fabrication approach



Water CA: polycarbonate - 75°±2°, superhydrophobic - 163°±2°, superhydrophilic - wet

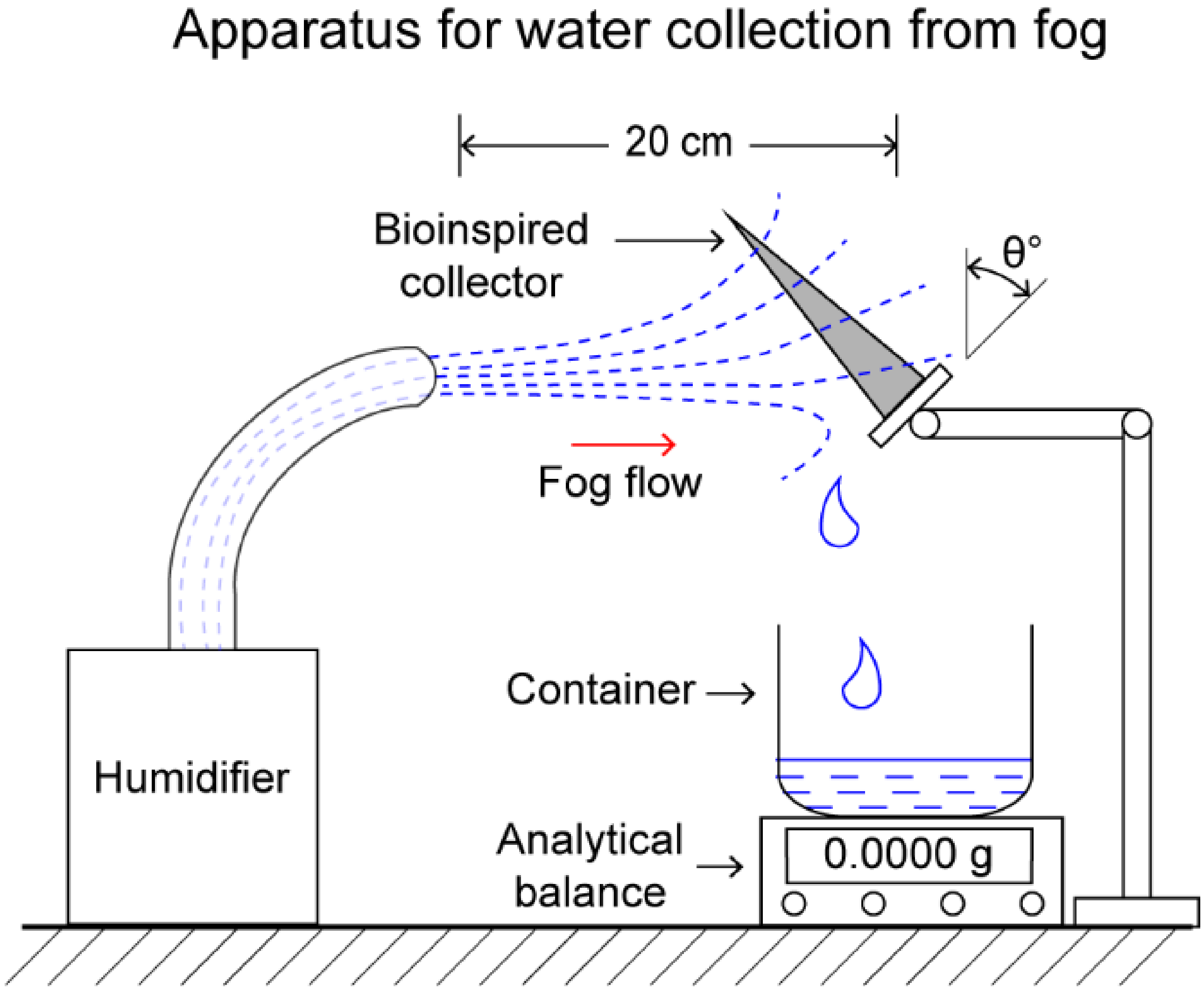
Beetle-, grass- and cactus-inspired water collectors

Material - hydrophilic acrylic polymer, water CA - 61°±2°



D. Gurera and B. Bhushan (2019), “Optimization of Bioinspired Conical Surfaces for Water Collection from Fog,” *J. Colloid Interface Sci.* **551**, 26-38.

