

Review

Lotus-Leaf-Inspired Biomimetic Coatings: Different Types, Key Properties, and Applications in Infrastructures

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Abstract: 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. The present study was conducted to explore any attempted biomimicry of the lotus leaf to produce biomimetic coatings. It focuses on anti-wetting characteristics (e.g., superhydrophobicity, sliding angle, contact angle), self-cleaning capability, durability, and some special properties (e.g., light absorbance and transmission, anti-icing capacity, anti-fouling ability) of lotus-leaf-inspired biomimetic coatings. This study also highlights the potential applications of such coatings, particularly in infrastructures. The most abundant research across coating materials showed superhydrophobicity as being well-tested while self-cleaning capacity and durability remain among the properties that require further research with existing promise. In addition, the special properties of many coating materials should be validated before practical applications.



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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 [3–5]. 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 $>150^\circ$ [6–8].

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 a relatively recent development in coating technology. Lotus leaf, specifically the *Nelumbo nucifera*, has the natural ability to repel water droplets at a high contact angle ($>150^\circ$), thus being superhydrophobic [13,14]. In addition, the lotus leaf utilizes its high contact angle to cause the water droplets to roll off the leaf at a low sliding angle ($<5^\circ$)—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 a number of 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. Based on nanotechnology and biomimicry, the researchers attempted to replicate the micro-nano surface structure of the lotus leaf in creating superhydrophobic coating materials. 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.

The purpose of this study is to examine the surface structure and characteristics of the generic lotus leaf and compare them to those of attempted biomimetic coatings that were intended for specific applications in different areas, including infrastructures. It is with hopes that by examining these applications one can pinpoint a proper coating that comes closest to replicate the superhydrophobic nature of the lotus leaf. It is also important to formulate a surface coating that can withstand moisture damage and maintain good durability in service conditions.

2. Surface Structure and Characteristics of Lotus Leaf

The nanoscale hair-like wax crystals and microscale epidermal cells of the lotus leaf are related to its lotus effect [23–25]. Figure 2 provides a simple diagram of the hydrophobic structure of a lotus leaf 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 water droplets cannot reach the valley areas due to their larger size. In addition, the debris never enter deep enough into the valleys due to 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].

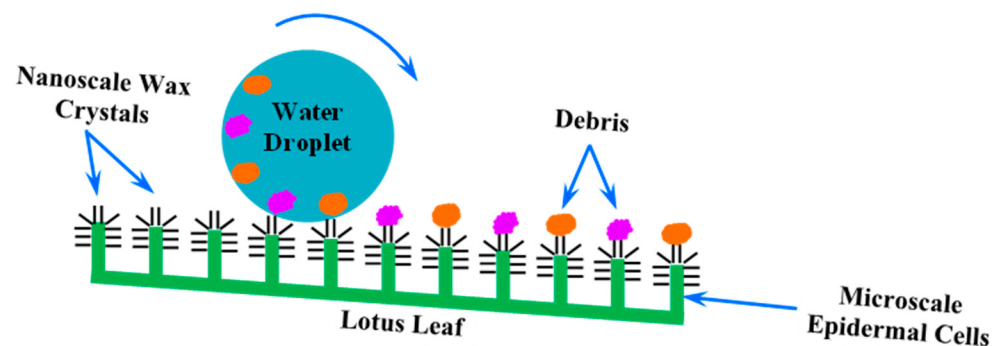


Figure 2. A simple schematic for understanding of the lotus effect. The water droplet collects the debris as it descends from the leaf. The figure has been created by the authors based on the concept illustrated by Poole [27].

