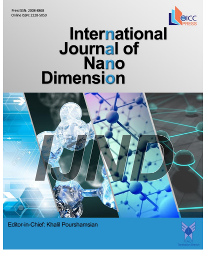

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Superhydrophobic wonders: A comprehensive review of nanomaterial-based surfaces and their myriad applications

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Abstract:

Superhydrophobic surfaces (SHSs) exhibit exceptional water repellency characterized by a high contact angle (>150°), extremely low surface energy, and minimal sliding angle (<5°). They demonstrate minimal contact angle hysteresis (<10°) and excellent Cassie-Baxter state stability. These properties, attributed to the surface's unique micro- and nano-structures or tailored chemical composition, induce a non-wetting behavior. SHSs hold significant promise for a wide range of applications due to their captivating functionalities, including efficient oil-water separation, drag reduction, anti-fogging, anti-biofouling, self-cleaning capabilities, and more. Their inherent durability and diverse functionalities render them attractive for various commercial and everyday applications. This review provides a comprehensive overview of the materials and fabrication processes employed to create SHSs, encompassing micro- and nano-structuring techniques, chemical modification strategies, and superhydrophobic coating deposition methods. We further delve into the extensive and multifaceted applications of SHSs across the transportation, energy, and biomedical engineering sectors. Despite their demonstrated potential, challenges persist in the development and practical implementation of SHSs. addressing these challenges necessitates continued research and innovation. This review aims to stimulate further progress in the field by identifying potential future research directions and unlocking the full potential of SHSs for groundbreaking applications.

Keywords: Contact angle; Cassie-model state; Nanomaterial; Self-cleaning; Superhydrophobic; Surface energy; Wetting

1. Introduction

The remarkable self-cleaning behavior observed on lotus leaves, where water droplets readily roll off the surface, has been a scientific curiosity for some time. This phenomenon, known as the "lotus effect," arises from the unique surface architecture of Nelumbo (lotus) leaves. Barthlott et al. proposed the superhydrophobicity of these leaves originates came from a combination of surface features. These features include: (1) a waxy epicuticular layer and (2) a hierarchical micro/nanoscale roughness with micropapillae (microscopic bumps) and nano cuticular wax crystals [1–7]. Nature offers a treasure trove of inspiration for scientists due to the remarkable properties exhibited by biological materials with intricate microscopic structures. Numerous examples exist, including lotus leaves [2], water striders' legs [8], spider silks [9], desert beetle shells [10], fish scales,

butterfly wings, Redmond rose petals, mosquito eyes, and cicada's wings. These surfaces display exceptional hydrophobicity, causing water to form droplets that minimize their contact area with the surface, resulting in a very small contact angle. This phenomenon is attributed to a synergistic interplay between the surface chemistry and the hierarchical micro/nanoscale roughness, often characterized by features like micropapillae and nanometer-sized waxy protrusions Replicating these intricate structures in artificial materials presents a significant challenge, but the potential benefits make it a worthwhile pursuit [11–13].
Research in the field of superhydrophobicity has witnessed significant growth since the early 2000s. Numerous review articles have been published, highlighting various aspects of these surfaces, from fundamental research to potential applications [14]. Superhydrophobic materials are characterized by a water contact angle exceeding 150° and low surface energy. This unique property, as illustrated in Figure 1, allows them to repel a wide range of liquids, including water, making them highly attractive for diverse applications [1, 15–18]. Two crucial aspects of superhydrophobic surfaces are their self-cleaning and super-repellent behaviors [4, 19–23]. Superhydrophobic surfaces, also known as artificial superhydrophobic surfaces (SHSs), have emerged as a significant area of research due to their diverse potential applications in engineering, technology, and even biology [22]. These surfaces offer a multitude of functionalities, including self-cleaning [11, 23], super-repellency, energy conversion, enhanced sensing capabilities, corrosion resistance, drag reduction, water-resistant fabrics, microfluidics, and anti-icing properties. These characteristics make SHSs highly advantageous for various everyday applications, particularly in the realm of energy conservation [24–30]. Surface modification techniques can be employed to fabricate SHSs. These techniques typically involve either increasing the surface roughness or applying a chemical coating to lower surface energy [31]. A variety of approaches can be utilized to create SHSs, including micro- and nano-structuring, chemical modification, and the use of hydrophobic coatings [32–35]. Parvate et al. [11] explored the development of biomimetic Nano surfaces, which replicate the water-repellent properties observed in natural surfaces using advanced fabrication techniques. Their study analyzes recent advancements in achieving superhydrophobicity through tailored surface architecture and chemistry. The research discusses both theoretical models and practical fabrication methods for superhydrophobic surfaces. Parvate et al. propose guidelines for designing durable superhydrophobic coatings. Additionally, the study emphasizes the importance of sustainable practices in developing environmentally friendly superhydrophobic coatings. This focus on balancing high performance with eco-friendliness paves the way for robust and sustainable solutions [11, 36].
This review aims to provide a comprehensive understanding of superhydrophobic surfaces and their durable functionalities. We begin by offering a concise description of these surfaces, followed by an overview of the theoretical underpinnings of surface wettability. Subsequently, we present established methods for fabricating superhydrophobic surfaces suitable for diverse industrial applications [37, 38]. Finally, the review highlights some key challenges and explores promising future directions for research on the fabrication of superhydrophobic patterns on superhydrophobic surfaces (SHSs).