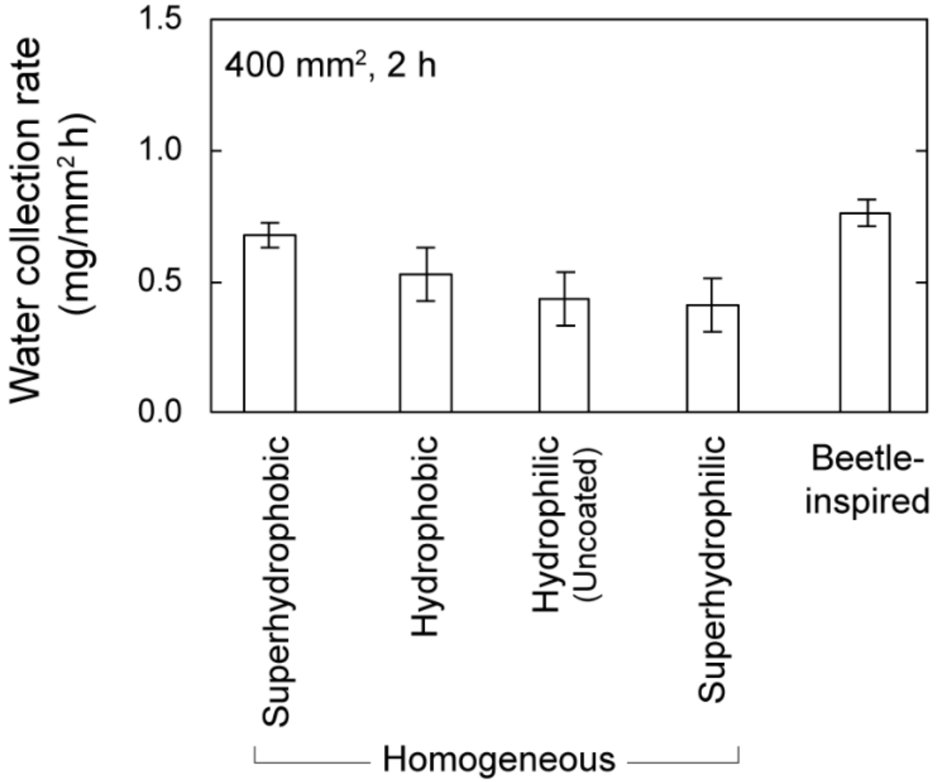
Fog



Apparatus for water collection from fog
20 cm
Bioinspired collector
θ°
Fog flow
Container
Humidifier
Analytical balance
0.0000 g

Beetle-inspired and homogeneous wettable surfaces

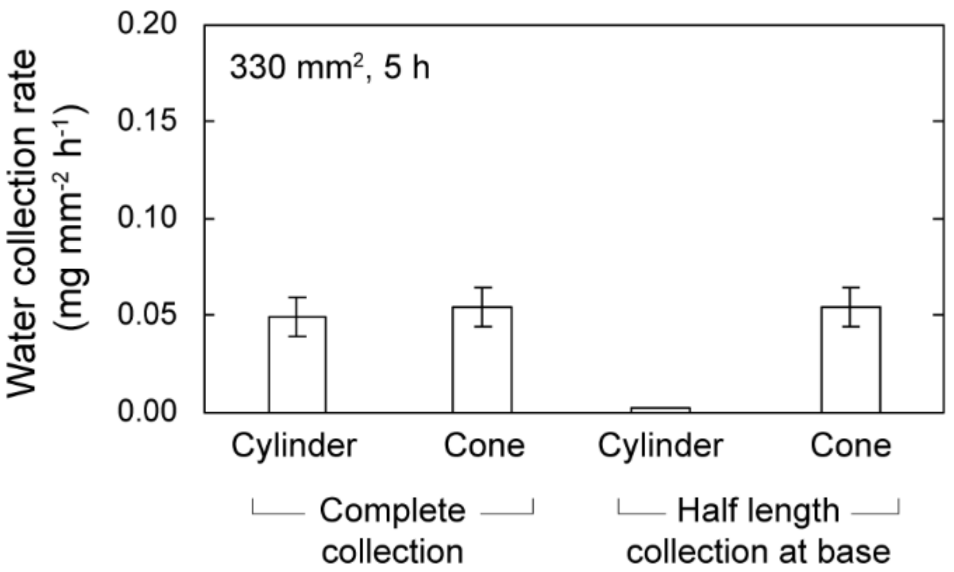
Flat surfaces with various wettabilities at 45° inclination

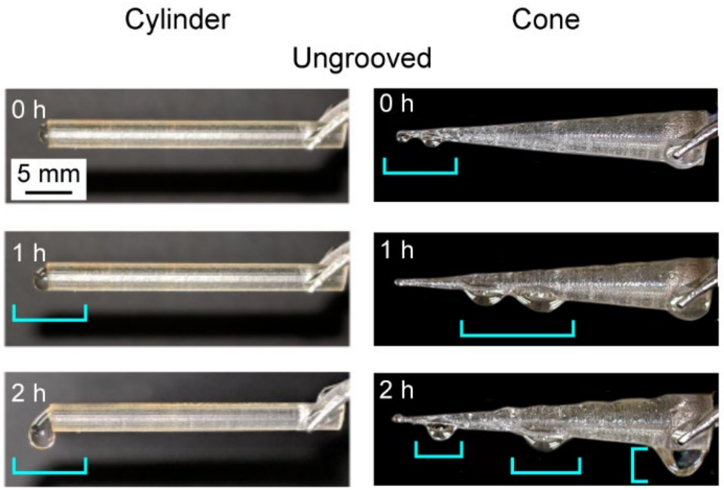


- Among surfaces with homogeneous wettability, superhydrophobic surface provided the highest water collection. In highly repellant surfaces, spherical droplets roll off rapidly with minimum evaporation.
- Among all surfaces, beetle-inspired surfaces provided the highest collection. Because of heterogeneity, droplets can slide/roll off the surface at a faster rate.

Conical Geometry

To study role of conical geometry, measurements on Cylinder vs. Cone





Droplet grows at the tip and drops and no force is pushing droplet to the base

Droplet grows at the tip, travels to the base, due to Laplace pressure gradient, and drops

Water collection rates per unit surface area for single cylinder and cone. Measurements made over the entire region and just at the base (as in nature).