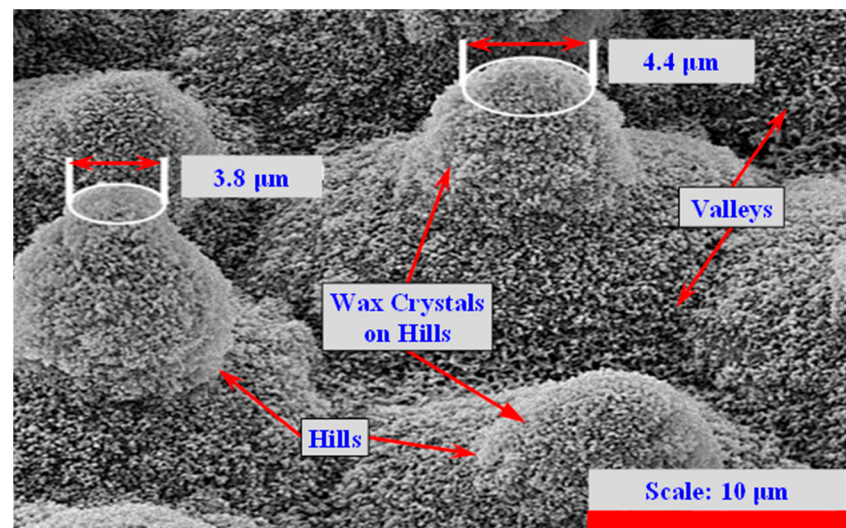


Figure 3. An SEM image of the lotus leaf (modified from Ensikat et al. [28]). This image depicts the microscale structure comprising hills with the valleys among them, as well as the nanoscale wax crystals. The diameters of two mountain peaks are also shown.

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 main 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; self-cleaning; chemically and thermally stable; stretchable.	Creation of inverse-trapezoidal microstructures; microfabrication with micropillars/nanohairs.	[32–35]
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/anti-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 a Cu concentration of 5 g/L and optimal brush speed; a sliding angle of 5°.	Substrate protection; anti-corrosion surface coatings.	[39,40]
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 and anti-fouling/anti-icing.	Surface treatment of materials and products (Zn plate, PU (polyurethane) 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.	[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.	[44–46]
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]

Table 1. *Cont.*

Coating Material	Key Characteristics	Specific Purposes	References
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 with 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 fabrications; anti-corrosion composite coatings.	[51–53]
Photopolymer (PP)	Transparent and anti-reflective; self-cleaning; 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/superoleophobic; 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	[58–60]
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-icing/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.	[62–64]
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; UV-durable; protected from oxidation; 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.	[67–70]

4. Key Properties of Lotus-Leaf-Inspired Biomimetic Coatings

4.1. Hydrophobicity and Self-Cleaning Ability

Lotus-leaf-inspired biomimetic coatings possess high hydrophobicity (water repellence) and exhibit self-cleaning ability. The important parameters to consider for the hydrophobicity and self-cleaning capacity of biomimetic coating materials are their contact

and sliding angles [23,71]. The lotus leaf is considered superhydrophobic and self-cleaning for having a contact angle $>150^\circ$ (refer to Figure 4) with a sliding angle of approximately 5° , guaranteeing the water droplets will clean debris [25,48]. Figure 5 presents the sliding angles of the lotus leaf and various biomimetic coating materials as well as their mean values reported in many published papers. There are few that fulfill the requirement of sliding angle in comparison to the required contact angle due to more emphasis on hydrophobicity than self-cleaning in certain considerations.

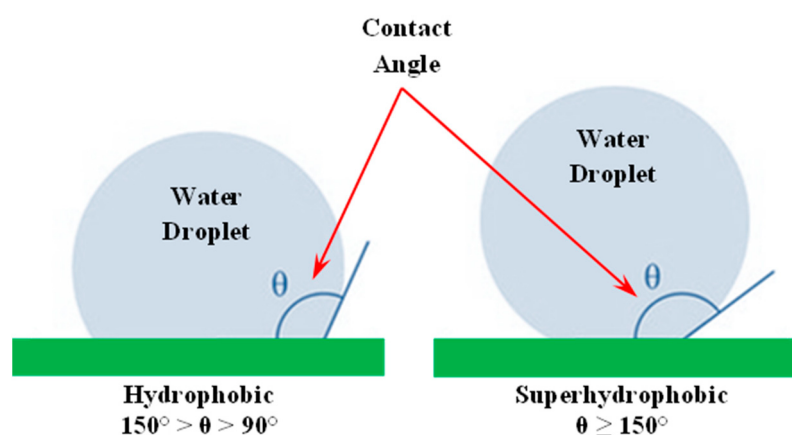


Figure 4. Contact angles required for hydrophobicity and superhydrophobicity. This figure has been created by the authors based on the concept illustrated by Koch et al. [72].

