Lotus-Leaf-Inspired Biomimetic Coatings

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A universal infrastructural issue is wetting of surfaces; millions of dollars are invested annually for rehabilitation and maintenance of infrastructures including roadways and buildings to fix the damages caused by moisture and frost. The biomimicry of the lotus leaf can provide superhydrophobic surfaces that can repel water droplets, thus reducing the penetration of moisture, which is linked with many deterioration mechanisms in infrastructures, such as steel corrosion, sulfate attack, alkali-aggregate reactions, and freezing and thawing. In cold-region countries, the extent of frost damage due to freezing of moisture in many components of infrastructures will be decreased significantly if water penetration can be minimized. Consequently, it will greatly reduce the maintenance and rehabilitation costs of infrastructures.

Keywords: biomimetic coating ; durability ; infrastructures ; lotus leaf ; self-cleaning ; superhydrophobicity

1. Introduction

A consistent problem across several infrastructural fields is moisture damage. Rain and snow can create moisture damage to surfaces which are exasperated during winter months, when the surfaces can deteriorate even further due to salt and frost actions [1][2]. This is most common in pavements of the winter-region countries, such as Canada, Sweden, Russia, and Finland [3][4][5]. During the winter months, cracking damage can occur in pavements that increases the rehabilitation and maintenance costs as well as injures vehicles if left unrepaired for a long time. While current research does exist to give a solution by creating hydrophobic materials, it would not be improbable to consider superhydrophobic surfaces with a contact angle >150° [6][7][8].

Biomimicry has been used to produce superhydrophobic surfaces for various purposes. Biomimicry is the practice of replicating naturally occurring phenomena from the environment via artificial means to resolve problems or provide a service [9][10]. This has been done several times in the past through innovation and application such as the inventions of Velcro (replicating the Burdock plant's adhesion) [11] and the bullet train's streamlined forefront (alike the kingfisher's beak) [12]. The replication of the lotus leaf is relatively a recent development in coating technology. Lotus leaf, specifically the *Nelumbo nucifera*, has the natural ability to repel water droplets at a high contact angle, thus being superhydrophobic [13][14]. Along with this, the lotus leaf utilizes its high contact angle to cause the water droplets to roll off the leaf—the rolling droplets collect any debris that the leaf contains, thus providing a naturally occurring self-cleaning property [15][16]. This is referred to as the "Lotus Effect". This can be best demonstrated by **Figure 1** below that features an image of the lotus leaf containing several water droplets which have not contracted but remained buoyant.

Researchers are recently trying to use nanotechnology in coordination with biomimicry. As the term suggests, nanotechnology is the application of materials, which fit between 1 and 100 nm that can affect the properties, interactions, and conditions of materials on a nano scale [17]. In nanotechnology, the properties of materials are dictated by the fundamental behavior of atoms [18][19] due to the technology's ability to capture electrons. The biomimicry attempts to replicate the micro-nano surface structure of the lotus leaf in coating materials to perform with superhydrophobic capability. Biomimetic superhydrophobic and self-cleaning surfaces have already been developed using the natural lotus leaf as a model [20][21].