- At the base, cone collects more water than the cylinder.
- Whereas total water collection rates are comparable.

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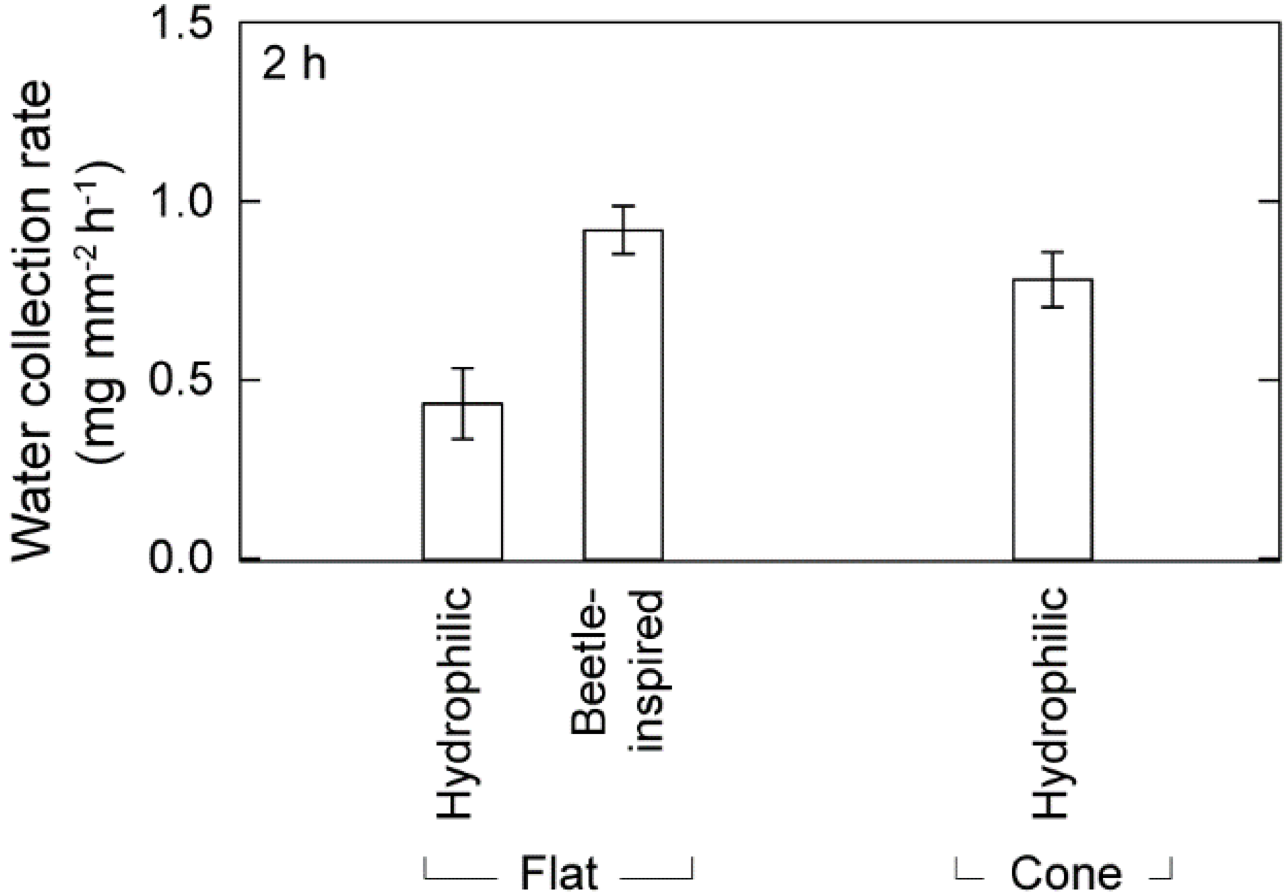
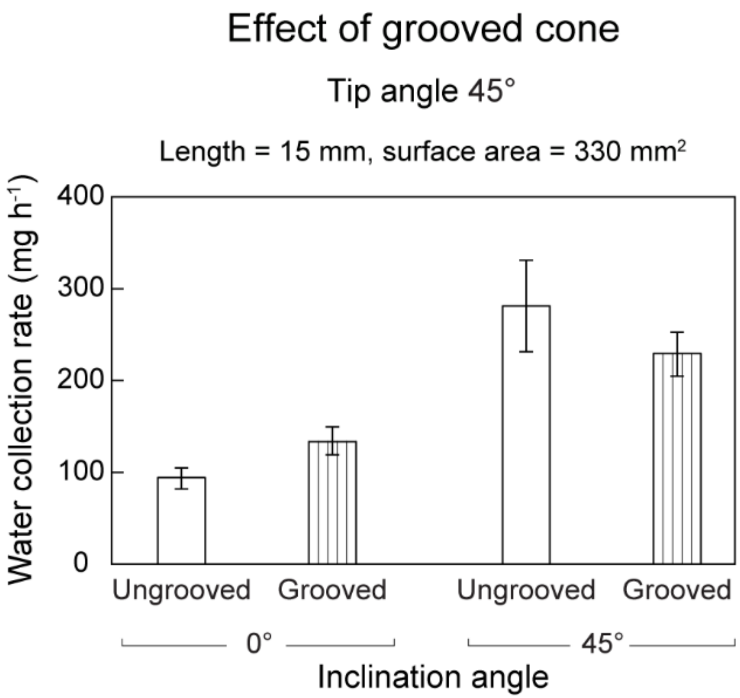
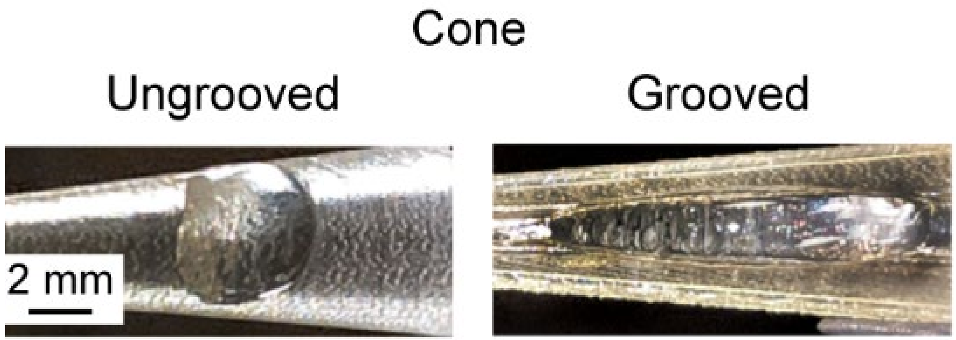
Cone at 45º inclination and comparison with flat surfaces