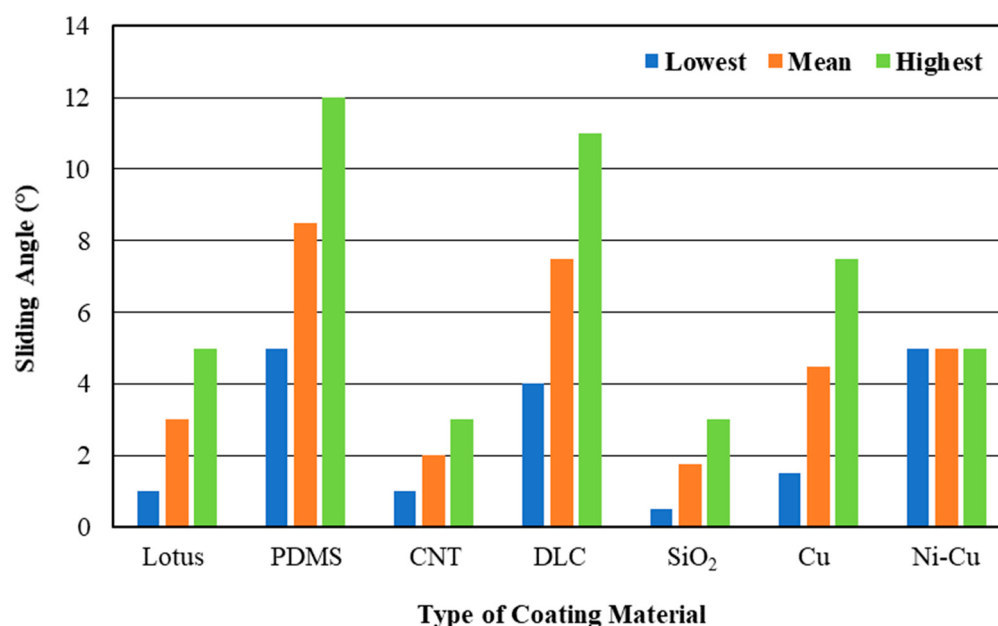


Figure 5. An analysis of the recorded sliding angles for some coating materials. Any sliding angle $<5^\circ$ is considered on a par with that of the lotus leaf.

The sliding angles of SiO₂, CNT, and Ni-Cu coatings fall in the range of 0.5 – 5° , as can be seen in Figure 5, which also includes the sliding angle of the lotus leaf. A large variation in the sliding angle exists for DLC, Cu, and PDMS coatings (refer to Figure 5). The sliding angles of DLC and Cu coatings depend on their reported experiments; DLC's sliding angle is dependent on the flexibility and Cu's is dependent on the concentration of Cu atoms. DLC as well as PDMS exhibited the largest variation in the sliding angle. The individual mean sliding angles of CNT, SiO₂, Cu, and Ni-Cu are 2° , 1.75° , 4.5° , and 5° , respectively.

and are $\leq 5^\circ$, as can be seen in Figure 5. In contrast, the individual mean sliding angles of PDMS and DLS are 8.5° and 7.5° , respectively, and both are $>5^\circ$.

Reports for the contact angle are more prevalent. Figure 6 contains a bounty of materials analyzed for the water contact angles. This figure shows that different coatings can result in a lower or higher contact angle for water droplets. Even the same coating may show a significantly large difference between the lower and higher values of contact angle, as evident from Figure 6. These differences could be due to several variables including viscosity, concentration, and adhesion.