2. Addition of different materials for the fabrication of superhydrophobic surfaces

The development of superhydrophobic nanosurfaces can be achieved through various techniques. These primarily fall into three categories: (i) incorporation of nanomaterials [39], (ii) surface modification with low-energy materials such as silicones and fluorochemicals, and (iii) a hybrid approach that combines nanofillers with low-surface-energy elements for synergistic effects. Figure 2 provides a visual representation of these strategies and the materials commonly employed. This section delves into each approach, exploring not only the materials themselves but also the diverse fabrication procedures involved. These procedures range from straightforward techniques to more sophisticated methods [13], all intending to achieve superhydrophobicity. Notably, the section on organic and inorganic materials provides specific examples of hybrid materials. Additionally, it offers a concise overview of methods for creating various nano-microstructural morphologies using different types of nanomaterials [40], including nanoparticles [41–43], microfibers, nanosheets, nanoflakes, nanowires, nanotubes [44, 45], and nanorods [11, 16, 46]. Figure 2 further complements this discussion by classifying commonly used materials for superhydrophobic surface fabrication based on their organic or inorganic nature.

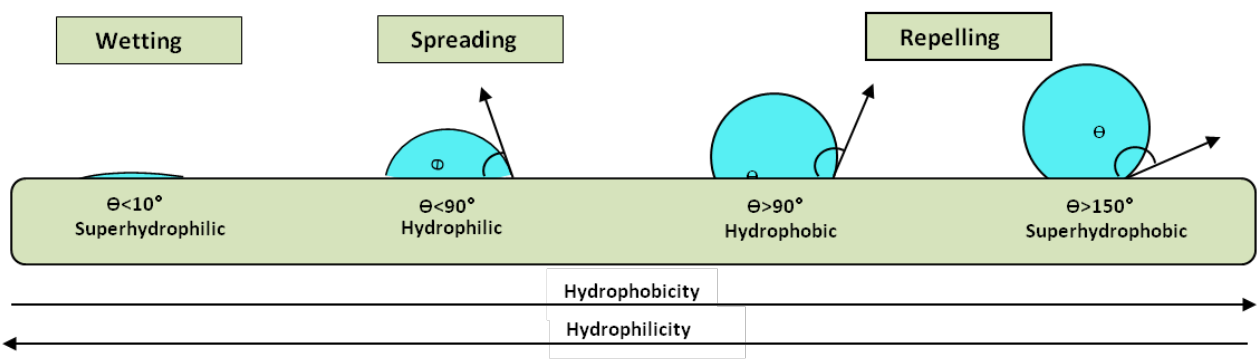

Figure 1. Water droplet scale on a solid surface in various states (0–180° angle) and their relevant wetting behavior.