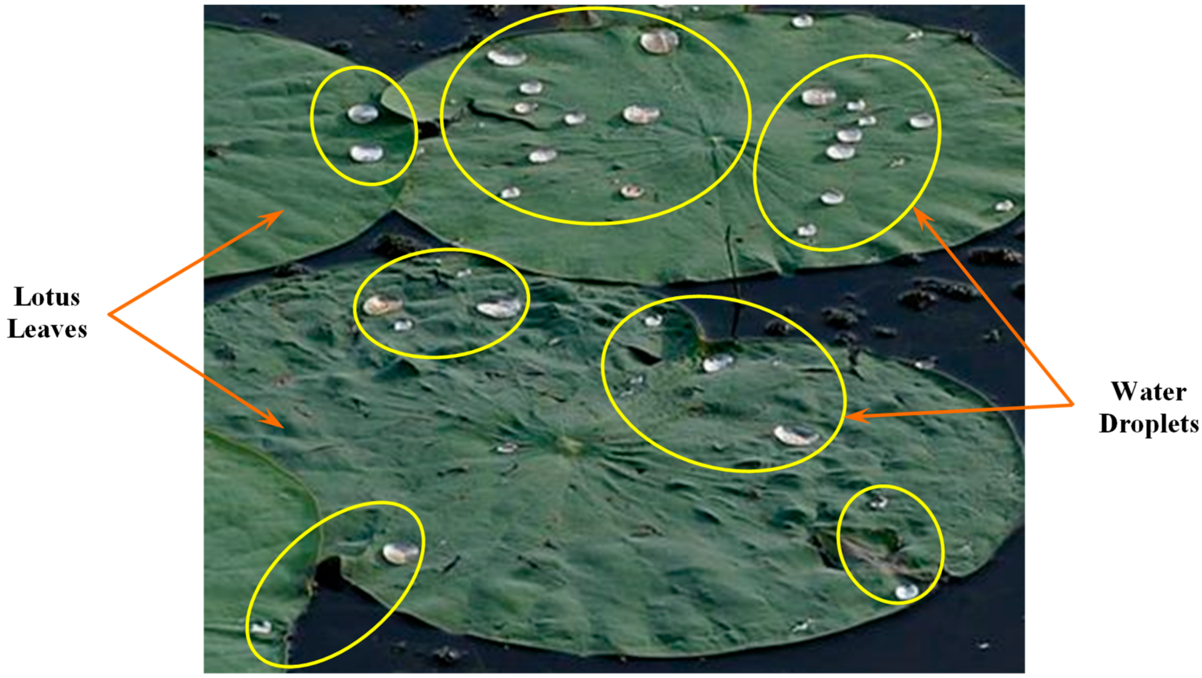

Figure 1. Lotus leaves with "lotus effect" (courtesy of Hossain [22]). The water droplets do not contract and remain buoyant with a spherical structure.

2. Surface Structure and Characteristics of Lotus Leaf

The nanoscale hair-like wax crystals and microscale epidermal cells of a lotus leaf are attributed to its lotus effect [23][24][25]. **Figure 2** provides a simple diagram of the hydrophobic structure that governs the lotus effect. The high contact angle creates a rolling effect of the water droplets supported by the micro-protrusions (microscale epidermal cells). The nanoscale wax crystals facilitate the water droplets to remain buoyant, roll down, and collect the debris before descending from the leaf.

The unique nature of the lotus leaf appears more obvious when examined by a scanning electron microscope, as viewed in **Figure 3**, which resembles a natural terrain consisting of hills and valleys. The valleys exist between and around the hills, which can be alluded to form the earlier discussed microscale structure. The debris never enter deep enough into the valleys due to the larger size of the particles and the repelling nature of the nanoscale hair-like structure, which pushes the debris up so it can be collected by the rolling water droplets [23][26].

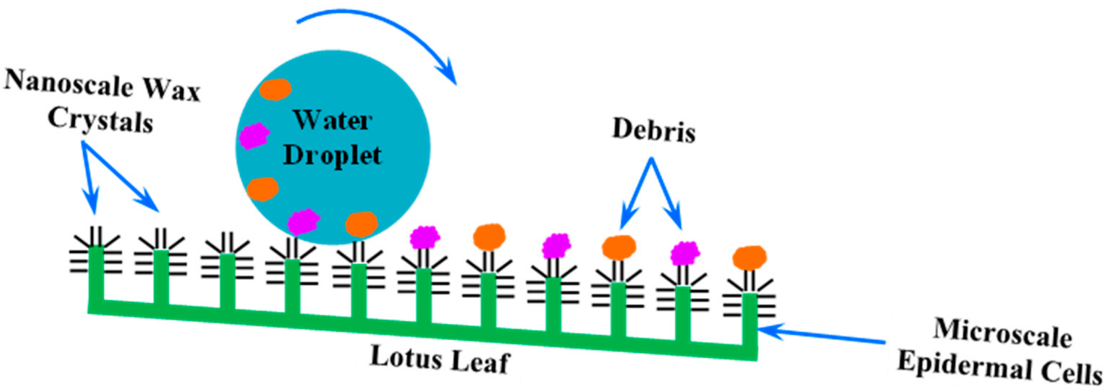

Figure 2. A simple schematic for understanding of the lotus effect. The water droplet collects the debris as it descends from the leaf. The figure has been created by the authors based on the concept illustrated by Poole [27].