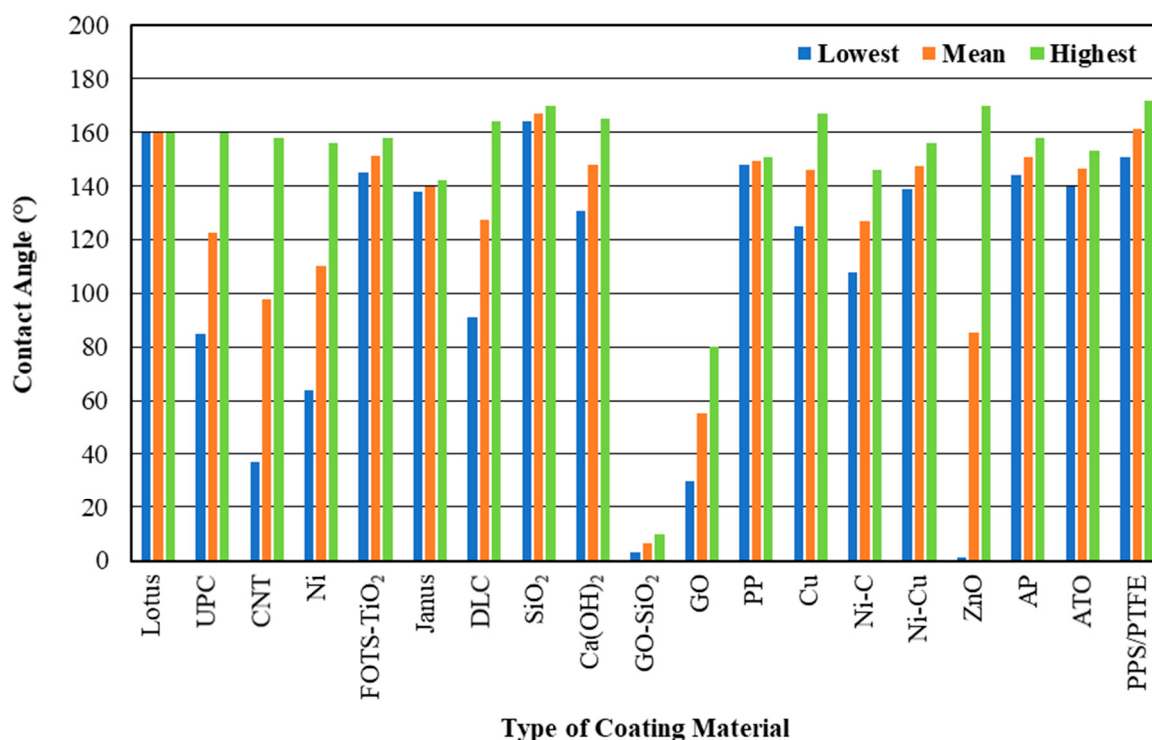


Figure 6. An analysis of the recorded contact angles for various coating materials. Any contact angle $>150^\circ$ is considered on a par with that of the lotus leaf.

The coating materials that make a mean contact angle $\geq 150^\circ$ for water droplets include FOTS-TiO₂, SiO₂, PP, AP, and PPS-PTFE. The mean contact angle is also very close to 150° in the cases of Ca(OH)₂, Cu, Ni-Cu, and ATO. The above-mentioned coatings create a contact angle alike the lotus leaf for a variety of reasons, including a similar replication of the lotus's hair-like nanostructure and microscale protrusions with an equivalent size. It is also obvious from Figure 6 that UPC, CNT, Ni, DLC, and ZnO can produce a contact angle $>150^\circ$ for water droplets although they show a large variation. Some of these coating materials, such as ZnO, have a unique aspect regarding the affinity to water. ZnO requires the addition of Teflon AF to make the difference between being superhydrophilic or superhydrophobic [60]. This may be due to Teflon AF's adhesive capability and integrational ability. Furthermore, compared to many other coatings, GO-SiO₂ creates a very low contact angle for water droplets due to its superhydrophilicity. The purpose of adding a superhydrophilic material, GO-SiO₂, in this study was to present that while water repellence is a key factor to consider for fabrication of any hydrophobic coating, there can be uses for hydrophilic coatings in some cases, such as water-purifying membranes and medical devices [52].

The most optimal coating material in terms of hydrophobicity and self-cleaning should contain excellent results for both sliding and contact angles. It can be deduced from the charts (Figures 5 and 6) that CNT, SiO₂, Ni-Cu, and Cu appear as superhydrophobic self-cleaning coatings with appropriate sliding and contact angles. These are all dependent on additives or concentration of the material to ensure a proper range. Besides, compared to

many other coating materials, FOTS-TiO₂, PP, AP, and PPS-PTFE give excellent contact angle required for superhydrophobicity. However, due to the lack of information on their sliding angles, it is not certain that they perform best as a self-cleaning coating, and therefore further research should be encouraged to have a complete picture of their behaviors. This having been said, the reported contact angles provide a keen foundation for future insight by focusing on the materials that exceed the contact angle required for superhydrophobicity.