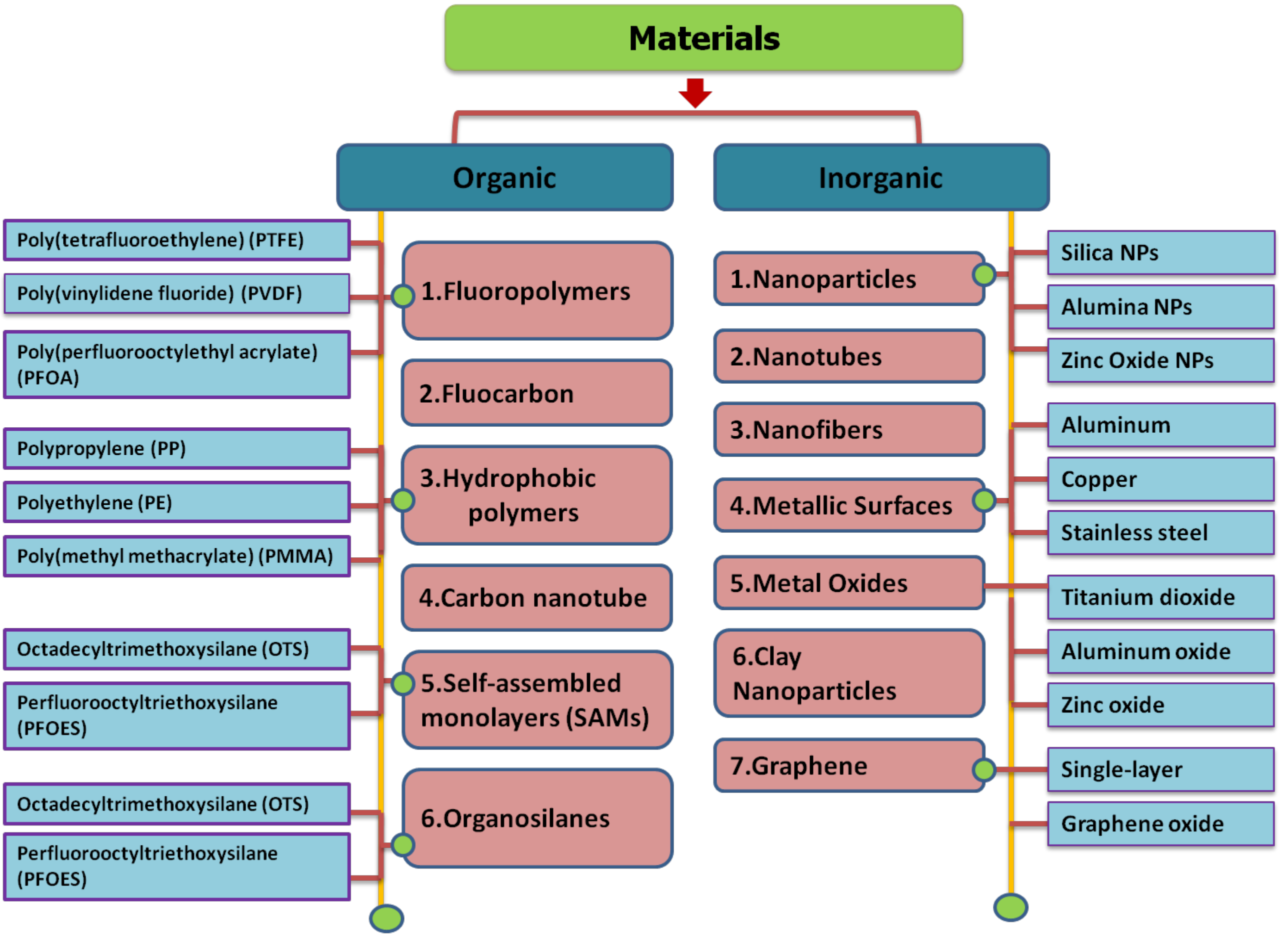

Figure 2. List of various materials that are utilized to create superhydrophobic surfaces.

3. Fabrication techniques/methods

A multitude of techniques exist for the fabrication of superhydrophobic surfaces (SHSs). Recent advancements have yielded numerous attractive methods for their synthesis, encompassing both chemical and physical approaches. While some techniques involve complex procedures and expensive equipment, others offer relative ease of use [14, 47, 48]. To achieve high-performance SHSs, two key characteristics are paramount: surface roughness and low surface energy. These properties synergistically contribute to the overall functionality of the resulting material [49]. Broadly, two main approaches govern the synthesis of SHSs: top-down and bottom-up. These approaches are categorized based on the underlying fabrication mechanisms. Significantly, a combined approach utilizing both top-down and bottom-up strategies can also be employed for SHS fabrication [49, 50]. Figure 3 provides a comprehensive illustration of these diverse tactics.

3.1 Micro- and nano-structuring

One of the most popular techniques for creating superhydrophobic surfaces is micro and nanostructuring. This approach involves creating a rough, textured surface at the micro- or nanoscale using various methods, such as laser ablation, lithography, and etching. The resulting surface roughness promotes the formation of air pockets between the textured features and the water droplet, effectively reducing the solid-liquid contact area. This minimized contact area leads to a high water contact angle, a key characteristic of superhydrophobicity [51–53].

Micro- and nano-structuring offers several advantages for the fabrication of superhydrophobic surfaces. One key benefit is the precise control over surface roughness, allowing for fine-tuning to achieve the desired water contact angle [53–56]. This technique demonstrates versatility, as it can be applied to create superhydrophobic surfaces on diverse materials such as ceramics, metals, and polymers. Su et al. [57] exemplified this versatility by employing a combination of laser treatment and ripple generation to mimic the micro- and nano-scale leaf structures of lotus plants. These structures were then replicated onto poly (dimethylsiloxane) (PDMS) using a polymer casting technique. This approach yielded PDMS surfaces with a high water contact angle of 157° and robust hydrophobic properties. Additionally, this method offers a cost-effective approach for large-scale production of hydrophobic plastic surfaces [57]. Despite its advantages, micro- and nano-structuring presents certain challenges for large-scale superhydrophobic surface fabrication. The process can be time-consuming and labor-intensive, particularly for treating extensive areas [58, 59]. While alternative approaches, such as the PDMS nanocomposite coating explored by J.H. Markna et al., offer promise [60, 61], maintaining surface roughness over time remains a