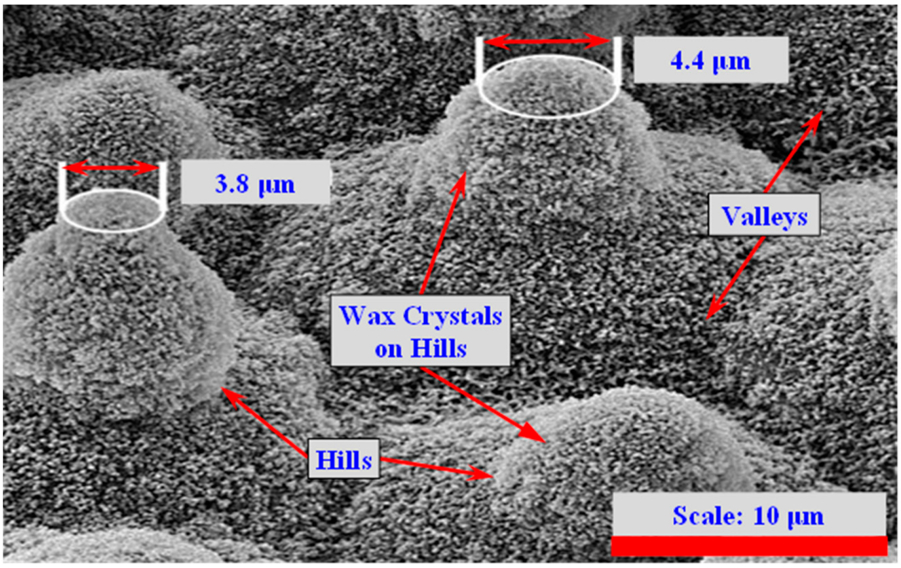

Figure 3. An SEM image of a lotus leaf (modified from Ensikat et al. [28]). This image depicts the microscale structure comprising hills with the valleys among them, as well as the nanoscale wax crystals. The diameters of two mountain peaks are also shown.

3. Lotus-Leaf-Inspired Biomimetic Coatings

Various biomimetic coatings have been developed replicating the micro-nano surface structure of the lotus leaf, as can be seen from **Table 1**. The purpose behind each of them is to quickly repel water droplets for reducing the risk of moisture damage, taking the advantage of the lotus leaf's natural ability to self-clean. The repelling of water droplets is crucial for urban projects as the water damage of pavements and buildings can be expensive for the public and private sectors in the form of insurance claims and uninsured property damage [29]. Despite various attempts for replication of the lotus effect, there is no set-method yet to imitate the micro-nano surface structure of the lotus leaf. **Table 1** contains many examples of lotus-leaf-inspired biomimetic coating materials, some of which have been used to alleviate certain infrastructural issues [30][31].

Table 1. Various biomimetic coating materials.

Coating Material	Key Characteristics	Specific Purposes	References
PDMS (Polydimethylsiloxane)	Intrinsic hydrophobic surface; remarkably high contact angle (close to 170°); sliding angle close to that of the lotus leaf; highly water-resistant; good self-cleaning property; chemically and thermally stable; stretchable.	Inverse-trapezoidal microstructures; microfabrication with micropillars/nanohairs.	[32][33][34][35]
UPC (Ultrafine powder coating)	At 3% PTFE (polytetrafluoroethylene): High contact angle (˃160°) and low sliding angle (˂5°); lower film thickness (controllable to 1 mil); reduced surface roughness; high-quality surface finishing.	Surface protection from moisture intervention	[13][36]
CNT (Carbon nanotube) film	Excellent anti-aging performance; effective to prevent the penetration of small water droplets; long-term durability after exposure to air and corrosive liquids.	Electrodes, biosensors, anti-fogging/icing and anti-aging materials.	[37][38]
Nickel (Ni), Ni/Nano-C, Ni/Nano-Cu	PFPE (perfluoropolyether) treated Ni: high contact angle (156°) and a rough surface; reduced friction coefficient; high hardness. Ni/Nano-C (Ni-C): better anti-corrosion performance. Ni/Nano-Cu (Ni-Cu): Large contact angle (155.5°) at optimal brush speed and a Cu concentration of 5 g/L; a sliding angle of 5°.	Substrate protection; anti-corrosion surface coatings.	[39][40]