4.2. Durability

A key aspect of the coating materials for practical applications is their durability. It is the ability of a coating material to remain functional for a long time without significant deterioration in various environments. Lotus-leaf-inspired biomimetic coatings must be durable to provide optimal performance despite natural interferences (e.g., rain, snow, temperature) or non-natural disturbances (e.g., traffic abrasion, mechanical wear). Although numerical and scientific details are lacking, there have been some coating materials that provide good durability inherently. These include but are not limited to UPC [13], CNT [38], Ni-C [40], Janus particles [43], and DLC [46].

Lotus-leaf-inspired biomimetic coatings can show excellent anti-corrosion performance due to their superior moisture resistance. A number of such coatings have already been successfully developed for corrosion protection of different metals and their alloys, including aluminum, copper, magnesium, and steel [73]. Several coating materials (e.g., Ni-C [40], DLC [45], Ca(OH)₂ microcapsules [49]) listed in Table 1 had shown to have better or superior anti-corrosive properties along with their hydrophobicity. It can also be seen in Table 1 that some superhydrophobic lotus-leaf biomimetic coatings (e.g., FOTS-TiO₂ [41], ATO/PU [63], PPS/PTFE [69]) possess high thermal stability and some other (e.g., PDMS [34], Cu [56], PMMA [65]) have high chemical stability.

Many lotus-leaf-inspired biomimetic coatings (e.g., SiO₂ [48], PMMA [65], ZnO [59]) are UV-durable and thus would enhance the performance of materials and products used in outdoor conditions, as they can remain robust and stable to maintain their hydrophobicity with increasing UV exposure time [48,59]. Some coating materials (e.g., CNT [37,38], PMMA [65]) are protected from degradation caused by oxidation and hence can retain the original aesthetic appearance for a longer time. The UV-durability and oxidation-resistance of the aforementioned coating materials suggest that they would show better anti-aging performance by weakening the powdering, blistering, and color-change phenomena. Furthermore, some coating materials (e.g., SiO₂ [47], PMMA [65], PPS/PTFE [67,69]) can have high abrasion or wear resistance and good anti-scaling ability (refer to Table 1) due to their strong binding adhesion with underlying substrate [48].

In brief, it can be inferred that, while consistent numerical analysis is difficult, the property improvements in the context of durability cannot be ignored for some of the coating materials considered in this study. Superhydrophobicity plays the major role for the durability of lotus-leaf-inspired biomimetic coatings. However, further research is required to understand the mechanisms of improvement for certain durability-related properties.

4.3. Special Properties

While the major objective of this report is to explore the hydrophobicity, self-cleaning capacity, and durability of various coating materials inspired by the micro-nano surface structure of the lotus leaf, certain coatings are found to possess special alternative abilities arisen from the modification and fabrication processes. Some of these include the following:

- High light absorbance and transmission [48,54] inspired by the photosynthetic capability of the lotus leaf—the photovoltaic efficiency can be increased by up to 17% to increase the efficacy of solar cells in energy harvesting [66]. This is credited to the rough, wrinkled, micro-nano surface structure of lotus-leaf biomimetic coatings that can reduce the reflection of sunlight [54,66], thus increasing the light absorbance. Moreover, Huang et al. [66] reported that good optical transparency (>80%) contribut-

ing to high light transmission capacity can be achieved for a transparent lotus-leaf biomimetic coating.

- Anti-icing capacity [31,38]—it prevents damages caused by the frost action during winter with freezing conditions. The anti-icing capability of a lotus-leaf biomimetic coating depends on its superhydrophobicity and the size of the particles exposed on the surface—the icing probability is negligible or nil for the particle sizes of 10–100 nm, where the contact angle of water droplets can be in the range of 153.5–158.5°, which greatly decreases the surface wettability [30]. It implies that the hair-like nanoscale wax crystals (refer to Figure 2) play a critical role against the ice formation. Even if the ice is formed, its binding adhesion with coating will be significantly lower due to the reduced liquid/solid interface, and therefore it can be easily removed [74]. The entire micro-nano structure of coating keeps the water droplets buoyant on the surface, thus reducing the contact area between water and coating; moreover, instead of water, air will exist in microscale valley areas and form voids under the ice layer—these phenomena will weaken the ice-coating bond.
- Anti-fouling ability—some lotus-leaf-inspired biomimetic coatings, for example, Cu [57] and FOTS-TiO₂ [31] can be superamphiphobic (superhydrophobic/superoleophobic). They can repel not only pure water but also salt water, as well as acidic and basic liquids. In addition, superamphiphobic coatings exhibit anti-bacterial activity along with anti-wetting and self-cleaning capacities, as they can inhibit the adhesion of bacteria [75]. Such abilities make them to work as anti-fouling materials in various environments [76,77].