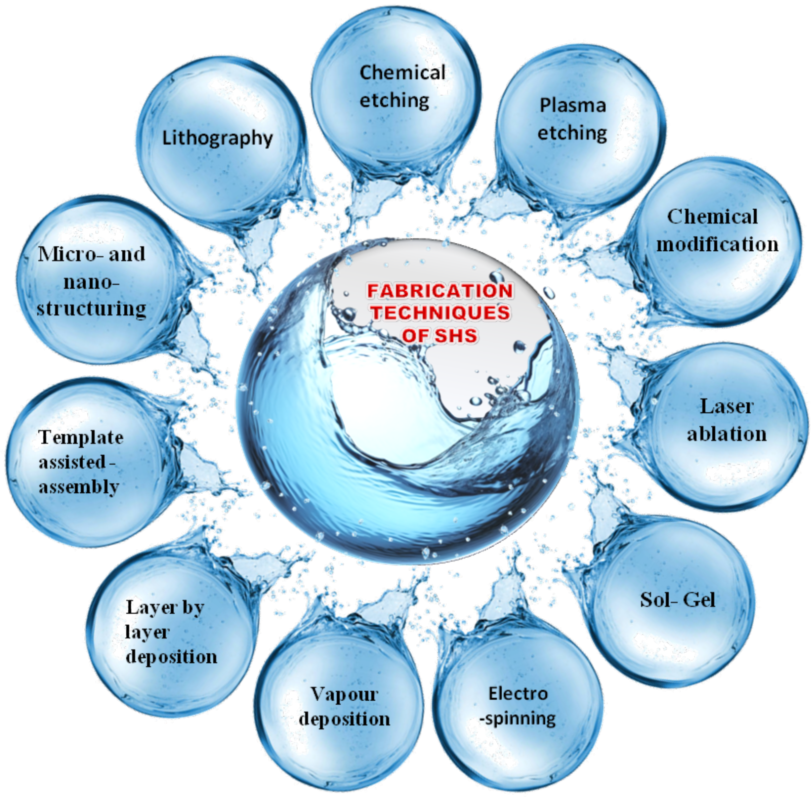

Figure 3. A schematic showing various methods for producing superhydrophobic surfaces.

concern. Wear and tear, along with dust accumulation, can lead to a degradation of surface roughness and a subsequent decrease in water contact angle. Nevertheless, micro- and nano-structuring continues to be a valuable technique for creating superhydrophobic surfaces with potential applications across various sectors [58, 62].

3.2 Chemical modification

The chemical modification offers a versatile approach to fabricating superhydrophobic surfaces. This technique involves applying a chemical coating to a material's surface, specifically to reduce its surface energy and enhance water repellency. The coating can be applied using various methods like dipping, spraying, electrospinning, or spin coating. This approach demonstrates broad applicability, as it can be used to create superhydrophobic surfaces on diverse materials, including metals, polymers, and ceramics [63, 64]. Hydrophobic coatings, typically composed of a polymer-nanoparticle combination, present another avenue for achieving superhydrophobicity. These coatings can be applied using similar methods as chemical modifications and often exhibit superior durability and longevity compared to unmodified surfaces. Y. Zhang et al. [65] demonstrated the effectiveness of a multi-step approach for creating superhydrophobic surfaces. Their method employed electroless plating to generate Ni-B/GO composite coatings on an AZ91 magnesium alloy, followed by chemical modification with a stearic acid-ethanol solution. This approach resulted in a surface with exceptional water repellency, exhibiting a water contact angle of 162.8° [64, 65]. To obtain such superhydrophobic surfaces, various chemicals and physical techniques have been utilized, which are generally divided into two categories: single-step and multi-step procedures, as shown in Figure 4.

3.3 Etching

Nature's flora and fauna serve as a significant source of inspiration for the development of superhydrophobic surfaces through etching techniques. Etching involves the controlled removal of material from a surface using a chemical reaction, resulting in a textured and roughened topography [66–68]. This process is highly selective, targeting specific materials on the surface. Following the generation of micro- and nano-scale roughness features, a low surface energy material is introduced to create the superhydrophobic property. Etching techniques can be broadly categorized into wet etching (using liquid solutions), dry etching (using a plasma environment), laser etching, and chemical etching [69]. For instance, Li et al. successfully fabricated superhydrophobic aluminum alloy surfaces by immersing the material in an etching solution containing hydrofluoric acid and ammonium bifluoride [70]. It is worth mentioning that the use of plasma or laser treatment can induce random shrinkage in polymers, leading to the formation of rough