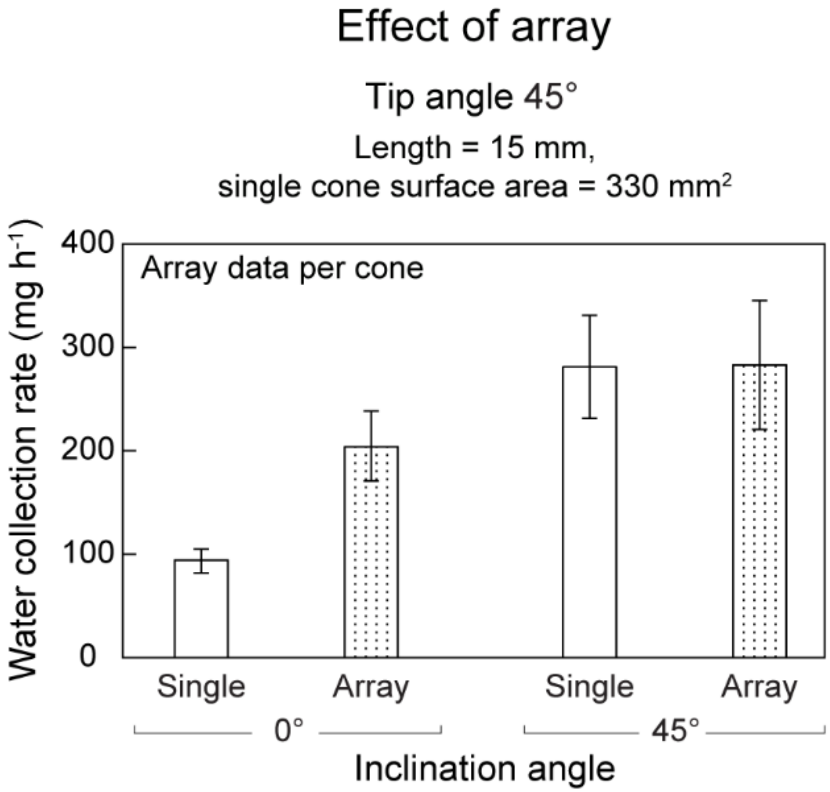
- Water collected on cone at 45º inclination is an order of magnitude larger than at 0º inclination (data presented earlier).
- The cone surface and beetle-inspired surfaces collects twice as much as water as that for a flat surface.





- At 0º inclination, grooved cone has higher collection rate than ungrooved.
- Grooves help in channeling the water.

- At 45º inclination, gravity dominates and grooves do not contribute.

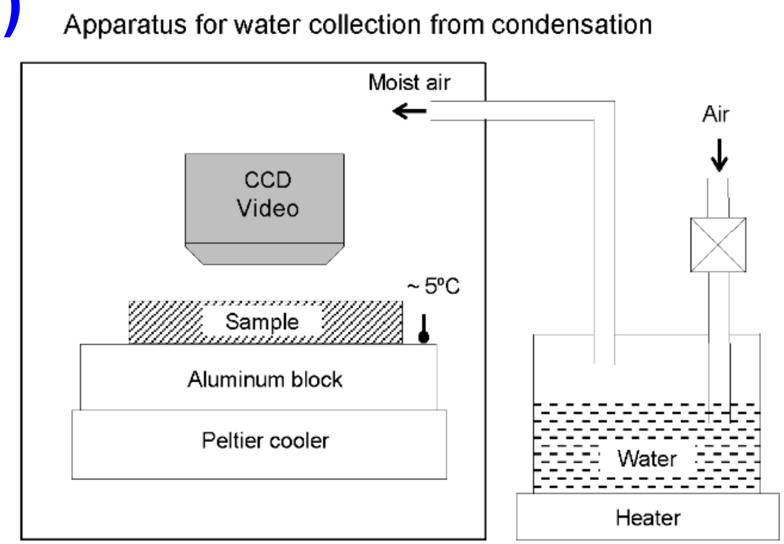


Droplets falling from the top cone coalesce with droplets stuck to cone underneath.