In fine, the above-mentioned special properties of biomimetic coatings are linked with their micro-nano surface structure like that of the lotus leaf. The researchers have realized the micro-nano-structural features of the lotus-leaf surface in making various coating materials. They have mimicked the hydrophobicity and self-cleaning mechanism of the lotus leaf to produce a number of biomimetic coatings. However, the fundamental scientific reasons for all of the aforementioned special properties are not yet well-understood by the researchers and therefore more investigations are required for further insight of lotus-leaf biomimetic coatings to fill in this knowledge gap.

5. Applications of Lotus-Leaf-Inspired Biomimetic Coatings in Infrastructures

The potential applications of lotus-leaf-inspired biomimetic coatings are insurmountable. There already exists a plenty of research on the use of these coatings. They have the capacity to extend the service life of infrastructures through reduced moisture damage due to their superior water repellence or hydrophobicity if applied as a self-cleaning surface treatment [23,48]. Moisture is required for many deterioration mechanisms of concrete, such as freeze-thaw, salt-scaling, rebar corrosion, sulfate attack, and alkali-aggregate reactions, which can cause severe damages in infrastructures. These damages can be alleviated significantly by applying superhydrophobic coatings, which will inhibit the movement of moisture through concrete surfaces. Superhydrophobic lotus-leaf biomimetic coatings can also protect many metallic materials and products used in infrastructures by acting as an anti-corrosion protective layer or a corrosion barrier [73] to prevent moisture and other corrosive agents (e.g., chlorides, sulfates) from breaching metal surfaces.

Lotus-leaf-inspired biomimetic coatings can be used for a myriad of civil structures including but not limited to buildings, bridges, pavements, and sewers [26,78]. They can be applied on the exterior walls or facades, roofs, and floors of buildings to minimize the dampness due to water absorption [26,65,78]. Lotus-leaf biomimetic coatings will provide dust-free, self-cleaned, dry surfaces in the cases of walls or facades. This is because water droplets will roll down swiftly with debris and dust will not be accumulated on the surface due to high water repellence of such coatings. Moisture-resistant floors and roofs can also be obtained by applying lotus-leaf biomimetic coatings [26,65]. Moisture is involved in the deterioration of the flooring and roofing systems of buildings. Lotus-leaf biomimetic coatings will decrease the moisture movement into the flooring and roofing

systems of a building due to the lotus effect. These coatings will also accelerate the drainage of snow-melt water or rainwater from the roof of a building, thus reducing the likelihood of moisture-induced damages. Furthermore, due to superhydrophobic nature, lotus-leaf biomimetic coatings will prevent mold, mildew, and algae from growing on the wall, floor, or roof surfaces and thereby improve the health of buildings for a longer service life.

Superhydrophobic lotus-leaf biomimetic coatings can be applied on bridge decks or road pavements for fast drainage, thus allowing them to dry quickly during the wet season for enhanced durability and safe driving conditions [17,26]. However, the frictional properties of deck or pavement surfaces required for traffic safety must be ensured in such applications. Indeed, it was observed during an investigation that a lotus-leaf biomimetic coating can provide the required frictional resistance when applied on the broom finished concrete surface [19]. This type of coatings can also be used on other components of bridge structures such as pier, railing, divider, and abutment to enhance their durability with greater moisture resistance.

Anti-icing superhydrophobic lotus-leaf biomimetic coatings can be applied on highways to maintain service conditions in adverse weather and to ease road maintenance in winter-region countries given they do not impair the frictional properties of pavements [74]. They will also decrease the salt-scaling and frost-induced cracking of road surfaces. Furthermore, anti-icing lotus-leaf biomimetic coatings will be useful for the maintenance of buildings and other infrastructures. Ice buildup on the roof, patio, and driveway of a building can cause severe damage requiring costly repairs. Freezing water can cause short circuits and ruin electrical equipment. Ice buildup on electrical transmission lines and towers may have fatal consequences. These issues can be minimized or eliminated by using anti-icing superhydrophobic coatings.