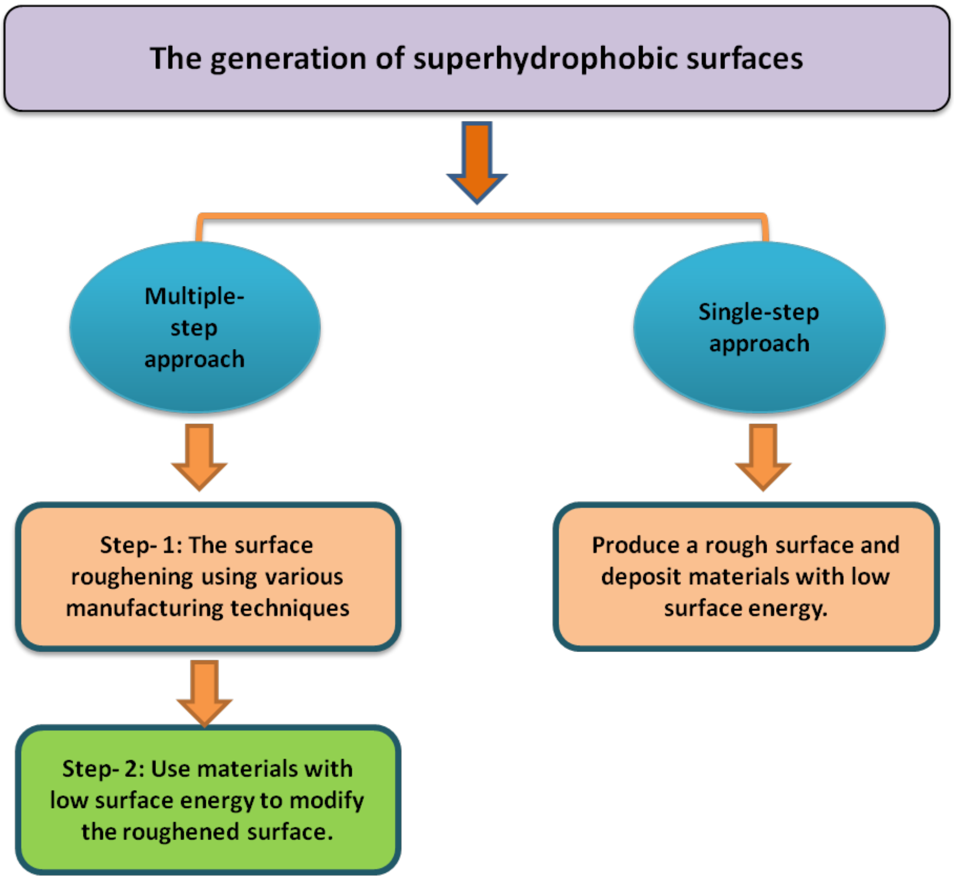

Figure 4. The approaches for generating superhydrophobic surfaces.

surfaces. These surfaces can be further manipulated using etching techniques to create unique and functional patterns by leveraging the microscopic roughness. Additionally, a post-treatment with a suitable chemical agent can further enhance the hydrophobicity of the surface, if desired [71].

3.3.1 Laser ablation

Laser ablation has emerged as a promising technique for creating superhydrophobic surfaces on various metal substrates due to its ability to generate well-defined micro- and nano-scale structures with high automation and minimal environmental impact [72, 73]. In this process, a pulsed laser beam vaporizes or removes material from the surface, resulting in the formation of microscopic patterns or grooves that create a roughened texture. This textured surface morphology is a key factor in achieving superhydrophobicity. Additionally, laser ablation offers several advantages, including high repetition rate, stability, and minimal environmental pollution [71, 74, 75]. Picosecond, femtosecond, and nanosecond lasers are commonly employed for laser ablation in the fabrication of superhydrophobic surfaces [76]. For instance, Chen et al. successfully created superhydrophobic surfaces on stainless steel using laser ablation to generate microstructures on the surface through laser irradiation. A key advantage of laser ablation is its precise control over the structural properties of the micro- and nanostructures, such as spacing, size, and depth. This precise control allows for tailoring the surface properties to achieve the desired level of superhydrophobicity [77, 78].

3.3.2 Plasma etching

Plasma etching is a vital technique within the broader category of plasma treatments for surface modification. Plasma itself offers a straightforward yet efficient approach to creating superhydrophobic surfaces [47]. This technique has the advantageous capability of simultaneously reducing a surface's energy and increasing its roughness, both of which contribute to superhydrophobicity [71]. Plasma treatment can significantly alter surface structures through a process called anisotropic etching, which selectively removes material from different layers of the surface [66, 79]. Plasma etching utilizes highly directional plasma (often referred to as micro-nanofabrication of plasma) to create surface patterns ranging from coarse and random to well-organized. The dry etching technique of plasma etching involves the generation of reactive ions or atoms (such as fluorine, chlorine, and oxygen) through a gas discharge. The high directionality of ions allows for their acceleration within the sheath (boundary layer) between the substrate and plasma, enabling reactive ion etching to produce deep grooves with steep walls [80].

As previously mentioned, plasma treatment, a dry etching process, readily generates rough surfaces. Furthermore, depending on the gas employed (e.g., tetrafluoroethane, argon, ammonia, or oxygen), various functionalities can be incorporated into the surface through the introduction of specific elements [19]. This plasma system doesn't need any vacuum equipment and runs in an in-line manner as opposed to a batch mode. This feature facilitates the straightforward scalability of the method for continuous processing and treatment of larger substrates. Superhydrophobic coatings offer promising solutions for deicing and self-cleaning properties in metals and alloys. However, a significant challenge lies in the limited durability of these surfaces due to weak interfacial bonding between the substrate and the coating. Consequently, current research efforts are heavily focused on developing superhydrophobic coatings with exceptional durability [81].

While oxygen plasma offers a straightforward method for creating superhydrophobic surfaces, a significant challenge lies in their long-term stability, often referred to as "aging". For applications requiring superhydrophobic coatings with specific optical properties, surface roughness plays a critical role. Plasma treatment allows for precise control over surface roughness through controlled etching processes. The surface roughness formed by the plasma may be easily changed, according to the review, P. Dimitrakellis and their research team's research delve into the utilization of the atmosphere pressure plasmas (APPs) in polymer plasma etching processes, including cleaning, nanopattern creation, nanotexturing, and the creation of superhydrophobic surfaces. It demonstrates the production of superhydrophobic surfaces, damage to thick films, and high-rate, homogeneous etching of polymers. The study emphasizes the adaptability and economical processing of APPs. With low-pressure plasma deposition and an optimized plasma etching period, surfaces that are superhydrophobic with a 158° water contact angle and 9° hysteresis were produced [82]. Plasma processing has become a well-established technique for creating superhydrophobic surfaces, as evidenced by numerous studies. Pioneering work by Coulson et al., and Zhang et al. have established the effectiveness of this approach [20, 83].

