Lotus-Inspired Nanotechnology Applications

B Karthick and Ramesh Maheshwari

The water-repellent surface of lotus (*Nelumbo nucifera*) leaf and flower is due to nanosized wax papillae on the upper side of each epidermal cell. As a result, raindrops make a high contact angle with the papillae and roll off carrying dust and dirt particles, leaving the surface clean. This self-cleaning property of highly hydrophobic surfaces, termed as the lotus effect, has opened the possibilities of fabricating superhydrophobic surfaces for a variety of products.

B Karthick is a research scholar in the Centre for Ecological Sciences, Indian Institute of Science, Bangalore. His research interests are in taxonomy and ecology of diatoms and ecology of wetlands.

Ramesh Maheshwari is a former professor in biochemistry at the Indian Institute of Science.

Lotus, botanically named *Nelumbo nucifera*, is regarded as a sacred plant in Hindu mythology. Lotus is also India's national flower (*Figure* 1) and is regarded as a symbol of purity. Its leaf and flower are water-repellant. A falling raindrop turns into a water bead and rolls off, taking along with it the dust and the dirt particle. Hence, despite growing in muddy waters, the lotus leaf surface stays relatively clean (*Figure* 2).

Figure 1. Lotus, the national flower of India featured on a postage stamp issued on September 1, 1977.

Although the water repellency of lotus had long been recognized, its scientific basis was understood only in 1997 [1] when two botanists, Wilhelm Barthlott (*Figure* 3) and Christoph Neinhuis, at the University of Bonn in Germany examined leaf surfaces of lotus and several other plants using a scanning electron microscope which resolves structures as small as 1–20 nm (one nm = billionth or 10^{-9} of a meter). They established that the self-cleaning property is due to the presence of convex papillae on the surface of leaves, coated with wax crystals of nanoscopic dimension: ~10 to ~100 nm (*Figure* 4). The papilla greatly reduces the contact area of water droplets with it. The water droplet, as for example due to rain or fog or dew, is dislodged, often coalescing into a bigger drop at the center of leaf surface that falls off with swaying of the leaf.

Keywords
Lotus, self-cleaning, hydrophobicity, nanotechnology.

Wax is comprised of a mixture of long-chain hydrocarbons:

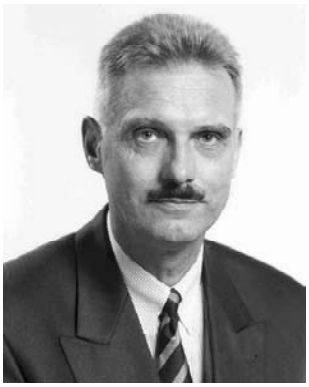


Figure 3. Professor Wilhelm Barthlott, Director of Botanical Garden of the University of Bonn, discovered the lotus effect and conceived the fabrication of surfaces with nanoscopic bumps to make them self-cleaning and patented Lotus Effect in 1980.
Photo courtesy: Kerstin Koch.

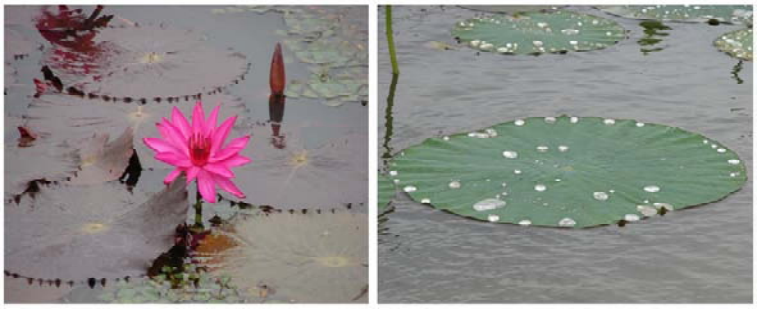
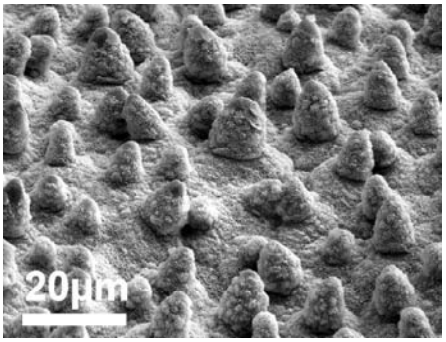


Figure 2. Floating lotus leaves and a blooming flower in a pond (Left); Water drops forming beads on the leaf surface (Right). Photo courtesy: K V Gururaja and M Boominathan.

primary and secondary alcohols, aldehydes and triterpenes. Since the phenomenon of water repellency and self-cleaning is best studied in the lotus, it has come to be known as the 'Lotus effect'. Barthlott and his associates examined over 13,000 plants. Barthlott is quoted as advising, "Do trust your own eyes and not the textbooks, and if your observation is repeatedly confirmed, publish it. But take a deep breath – expect rejections of your manuscript" [2].