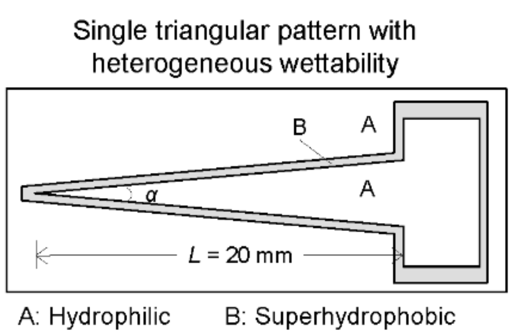
- At 0º inclination, conical array per cone provides higher collection than a single cone, due to cascading effect on a falling droplet.
- At 45º inclination, collection rates are comparable as gravity dominates the water transport.

Water Collection on Triangular Geometry

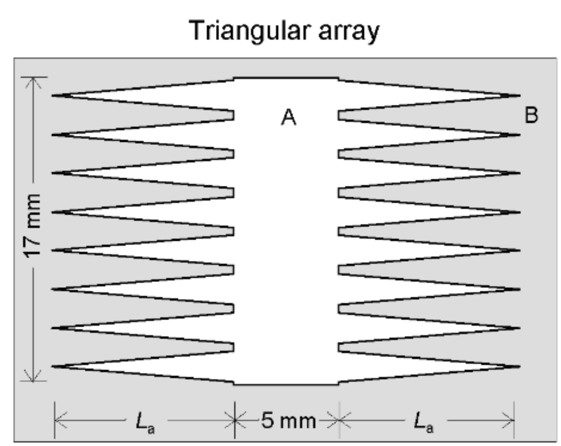
Triangular Geometry on Flat Surface, Condensation (w/ Dr. Dong Song)



(a)



(b)

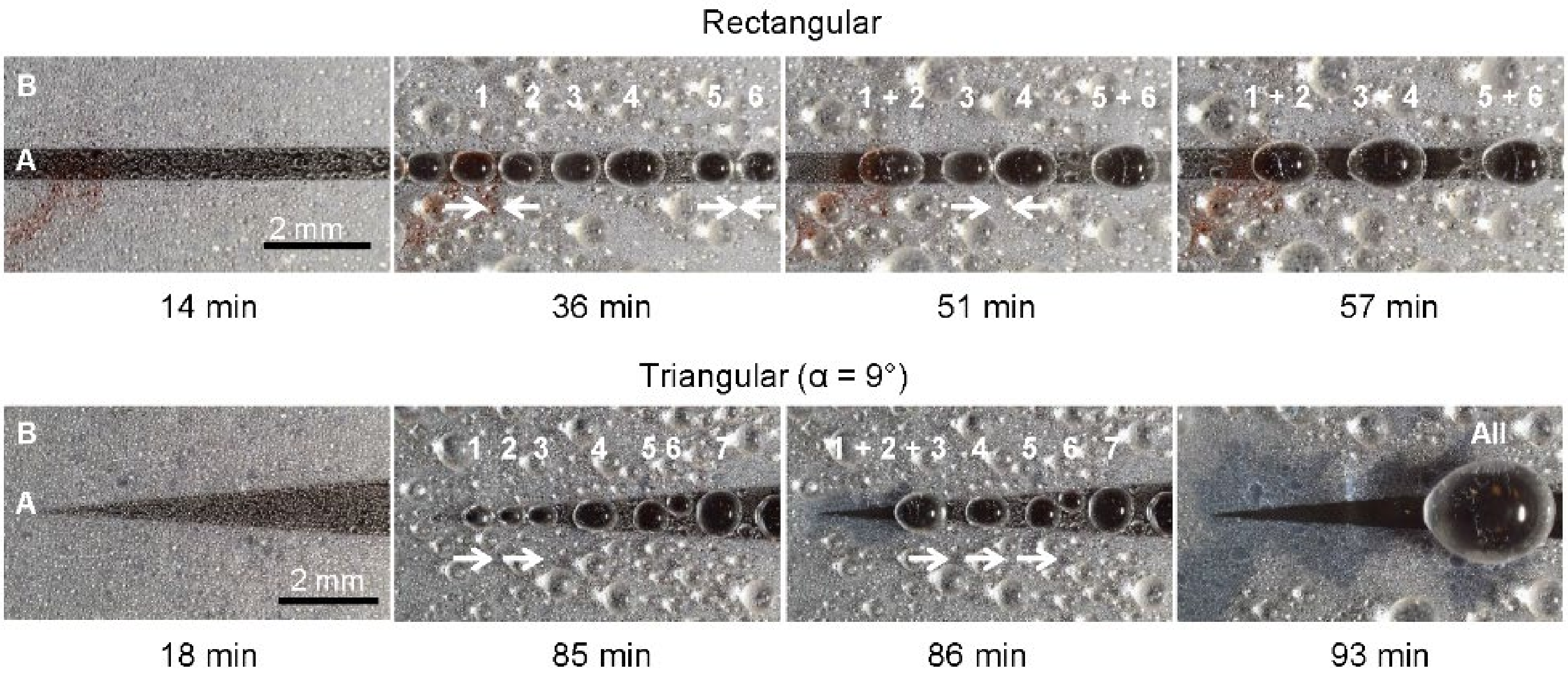


(c)

