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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 anti-wetting characteristics (e.g., superhydrophobicity, sliding angle, contact angle), self-cleaning, durability, and some special properties (e.g., light absorbance and transmission, anti-icing capacity, anti-fouling ability) of lotus-leaf-inspired biomimetic coating products. This study also highlights the potential applications of such coating products, particularly in infrastructures. The most abundant research across coating materials showed superhydrophobicity as being well-tested while self-cleaning 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.

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

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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° [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 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.

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 (resistance to weathering actions) in service conditions.

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 [23–25]. 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].

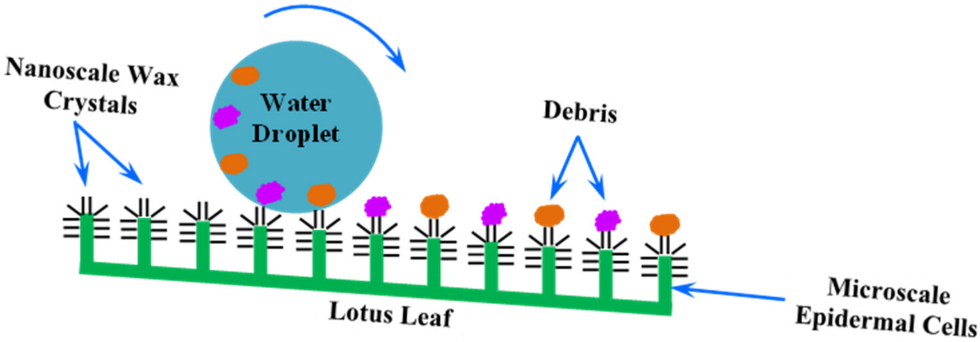

Figure 2. A simple schematic for understanding of the lotus effect. The water droplet collects the debris as it descends from the leaf. The figure has been created by the authors based on the concept illustrated by Poole [27].

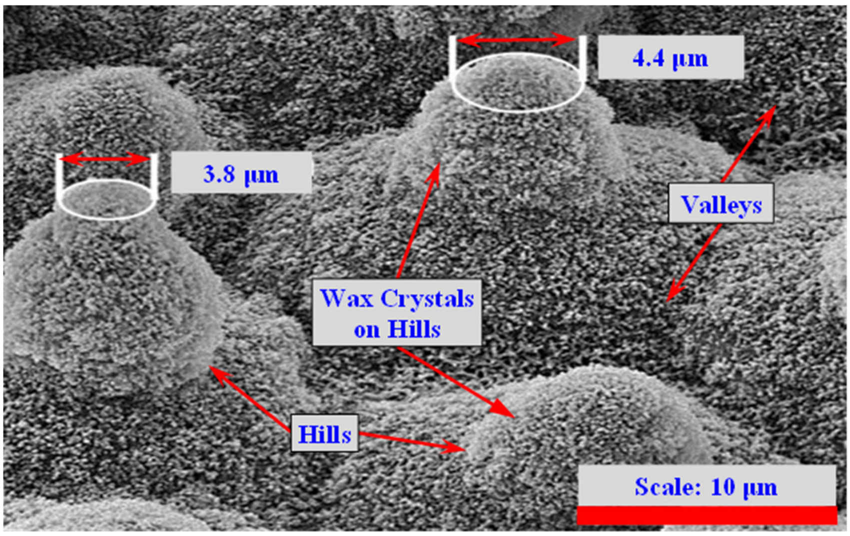

Figure 3. An SEM image of a lotus leaf (modified from Ensikat et al. [28]). This image depicts the microscale structure comprising hills with the valleys among them, as well as the nanoscale wax crystals. The diameters of two mountain peaks are also shown.

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.	[32–35]
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]
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.	[44–46]
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 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.	[51–53]
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 biosensor 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	[58–60]
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.	[62–64]
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; 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.	[67–70]

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

4.1. Hydrophobicity and Self-Cleaning Property

Lotus-leaf-inspired biomimetic coatings possess high hydrophobicity (water repellence) and exhibit self-cleaning ability. Important parameters to consider for the efficacy of hydrophobicity and self-cleaning performed by the biomimetic coating materials are their respective contact and sliding angles [23,71]. The lotus leaf is considered superhydrophobic and self-cleaning for having a contact angle >150° (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 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. The sliding angles of SiO_2, CNT, and Ni-Cu coatings fall in the range of 0.5–5°, 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 are dependent 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, SiO_2, Cu, and Ni-Cu are 2°, 1.75°, 4.5°, and 5°, respectively and are ≤5°, as can be seen from Figure 5. In contrast, the individual mean sliding angles of PDMS and DLS are 8.5° and 7.5°, respectively, and both are >5°.