A great diversity of structures has been observed on surfaces of the above-ground parts of the plants. Although the presently used system of plant classification relies on the sexual (floral) characteristics devised by the great Swedish botanist, Carl von Linnaeus (1707–1778), it is thought that once a uniform terminology of describing these structures is evolved, it is thought that micromorphologies of plant surfaces can be used as an aid in plant taxonomy. Here we note that the world is celebrating the tricentenary of the birth of Linnaeus who proposed the binomial system of nomenclature and classification of life forms.

Figure 4. Scanning electron microscope image of leaf surface of Nelumbo nucifera.
Photo courtesy: Prof. Wilhelm Barthlott.



Incidence of Water-Repellent Plant Surfaces

Interestingly, a majority of plants in the wetlands have water-repellent leaves. If this were not so, wetting would interfere with gas exchange through the stomata located on the upper (exposed) side of the floating

leaves. Another advantage of a water-repellant surface could be in reducing the risk of infection. Since spores of several pathogenic fungi require free water and air for germination, the evolution of a water-repellent surface by superimposing wax molecules on cuticle (the outermost covering) probably evolved to reduce the risk of infection by pathogenic bacteria and fungi. Water-repellency is not restricted to plants alone. It is manifested also by insects with large wings (such as butterflies and dragonflies) which cannot clean their flying structures by legs. In this case lotus effect works not only for the removal of particles, but also for maintenance of flight capability of insects, which otherwise is lost due to an unequal load on the wings.

The discovery of Lotus effect is a 'by product' of research on diversity of structure, morphology and wetting of plant surfaces.

Water-Repellant Nanostructures on Leaf Replica

Lotus effect can be reproduced on artificially made superhydrophobic films. In one of the procedures, a rough surface was etched into polydimethylsiloxane (PDMS). Using the lotus leaf, a negative PDMS template was made and the negative template then used to make a positive PDMS reproduced as a replica sheet of the original lotus leaf. The positive PDMS template had the same surface structures and extreme water repellency (superhydrophobic) as the lotus leaf. A plant epidermal cell extrudes wax molecules which self-assemble and crystallize as nanosized pillars. Thus, the hydrophobic cuticle has a double structure: the cuticle (a polyester called cutin), and crystalline wax on the cuticle. On a water-repellant leaf cuticle, the dirt particles, like a 'fakir lying on a carpet of nails' make only a minuscule contact with the top of the bumps present on the plant surface. A rolling water drop on contaminated surfaces easily picks up the dirt particle.

Physical Basis

Four classes of surface wettability are recognized (*Figure* 5): namely, superhydrophobic, hydrophobic, hydrophilic and superhydrophilic. Lotus leaf and petal surface exhibits superhydrophobicity, i.e., the contact angle (*Figure* 6) is high –

Superhydrophobicity, a prerequisite for self-cleaning, is characterized by very high contact angles of nanostructured surfaces.

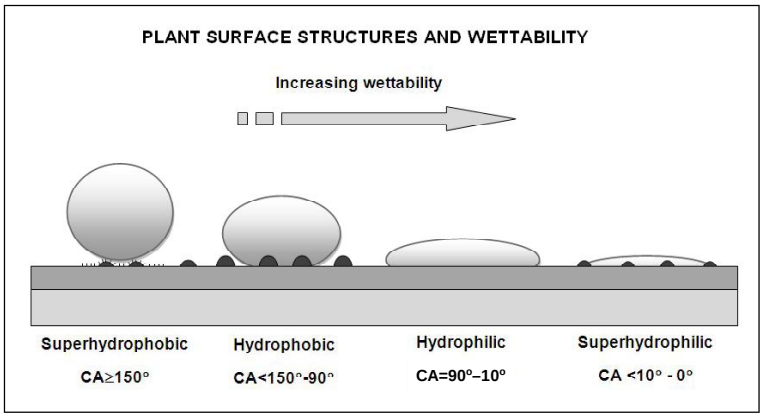


Figure 5. The four classes of surface wettability types of leaf surface based on their interaction with aqueous droplets.