D. Song and B. Bhushan (2019), "“Bioinspired Triangular Patterns for Water Collection from Fog,” *Phil.Trans. R. Soc. A* ***377***, 20190128

Rectangular vs. triangular patterns with heterogeneous wettability
RH = 85%

A: hydrophobic, B: superhydrophobic

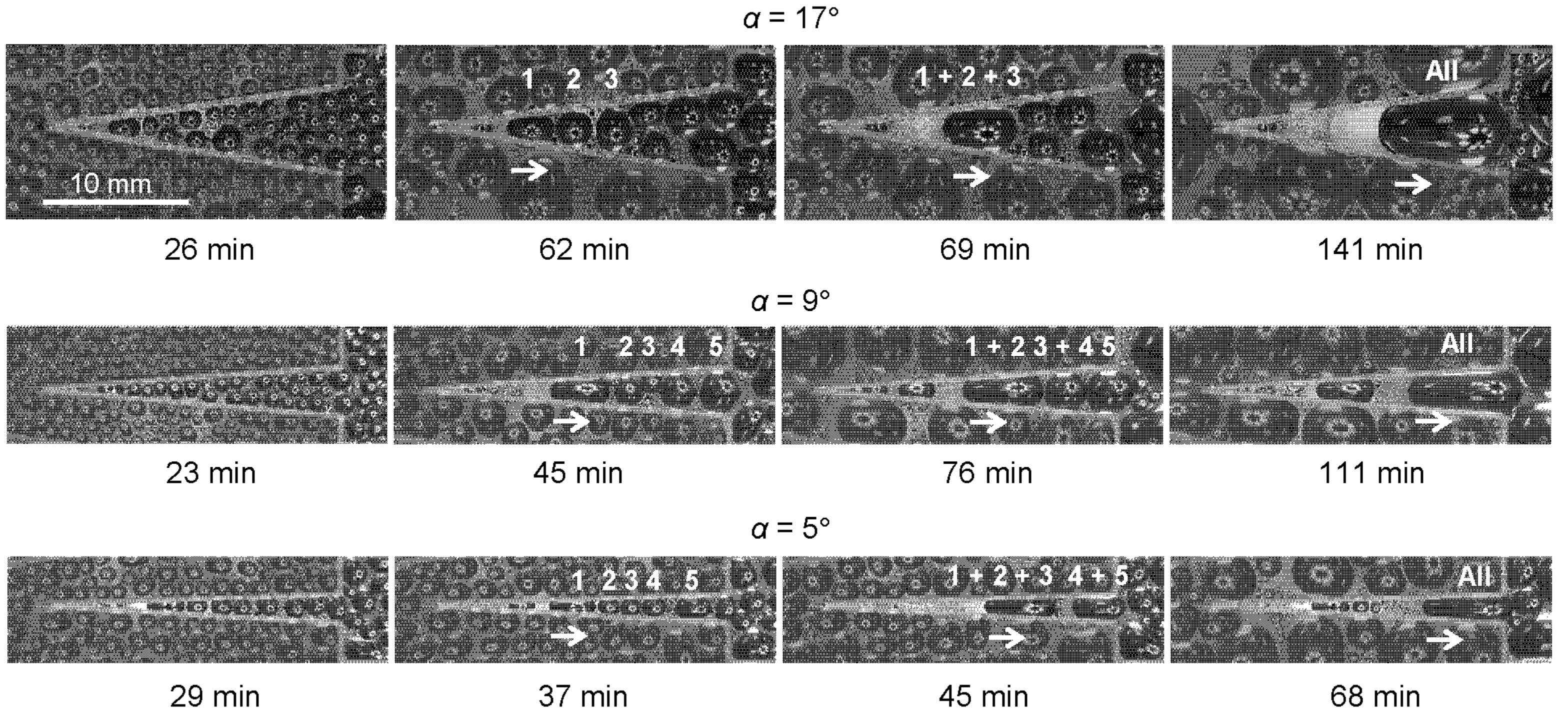


- As condensation continues, droplets grow and start to coalesce into bigger droplets.
- In triangular patterns, once they are big enough to touch the pattern borders, the motion is triggered driven by Laplace pr. gradient.

D. Song and B. Bhushan (2019), "“Water Condensation and Transport on Bioinspired Triangular Patterns with Heterogeneous Wettability at Low Temperature,” *Phil.Trans. R. Soc. A* **377** 20180335).