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. The coating materials that make a mean contact angle ≥150° for water droplets include FOTS-TiO_2, SiO_2, 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° for water droplets although they show a large variation. Some of these coating materials have a unique aspect, such as ZnO, which 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. Compared to many other coatings, GO-SiO_2 creates a very low contact angle for water droplets due to its superhydrophilicity. The purpose of adding a superhydrophilic material, GO-SiO_2, in this study was to present that while water repellence (hydrophobicity) is the most important factor to consider for any coating fabrication, there can be uses for hydrophilic coatings in some cases, such as water-purifying membranes and medical devices [52].

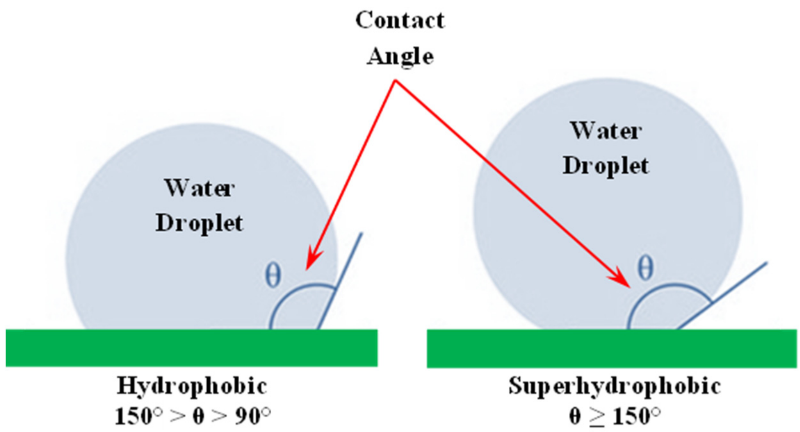

Figure 4. Contact angles required for hydrophobicity and superhydrophobicity. This figure has been created by the authors based on the concept illustrated by Koch et al. [72].

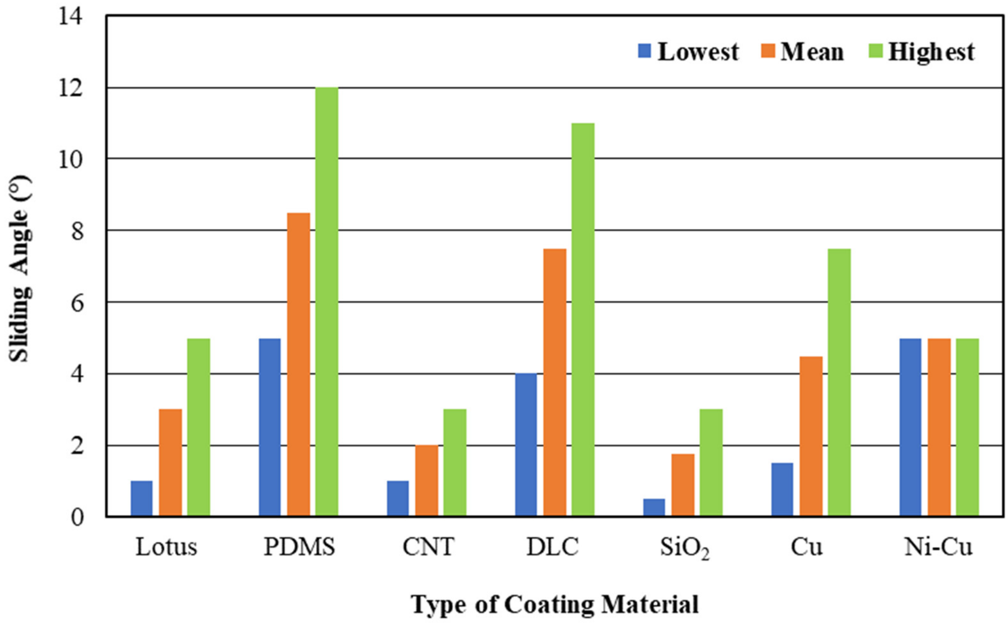

Figure 5. An analysis of the recorded sliding angles for some coating materials. Any sliding angle <5° is considered on a par with that of the lotus leaf.

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, SiO_2, Ni-Cu, and Cu appear as superhydrophobic self-cleaning coatings with appropriate sliding and contact angles. These are all dependent on respective additives or concentrations of the material to ensure a proper range. Compared to many other coating materials, FOTS-TiO_2, 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.