Redrawn from Koch et al, 2008.

exceeding 150 degrees. The drop, instead of sliding and spreading the dirt particles which have fallen on the cuticle, rolls off taking with it dirt (*Figure* 6). Lotus effect is inspiring material scientists into sculpturing superhydrophobic surfaces that will mimic this effect, minimizing labour and expense involved in frequent painting of facade, particularly in the high-rise buildings.

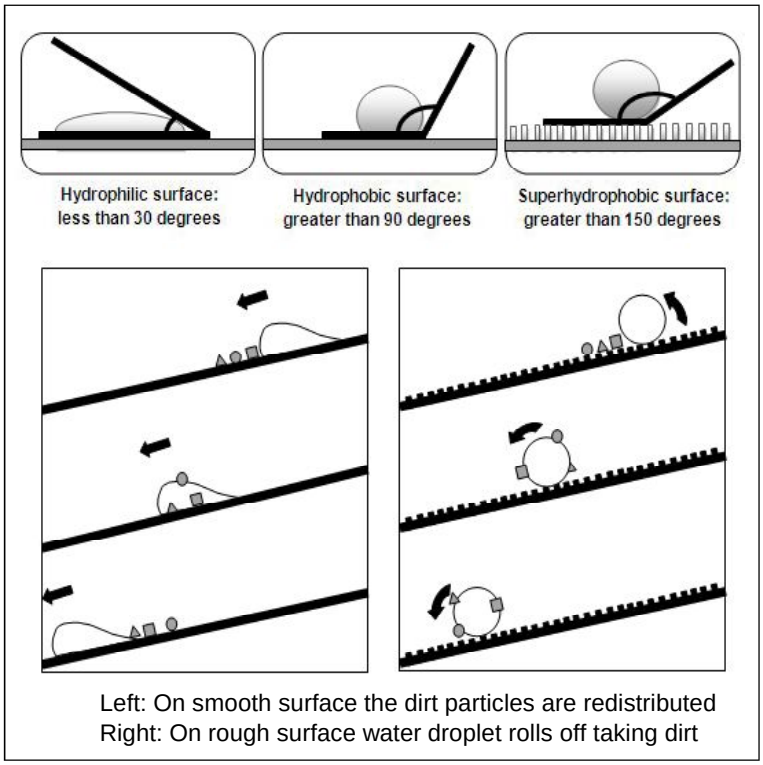


Figure 6. Physics of self-cleaning property of lotus. The large contact angle results from nanoscopic bumps that trap air between the water and the surface minimizing the contact with the surface. A drop of water rolls downwards on leaf surface, picking up dirt (Based on Forbes 2008).

Fabrication of Hydrophobic Surfaces

Optimizing water repellency requires consideration of the geometry of pillars (size, height) and spacing. Rough, nanoscopic finish can be exploited for several applications. Among the numerous applications of lotus effect are, non-wettable rain wear and sails for boats, paints for kitchen roofs and walls that make them soot-free, windows in high-rise buildings and glass for greenhouses avoiding their expensive and cumbersome cleaning, water repellant fibers for garments etc. Other applications can be in sanitary products in bathrooms and toilets and motor vehicle windshields for reducing sticking of dirt matter and easier cleaning.

Lotus effect is caused by combination of waxiness of leaf surface and the nanoscopic bumps that cover it.

Acknowledgement

We are thankful to Kerstin Koch, K V Gururaja and M Boominathan for allowing us to use their photographs.

Suggested Reading

[1] **W Barthlott, C Neinhuis, Purity of the sacred lotus, or escape from contamination in biological surfaces, *Planta*, Vol.202, pp.1–8, 1997.**

[2] **P Forbes, Self-cleaning materials, *Sci. Amer.*, August 2008.**

[3] **Y T Cheng, D E Rodak, C A Wong and C A Hayden, Effects of micro- and nano-structures on the self-cleaning behaviour of lotus leaves, *Nanotechnology*, Vol.17, pp.1359–1362, 2006.**

[4] **K Koch, B Bhushan and W Barthlott, Diversity of structure, morphology and wetting of plant surfaces, *Soft Matter*, Vol.4, pp.1943–1963, 2008.**

[5] **http://www.bionik.tu-berlin.de/institut/shanlec2.ppt#3**

Address for Correspondence
B Karthick
Centre for Ecological Sciences
Indian Institute of Science
Bangalore 560 012, India.
Email: *diatomist@gmail.com

Ramesh Maheshwari
Email: ramesh.maheshwari01@gmail.com