Effect of included angle of triangular patterns on water condensation and transport

RH = 85%

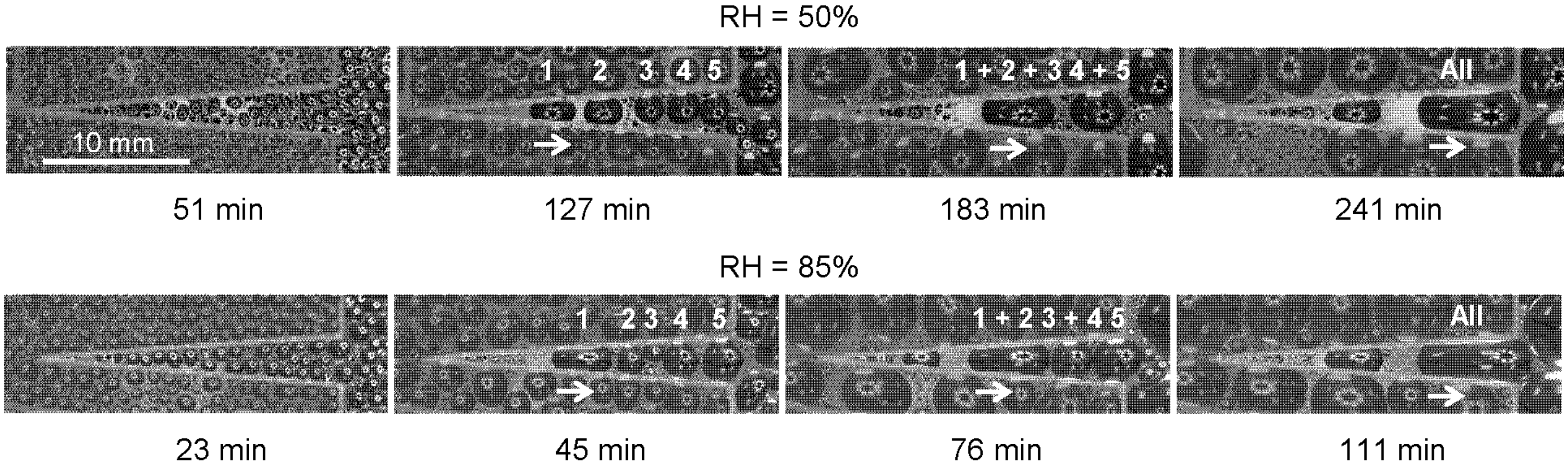


- Time to reservoir with lower included angle is lower because smaller droplets can touch the border earlier and start to move.
- However, with lower included angle droplet size reaching the reservoir is smaller.

D. Song and B. Bhushan (2019), "“Water Condensation and Transport on Bioinspired Triangular Patterns with Heterogeneous Wettability at Low Temperature,” *Phil.Trans. R. Soc. A* **377** 20180335).

Effect of humidity on water condensation and transport

$\alpha = 9°$

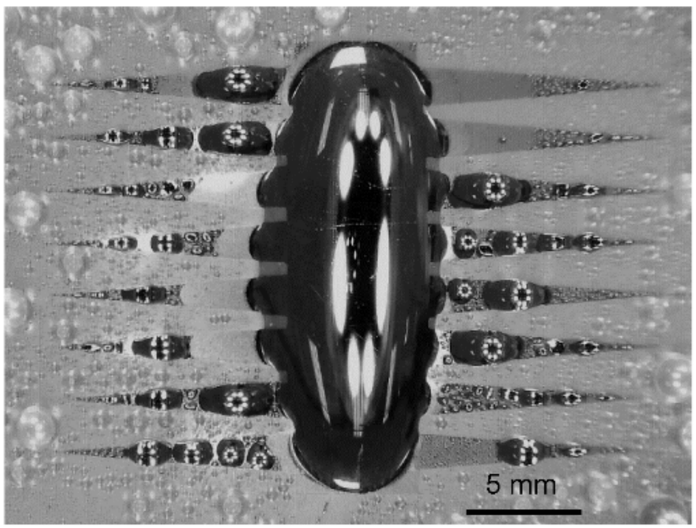


- Time to reservoir is lower at higher RH because of increased condensation.

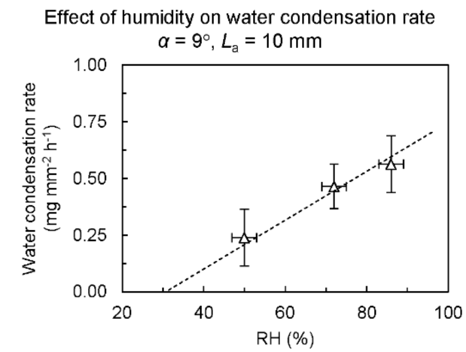
Water Collection Rate

Effect of humidity, included angle and length of triangular patterns on water condensation rate

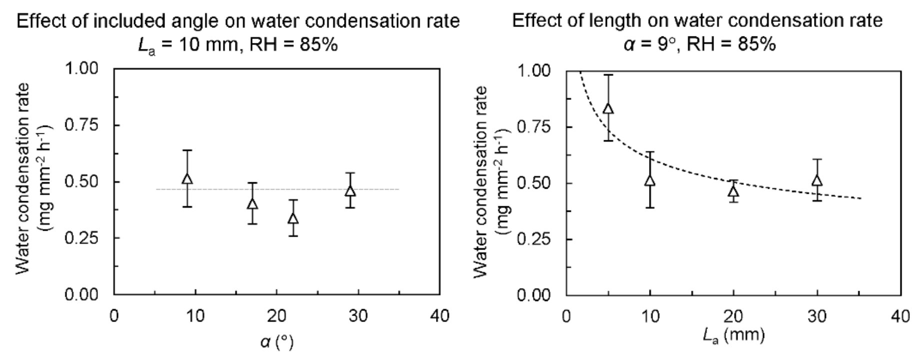
Reservoir with 16 triangular patterns, $\alpha = 9°$, $L_a = 10$ mm
RH = 50%, at 450 min