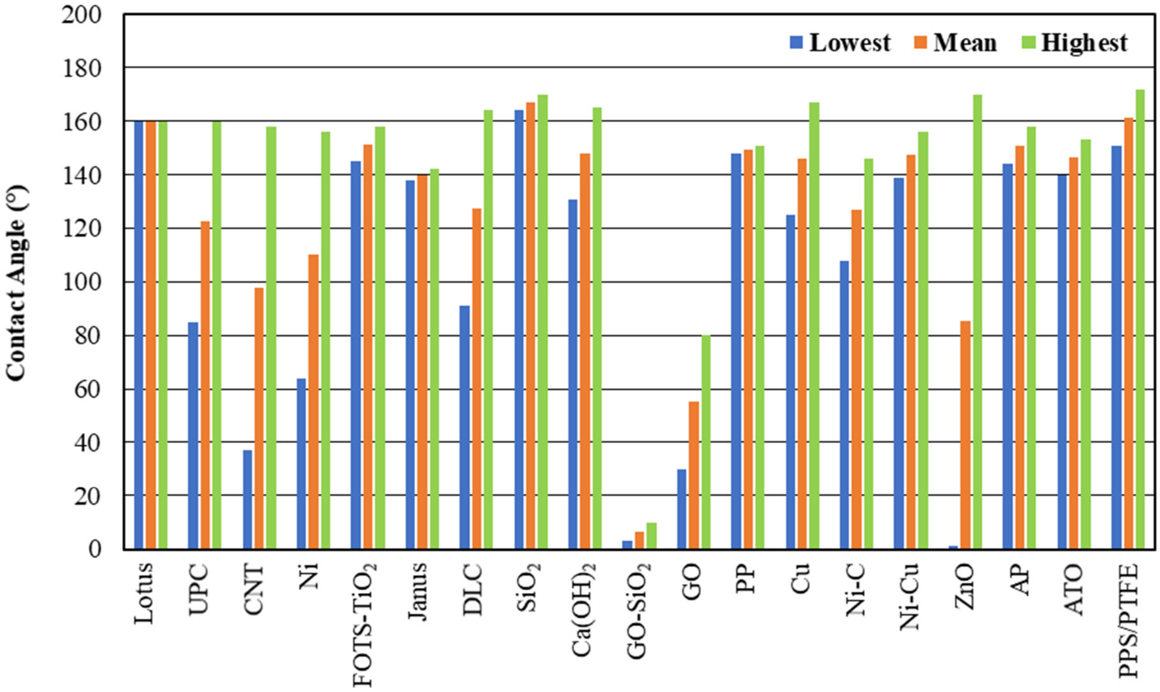

Figure 6. An analysis of the recorded contact angles for various coating materials. Any contact angle >150° is considered on a par with that of the lotus leaf.

4.2. Durability Properties

A key aspect of the coating materials for practical applications must be the ability to maintain its durability 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]. Several coating materials have high chemical stability (e.g., Cu, PDMS, PMMA) and better anti-corrosive properties (e.g., DLC, Ni-C, $Ca(OH)_2$ microcapsules) along with their hydrophobicity (refer to Table 1). It can also be seen in Table 1 that some superhydrophobic lotus-leaf biomimetic coatings (e.g., FOTS-TiO_2, ATO/PU, PPS/PTFE) possess high thermal stability. Some coatings (e.g., PMMA, SiO_2, ZnO) are UV-durable and thus would enhance the weathering 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]. Certain coating materials (e.g., CNT, PMMA) are protected from oxidation degradation [37,38,65] and hence can maintain 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, certain coating materials (e.g., PMMA, PPS/PTFE, SiO_2) can have high abrasion or wear resistance and good anti-scaling ability (see Table 1) due to strong binding adhesion [48]. Hence, 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 materials considered in this study. However, further research is required to comprehend the fundamental scientific reasons for improvement of certain durability properties.

Superhydrophobic lotus-leaf biomimetic coatings would extend the service life of infrastructures greatly through reduced moisture damage due to their excellent water repellence or hydrophobicity if applied as a self-cleaning surface treatment [23,48]. The moisture is involved in 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 lessened significantly by superhydrophobic coatings, which will inhibit the movement of moisture through concrete surfaces. Superhydrophobic 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] so that water and other corrosive agents (e.g., chlorides, sulfates) cannot breach metal surfaces.

4.3. Special Properties

While the major objective of this report is to examine the hydrophobic and durability properties of various coating materials inspired by the micro-nano surface structure of the lotus leaf, certain materials 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 the 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%) can be achieved for a transparent lotus-leaf biomimetic coating, thus indicating its high light transmission capacity.
- 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 particles in the size range 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—it contributes to reducing the contact area between water and coating; moreover, instead of water, air will exist in microscale valley areas—these phenomena will weaken the ice-coating bond.
- Anti-fouling ability—some lotus-leaf-inspired biomimetic coatings, for example, Cu [57] and FOTS-TiO_2 [31] can be both superhydrophobic and superoleophobic (superamphiphobic). 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, 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 summary, the above-mentioned special properties of biomimetic coatings are linked with the micro-nano surface structure of the lotus leaf. The researchers have realized the micro-nano-structural features of the lotus-leaf surface in making various coatings. They have mimicked the hydrophobicity and self-cleaning mechanism of the lotus leaf to produce various biomimetic coatings. However, the underlying 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 the lotus-leaf biomimetic coatings to fill in this knowledge gap.