3.3.3 Chemical etching

As previously established, both surface energy and surface structures play critical roles in achieving superhydrophobicity [84]. To create water-repellent surfaces, a combination of low surface energy and surface roughness is necessary. Various techniques have been explored to generate the desired level of roughness on the external surfaces of metals and alloys. However, many of these methods have limitations, including the requirement for specialized equipment, expensive materials, or labor-intensive processes. Consequently, industrial applications necessitate straightforward and scalable techniques such as chemical etching [84, 85].

Chemical etching offers a cost-effective and straightforward approach for generating micro- and nano-scale surface structures on metals. This technique involves immersing metal substrates in either acidic or basic solutions. Common etchants include strong bases like sodium hydroxide (NaOH) and strong acids like hydrochloric acid (HCl) and sulfuric acid (H_2SO_4). Additionally, chemical etching is a versatile technique applicable to a wide range of metals and alloys [86]. Following the creation of a rough surface texture through etching, the surface is modified by introducing a low surface energy material to achieve superhydrophobicity. Research has explored the influence of various etching solutions (e.g., Hydrochloric acid (HCl), Nitric acid (HNO_3)), their combinations, and temperature on the etching process of stainless steel [87, 88]. For instance, researchers employed continuous chemical etching to fabricate micro- and nano-structured surfaces on aluminum, demonstrating its anti-icing properties for power transmission lines. After 50 minutes of exposure, the superhydrophobic surface significantly reduced ice accumulation. This ability to repel freezing rain highlights the potential of such surfaces to prevent power outages and tower collapses [15].

3.4 Lithography

Lithography stands as a prominent technique for generating superhydrophobic surfaces with well-defined micro- and nano-scale patterns. This well-established process involves transferring a desired pattern onto a surface using a photolithographic technique. Lithography offers exceptional control over the surface morphology and structure, enabling the creation of diverse features with specified diameters, heights, and spacing. Examples include structures like square and star-shaped posts, and circular or square pillars [1].

The superhydrophobic properties arise from the replication of a master pattern onto the substrate surface, essentially creating a negative replica of the original structure. Photolithography, a specific type of lithography, involves exposing a photoactive polymer to light (typically ultraviolet) through a designed mask. The patterned mask dictates the removal of either exposed or unexposed polymer regions, resulting in a positive or negative image on the substrate after light exposure [1]. While ultraviolet light is most common, other radiation sources like X-rays, electron beams, and laser beams can also be employed. For applications requiring superhydrophobic surfaces with precise shapes and structures, lithography remains a highly valuable tool [89].

Lithographic techniques, such as photolithography and nanoimprint lithography, offer precise methods for creating superhydrophobic surfaces with well-defined patterns. As an example, Chen et al. employed nanoimprint lithography to fabricate superhydrophobic surfaces on polydimethylsiloxane (PDMS) by transferring a pre-defined pattern from a PDMS stamp onto a nanoparticle-coated substrate. While the fundamental concept behind both techniques involves transferring pre-designed patterns onto a target surface, the underlying mechanisms differ. Classic photolithography utilizes a photomask containing the desired pattern. Light exposure hardens specific regions of a photosensitive resist layer (photoresist) on the substrate, allowing for subsequent etching or deposition to replicate the pattern [49, 90]. Due to its widespread, practical application and great efficiency, photolithography is among the most commonly employed techniques for transferring geometric patterns that have been prepared on a photomask to a thin layer that is reactive photoresist through light. Soft lithography, a complementary technique, offers greater flexibility in material selection. Unlike photolithography, which is limited to photoresists, soft lithography can modify a broader range of materials, including elastomers, polymers, and gels [1]. This technique relies on elastomeric molds or masks to replicate patterns onto the target substrate. PDMS (polydimethylsiloxane) is a popular choice for soft lithography due to its affordability, low toxicity, mechanical adaptability, biocompatibility, and durability. Significantly, soft lithography can be combined with other techniques like replication molding and self-assembly to generate micro- and nano-scale structures [49, 91]. For instance, researchers successfully fabricated superhydrophobic coatings on silicon using a combination of wet chemical etching and nanoimprint lithography. This process involved imprinting a positive photoresist layer with a glass mold, followed by pattern transfer to Silicon dioxide (SiO_2) and silicon (Si) layers. After photoresist development and UV-ozone exposure, the researchers investigated water contact angles, demonstrating the successful creation of superhydrophobic silicon surfaces with water-repellent properties [92].

3.5 Template-assisted assembly

The templating method offers a versatile approach for replicating superhydrophobic and abrasive surfaces. This replication process involves three key steps: (1) fabricating a template with the desired micro- and nano-structures (insert, stamper, or inlay), (2) molding the pattern onto a polymer material using appropriate evaluation procedures, and (3) carefully demolding the polymer replica to preserve the delicate structures [93–95].

This approach involves filling appropriate 2D or 3D surface patterns with a material that is soft in the first phase, hardening the material, and removing the template while maintaining the integrity of the copy in the second step. The key benefit of this approach is how simple it is to replicate water-repellent surfaces that are natural on a big scale. This technique is reasonably inexpensive and excellent for designing soft materials like polymers because the design or template can typically be reused [94, 96]. The templating method offers a compelling strategy for replicating superhydrophobic and abrasive surfaces. However, the demolding stage presents a significant hurdle, particularly when dealing with delicate polymeric materials. High temperatures and strong chemicals, often necessary for demolding, can compromise the integrity of both the replicated structures and the template itself. This challenge is further amplified for mesoporous materials, where exposure to extreme conditions can trigger undesirable structural rearrangements or chemical modifications [97, 98].