(a)



(b)

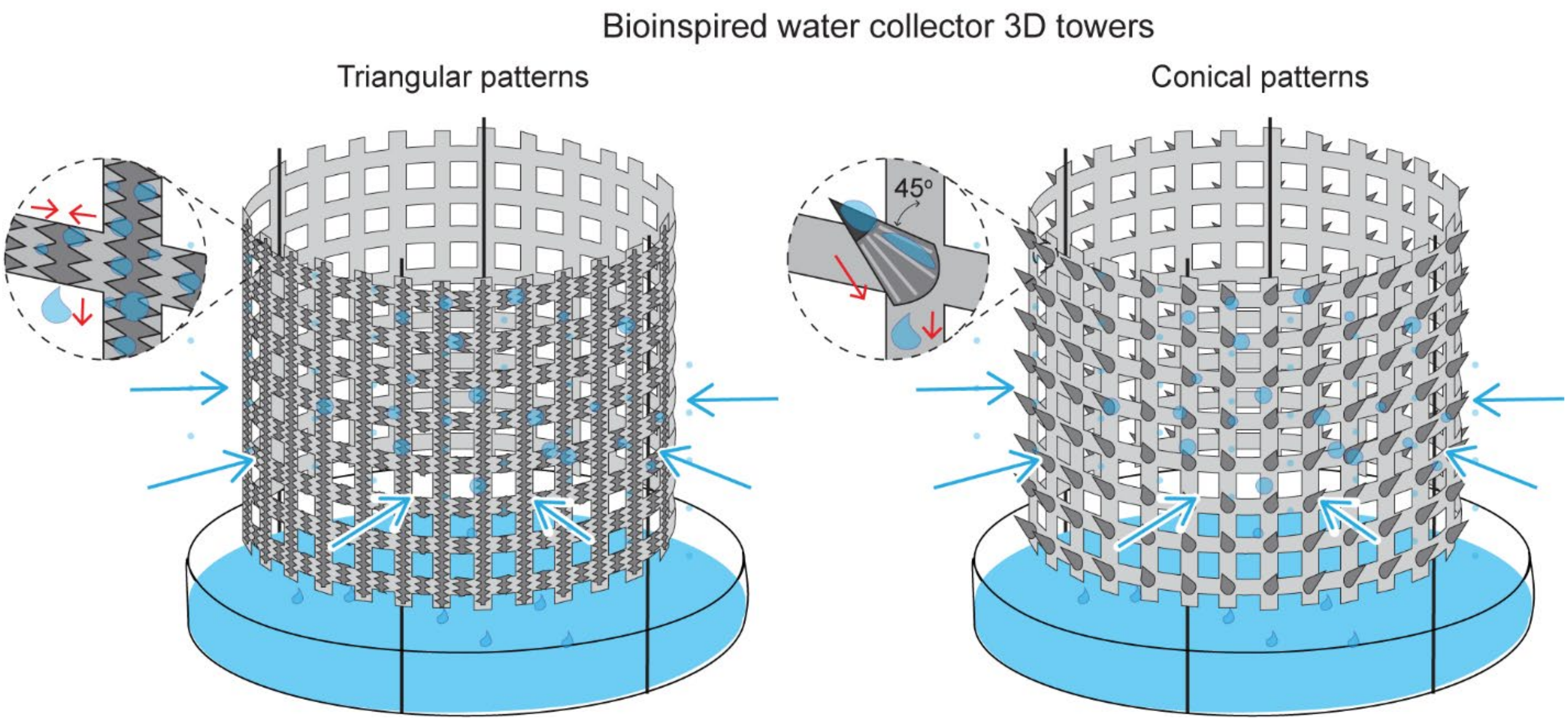


(c)

Water Collection rate increases with RH,
remains about the same at different included angles, and
decreases with length of the patterns.

Bioinspired Large Water Collection Towers and Portable Units

For scale-up, large nets or towers can be used to supply water to a community.



Water Collection Estimates

- In arid deserts, water collection rates are on the order of 2 L m^{-2} day^{-1}.
- The bioinspired surfaces covered with conical arrays can provide collection rates at least one order of magnitude larger than that of a flat hydrophilic surface, on the order of 20 L m^{-2} day^{-1}.
- For an example of 20 L m^{-2} day^{-1}, by a medium size tower covered with a bioinspired surface with a surface area of 200 m^2, water collection rate would be about 4,000 L day^{-1}.
- If the water consumption per capita is 100 L day^{-1}, a tower can provide sufficient water for about ten families with 4 people in each family.

Portable units can be used to supply a home or a camper.

In addition, portable units can be used for

- Various defense applications, such as combat and military bases in combat zones (e. g., cost of fresh water in Afghanistan ~ $300/gallon), and

- Emergency applications, such as fire zone.

Conclusions

- Bioinspired surfaces hold tremendous promise in water collection.
- Towers and portable units can be used to supply water to a large community, a home or for defense and emergency applications.
- Significant advances in nanofabrication allows one to replicate structures of interest in bioinspiration using smart materials.

Acknowledgements

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