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

The potential applications of a lotus-leaf-inspired biomimetic coatings are insurmountable. There already exists a plenty of research on the use of the lotus-leaf-inspired biomimetic coatings. They can be used for a myriad of civil structures including but not limited to buildings, bridges, pavements, and sewers [26,78]. Lotus-leaf biomimetic coatings 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]. In the cases of walls or facades, dust-free, self-cleaned wall surfaces will be obtained because water droplets will roll down swiftly with debris and dust will not be accumulated on the surface due to high water repellence of the lotus-leaf biomimetic coatings. The building walls or facades treated with a lotus-leaf biomimetic coating will self-cleanse during rain and stay dry due to the lotus effect. Lotus-leaf biomimetic coatings can also be used to produce water-repellent floors and roofs for enhanced service life of the buildings [26,65]. Moisture is involved in the damage mechanisms of many flooring and roofing systems. Water repellence will decrease the moisture movement into the flooring system of buildings and thus increase its service life. Water-repellent coatings will also accelerate the drainage of snow-melt water or rainwater from the roof of buildings and hence they will reduce 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.

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, it should be ensured that the frictional properties of deck or pavement surfaces are not affected in such applications to ensure the traffic safety. Indeed, it was observed from the results of British pendulum test that a lotus-leaf biomimetic coating can provide the required frictional resistance when applied on the concrete surface with broom finishing [19]. The water-repellent lotus-leaf biomimetic coatings can also be used on different components of bridge structures such as pier, deck, railing, divider, and abutment to enhance their service life with greater moisture resistance; in addition, it can be applied on the inner surface of drainage elements, such as storm and sanitary sewers, to increase the flowrate of stormwater, wastewater, or sanitary waste by decreasing the surface friction [26,78]. Lotus-leaf biomimetic coatings could be considered for use in culverts to enhance the flowrate of overland water for better drainage; it 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]. In addition, the aerodynamic effects of the trains or other vehicles could be reduced by applying a lotus-leaf biomimetic coating on the tunnel surface.

Anti-icing superhydrophobic coatings can be applied on highways to maintain the service conditions in adverse weather and to ease road maintenance in winter-region countries given they do not impair the friction property of pavements [74]. They will also decrease the salt-scaling and frost-induced cracking of the road surfaces. Anti-icing biomimetic coatings will also be useful for the maintenance of buildings and other infrastructures. Ice buildup on a roof or doorway of buildings can cause significant damage requiring costly repair. 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. Furthermore, the anti-aging properties of certain coating materials would lessen the oxidation and UV-degradation of the infrastructures. In summary, the aforementioned special properties of lotus-leaf-inspired biomimetic coatings may bring forth enormous economic and environmental benefits. However, further research should be carried out to verify the effectiveness of such coatings for the above-mentioned applications, particularly considering the cost and durability along with their key properties.

The special properties of the lotus-leaf biomimetic coatings can also be considered for their applications in infrastructure construction and management. The light transmission capability and antireflection property of a lotus-leaf biomimetic coating can be utilized to convert solar light into electrical energy for use in near-zero or net-zero energy buildings [66,79]. The heat- and UV-resistant biomimetic coatings can be used as a thermal barrier [80] and to reduce the UV-degradation of materials [48]. Anti-icing lotus-leaf biomimetic coatings can be applied on roads to minimize or eliminate road icing problems, thus increasing their traffic capacity and safety [74]. Besides, anti-aging biomimetic coating materials can be used to lessen the weathering degradation of infrastructures caused by 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].

6. Concluding Remarks and Recommendations

The key aspects of the lotus-leaf biomimetic coatings are their superhydrophobic, self-cleaning, and durability capabilities. The coating materials with a contact angle >150° and a sliding angle <5° are considered to have the first two parameters whereas the durability varies from one material to another material, as reveled from literature survey. A lotus-leaf biomimetic coating significantly decreases the ingress of water due to its superhydrophobic nature with a contact angle >150°, 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 off at a sliding angle <5°. The microscale hills and the hair-like nanoscale wax crystals keep the water droplets buoyant while they roll of the coating surface.

Lotus-leaf biomimetic coating has 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, for example, anti-icing capacity, light absorbance and transmission, and anti-fouling ability. However, the performance effectiveness of the coatings possessing various durability and special properties should be investigated thoroughly in various exposure conditions before specific applications.

The best recommendation to make given the literature existing and the materials available is to further research into durability considerations and provide a broad numerical aspect for each of the coating materials presented in this paper. It is also recommended that further tests on sliding angle proficiency 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 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. 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 long-term performance of coatings.

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