To address the demolding challenges associated with template replication, particularly for delicate materials, the development of easily detachable templates has emerged as a promising strategy. Recent advancements in this field focus on chemically modified templates that can either detach organically during the replication process or undergo complete dissolution in the reaction medium. For instance, metallic oxide templates have been utilized to facilitate the polymerization process. These templates can be designed to undergo a controlled change in oxidation state as the reaction progresses, ultimately transforming into a water-soluble phase. This allows for the facile removal of residual template material through simple washing procedures. Template-assisted chemical vapor deposition (CVD) offers another effective approach for overcoming demolding challenges. Researchers have successfully employed this technique to fabricate porous silica-coated copper mesh (PSCCM), demonstrating its exceptional potential for oil-water separation. Surface modification of PSCCM with hexamethyldisilazane (HMDS) imbues it with superhydrophobic and super-oleophilic properties, leading to excellent separation efficiency and selectivity. Additionally, PSCCM exhibits remarkable mechanical strength, chemical resistance, thermal stability, and recyclability, highlighting its promise as a viable solution for the critical challenge of oil-water separation [99]. Furthermore, template replication serves as a powerful tool for the large-scale production of well-defined hierarchical structures, underlining its significance in various scientific disciplines [100–103].

3.6 Sol-gel process

The Wenzel and Cassie-Baxter models provide theoretical frameworks for predicting the behavior of water droplets on superhydrophobic surfaces. The sol-gel method has emerged as a prominent technique for fabricating these surfaces due to its versatility and inherent advantages [104, 105]. This low-temperature approach offers a cost-effective and environmentally friendly route to generate porous network structures with precise control over final material properties. The sol-gel process leverages solution chemistry to develop macromolecular networks through the hydrolysis of metal alkoxide precursors, followed by condensation of the resulting Silanols [106–108]. Following hydrolysis, condensation of the metal hydroxides (Silanols) in a solvent leads to the formation of a colloidal suspension, known as a sol. Subsequent gelation, often driven by further condensation and polymerization, results in a three-dimensional network. This versatility positions the sol-gel method as a preferred approach for generating both amorphous and crystalline oxide coatings, eliminating the need for harsh solvents. However, achieving superhydrophobicity on metallic substrates with the sol-gel method requires additional modifications. The incorporation of low-surface-energy chemical components and Nano-sized particles into the gels is a crucial step for inducing this property [109, 110]. These modifications alter the surface chemistry and topography, ultimately leading to water-repellent behavior.

The sol-gel method, based on the Wenzel and Cassie-Baxter models, offers a versatile approach for fabricating superhydrophobic surfaces on a range of oxide substrates, including silica and alumina. By carefully controlling sol-gel processing parameters such as precursor solution composition, hydrolysis conditions, and polycondensation mechanisms, researchers can tailor the surface morphology and energy of the resulting films. This allows for the creation of surfaces with desired superhydrophobic properties [111–113]. For instance, a recent study demonstrated a cost-effective sol-gel route for generating superhydrophobic coatings using a combination of Polymethylhydrosiloxane (PMHS) and γ-Aminopropyltriethoxysilane (KH550) byproducts. By optimizing the KH550/PMHS mass ratio (0.25), the researchers achieved high water contact angles (WCA) of 157° and low water sliding angles (WSA) below 1° on glass substrates. Characterization revealed a hierarchical structure consisting of micro-balls (∼2 µm) and nano-spheres (<200 nm) with a diameter of approximately 40 µm. This work highlights the potential of this approach for creating superhydrophobic surfaces on various substrates [114]. The suitability of the sol-gel method for fabricating transparent superhydrophobic coatings on glass has further solidified its position as a preferred technique in this field [115–117].

3.7 Layer-by-layer deposition method

The layer-by-layer (LBL) assembly technique offers a versatile approach for constructing diverse nano/microstructures, including superhydrophobic surfaces. This method relies on the electrostatic interactions between oppositely charged species to build up multilayered thin films on a substrate [118, 119]. By alternating the deposition of materials with contrasting charges, the LBL approach allows for precise control over film thickness and composition at the molecular level. Additionally, the absence of masks, unlike techniques like lithography, makes LBL a maskless deposition method. A key advantage of LBL for superhydrophobic surface fabrication lies in its ability to enhance surface roughness through the incorporation of nano- or microparticles during the deposition process. This increased roughness contributes to the desired water-repellent behavior. Furthermore, the LBL method demonstrates remarkable adaptability, enabling the creation of superhydrophobic surfaces even on non-flat or uneven substrates [120–122].