Water-repellent lotus-leaf biomimetic coatings can be used to enhance the performance of drainage structures. They can be applied on the inner surface of storm and sanitary sewers to increase the flowrate of stormwater and wastewater, respectively by decreasing the surface friction [26,78]. In addition, this type of coatings can be considered for use in culverts to enhance the flowrate of overland water for faster drainage; they can also be applied on tunnel lining to keep the tunnel structures dry and to inhibit the growth of mold and mildew in tunnels [26]. Besides, the aerodynamic effects of the trains or other vehicles shall be reduced by applying a lotus-leaf biomimetic coating on the tunnel surface.

Light-absorbing and transparent lotus-leaf biomimetic coatings can be considered for their applications in infrastructures. The light transmission capability and anti-reflection property of a lotus-leaf biomimetic coating shall be implemented to convert solar light into electrical energy for use in near-zero or net-zero energy buildings [66,79]. Moreover, the heat-resistant biomimetic coatings shall be applied as a thermal barrier [80] in buildings. Lastly, anti-aging biomimetic coating materials can be used to lessen the weathering degradation of infrastructures caused by the reactions with oxygen and UV light [59,65], whereas anti-fouling coatings to prevent the marine structures and devices as well as the pipelines from biofouling [75–77].

In summary, lotus-leaf-inspired biomimetic coatings may bring forth enormous economic and environmental benefits based on their durability and special properties in conjunction with superhydrophobicity and self-cleaning capacity. However, further research should be conducted to verify the effectiveness of such coatings for the above-mentioned applications, particularly considering the cost and durability together with their special properties.

6. Concluding Remarks and Recommendations

The key aspects of lotus-leaf biomimetic coatings are their superhydrophobicity, self-cleaning capacity, and durability. The coating materials with a contact angle $>150^\circ$ and a sliding angle $<5^\circ$ are considered to possess the first two properties whereas the durability varies from one material to another material, as revealed from literature survey. A lotus-leaf biomimetic coating significantly decreases the ingress of water due to its superhydrophobic

nature with a contact angle $>150^\circ$ for water droplets and thus it lessens the damaging effects of moisture involved in many deterioration mechanisms, such as corrosion and frost action. Moreover, this type of coating offers self-cleaning with water droplets rolling down at a sliding angle $<5^\circ$. The microscale hills and the hair-like nanoscale wax crystals keep the water droplets buoyant while they roll down the coating surface.

Lotus-leaf biomimetic coatings have good potential for applications in different sectors of infrastructures, such as buildings, pavements, bridges, tunnels, electrical power transmission towers, and drainage structures (e.g., culvert, storm sewer, sanitary sewer). For many applications, coating materials should have good resistance to corrosion, moisture and ice damage, crack formation, and microbial growth, ergo material and environmental aspects must be considered when choosing a material for surface treatment. Certain lotus-leaf biomimetic coating materials can also possess special characteristics (e.g., anti-icing capacity, light absorbance and transmission, anti-fouling ability). However, the performance of the coatings possessing different durability-related properties and special features should be evaluated proficiently in various exposure conditions before specific applications.

The best recommendation to make given the literature existing and the materials available is to consider durability and provide a broad numerical aspect for each of the coating materials presented in this paper. It is also recommended that further tests for the sliding angles of various coatings are conducted, as such consideration is required to properly examine the self-cleaning capability of a coating material. Overall, many lotus-leaf biomimetic materials have been developed and their superhydrophobicity is well-tested across literature; the next step would be to further research into the durability and special properties to find the best material formulation of lotus-leaf biomimetic coating to be applied on infrastructures for a longer service life.

The performance of superhydrophobic lotus-leaf biomimetic coatings should be comprehensively studied for energy and cost savings, reliability in long-term service, and environmental safety. In the case of applications on highways, the abrasion resistance and skid resistance of these coatings are important for traffic safety. Moreover, some of the coating materials may not be economical despite their novel properties if expensive nanomaterials are included in their formulation. Therefore, the cost-benefit analysis should be performed before any applications, considering the special properties and durability of coatings.

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