Coating Material	Key Characteristics	Specific Purposes	References
FOTS-TiO_2 (Fluoro-octyl-trichloro-silane-titanium)	Superamphiphobic (superhydro-oleophobic); high contact angle with peanut oil; liquid repellence with a surface tension as low as 23.8 mN/m; high thermal stability; self-cleaning; anti-fouling/anti-icing.	Surface treatment of materials and products (Zn plate, PU sponge, filter paper, cotton fibers, etc.); civil infrastructure maintenance; temperature sensitive nanotechnology applications.	[31][41]
Janus particles	Superhydrophobic performance with nanoscale roughness; covalent binding with substrate; tolerant to high water flushing speeds and organic solvents.	Nanoprobes, nanosensors, display systems, water-repellent textiles, drug delivery and control systems, functional coatings, etc.	[42][43]
Diamond-like carbon (DLC)	Balance of hardness and flexibility due to microstructures; high contact angle; low friction coefficient; greater corrosion resistance.	Bio-robotics, bio-medical devices, anti-corrosion surface coatings.	[44][45][46]
Micro- and nanosized silica (SiO_2) particles	Strong liquid (e.g., water, brine, acidic solution) repellency with a high contact angle and a low sliding angle for droplets; strong binding adhesion with underlying substrate; high weathering resistance including UV (ultraviolet) protection; high transmission of light with low reflection; excellent wear and scratch resistance.	Anti-abrasion, anti-corrosion, and waterproofing applications; surface coatings for self-cleaning and energy harvesting.	[47][48]
Calcium hydroxide [$Ca(OH)_2$] microcapsules with polymeric shell	Regenerative lotus effect—controllable via sodium stearate solution; good resistance to water flushing; strong binding adhesion to substrate; superior corrosion resistance in chloride environment.	Substrate modifications, corrosion-resistant coatings.	[49][50]
Graphene oxide-silica (GO-SiO_2)	Highly hydrophilic; superior barrier performance and corrosion protection; good binding adhesion with substrate.	Electrode, capacitor, and biosensor fabrication; anti-corrosion composite coatings.	[51][52][53]
Photopolymer (PP)	Transparent; anti-reflective and self-cleaning abilities; increased solar light absorbance; UV- or electron-beam curable; resistant to acidic and basic conditions.	Harvesting of alternative energy—coating on solar cells; protective coatings and decorative finishes; surface modifications of fibers and films; coatings for biosensors and electrodes.	[54][55]
Copper (Cu)	Superhydrophobic/superolephobic; hierarchical flowerlike surface morphology; long-term chemical stability; high contact angle for pure water as well as under both acidic and basic conditions.	Protection of steel surfaces; self-cleaning steel structures; oil pipelines for anti-fouling and low fluid drag.	[56][57]
Zinc oxide (ZnO) film	Can be either superhydrophobic or superhydrophilic depending on surface morphology; superhydrophobicity with a contact angle of 155° to more than 170°; superhydrophilicity with a low contact angle of approximately 1–2.8°; UV-stable.	Self-cleaning PV (Photovoltaic) and glazing applications	[58][59][60]
Acrylic polymer (AP)	High water repellency; delayed ice nucleation; reduced binding adhesion with ice; lower freezing point of water.	Anti-icing coatings for pavement/building protection from frost damage; anti/de-icing systems for cars and airplanes, telecommunication antennas, or wind turbines.	[30][61]
Antimony doped tin oxide/polyurethane (ATO/PU) film	Superhydrophobicity and high heat-insulation; water contact angle up to about 155°; high visible light transmittance (76%); low infrared transmission; high thermal stability.	Self-cleaning solar cells; heat-insulating glass.	[62][63][64]

Coating Material	Key Characteristics	Specific Purposes	References
PMMA (Polymethyl methacrylate)	**Increased PV efficiency (up to 17% gains); high optical transparency (˃80%); low reflection; chemically resistant to aqueous alkalis and most acids; high moisture resistance; protected from oxygen; UV-durable; abrasion-resistant.**	**Natural light harvesting for alternative energy; roofing membranes; balcony and parking deck surfacing and waterproofing applications.**	[65][66]
PPS/PTFE (Polyphenylene sulfide/polytetrafluoroethylene)	**Superamphiphobic; high contact angle (151–172°); excellent impact and wear resistance; low coefficient of friction; high cohesion and thermal stability; high anti-scaling ability.**	**Lubricant surface coatings; anti-scaling coatings.**	[67][68][69][70]

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