The core principle of layer-by-layer (LBL) deposition lies in the electrostatic interactions between oppositely charged species. This technique allows for the construction of thin-layer coatings with precise control over both thickness and chemical composition at the molecular level. The LBL process involves the sequential adsorption of charged materials onto a substrate, building up a multilayered thin film. Unlike techniques like lithography, LBL does not necessitate the use of masks, making it a maskless deposition method, further contributing to its simplicity and potential cost-effectiveness [123, 124]. While the incorporation of nanoparticles during LBL assembly can be a valuable strategy for generating rough surfaces, it can also introduce challenges in precisely controlling surface patterns. An illustrative example of LBL for superhydrophobic surface fabrication is the work by Zhao and Tang [14, 120, 125]. Their study demonstrates the creation of superhydrophobic cotton fabric through an electrostatic LBL assembly process. This approach involved the layer-by-layer deposition of polyelectrolyte- PDDA (poly- diallyl dimethylammonium chloride) and silica nanoparticle layers onto cotton fibers, followed by a final treatment with fluoroalkyl silane for surface fluorination. This hierarchical structure, featuring both micro and nanoscale features, resulted in a superhydrophobic surface with a high water contact angle (157.1°) and a low sliding angle (3.1°) after only five bilayers. The readily available materials and straightforward nature of this LBL method suggest its potential for various applications [126].

3.8 Vapour deposition: In contrast with CVD, PVD

Physical vapor deposition (PVD) and chemical vapor deposition (CVD) are two cornerstone techniques for generating ultrathin coatings on diverse substrates [142]. PVD relies on the evaporation of high-purity materials to form the desired thin film. In contrast, CVD utilizes a mixture of chemically reactive precursors that undergo decomposition and subsequent deposition on the surface to create the targeted coating [94]. Superhydrophobic surfaces can be achieved by depositing minute quantities of vaporized low-surface-energy materials. These coatings render the surface water-repellent and water-shedding. Various methods, including thermal evaporation, plasma-enhanced deposition, or a combination of both, can be employed for this deposition process [125, 143]. A key advantage of plasma-assisted vaporization is its ability to achieve deposition often at significantly lower thermal energy input compared to traditional thermal evaporation [144].

The scope of vapor deposition coatings can be extended beyond inorganic metal oxides to encompass various organic low-energy compounds, depending on the specific application and the substrate being coated. This versatility allows for tailoring the coating properties to meet different requirements. Recent advancements have demonstrated the low-temperature (40 °C) surface-modulated deposition of silica using NH_3 as a catalyst within the processing chamber [145]. This approach offers a valuable strategy for dealing with coating materials that are susceptible to thermal degradation at higher temperatures. Chemical vapor deposition (CVD) has witnessed significant progress in controlling the crystallinity of polymeric coatings by manipulating the deposition conditions. Dong et al. demonstrated that the orientation of deposited polymer chains can significantly influence the resulting surface topography, impacting the final surface properties [146]. Carbon nanotubes and other graphene-based materials are inherently hydrophobic due to their combination of low surface energy and high surface roughness. This inherent property makes them attractive candidates as coatings for water-oil separation applications [147]. However, template-assisted vapor deposition of graphene, while gaining traction for its ability to improve porosity and morphological control, often requires additional hydrophobization through post-deposition treatment with non-polar polymers or similar coatings [148].

A distinct advantage of plasma-assisted vapor deposition (PA-VD) lies in its ability to achieve deposition at significantly lower thermal energy input compared to traditional techniques [3]. This characteristic can be crucial for substrates that are sensitive to high temperatures. Researchers have demonstrated the potential of this approach for creating superhydrophobic and highly transparent surfaces on polytetrafluoroethylene (PTFE) films. The strategy involves using a radiofrequency (rf)-sputtered PTFE film as a buffer layer for subsequent catalytic chemical vapor deposition (Cat-CVD). The rf-sputtered PTFE layer exhibits excellent adhesion to the glass substrate and displays a hydrophobic surface with a water contact angle (WCA) of 122.3°. Importantly, the Cat-CVD process, facilitated by the low surface energy of CF2 and CF3 groups and optimized catalyst temperature, allows for the creation of a superhydrophobic surface with a WCA exceeding 150° on top of the rf-sputtered PTFE. This approach holds promise for applications requiring both superhydrophobicity and transparency in PTFE surfaces [149]. While CVD offers a versatile technique for thin-film deposition, it presents challenges for large-scale applications. The complexity and time-consuming nature of the CVD process render it impractical to create superhydrophobic coatings on expansive structures such as roofs, buildings, and automobiles. Additionally, the controlled environment required for CVD often limits its suitability for outdoor applications [143, 150, 151].

3.9 Electrospinning

Electrospinning presents a versatile technique for fabricating superhydrophobic surfaces. It involves the creation of an ultrathin, fibrous coating on a substrate. The process utilizes a high-voltage electric field applied to a polymer solution or melt extruded through a needle or capillary tip. This electric field induces the polymer solution to elongate into a thin, continuous fiber that is deposited onto a collector, ultimately forming the desired coating. By manipulating the processing parameters, the electrospun fibers can be aligned in a specific direction or patterned to create a rough, textured surface that promotes superhydrophobicity [152]. Electrospinning offers several advantages for creating superhydrophobic surfaces. Firstly, it enables the fabrication of thin, lightweight coatings that are readily applicable to diverse substrates [153]. Secondly, the versatility of electrospinning allows for the generation of superhydrophobic finishes on various materials, including polymers, metals, and ceramics [154, 155]. Researchers have demonstrated the effectiveness of this approach by electrospinning a polyvinylidene fluoride (PVDF) and fluorinated silica mesoporous (FSM) composite coating onto glass. This dual-layer structure exhibited a remarkable water contact angle of 170.2° and a water roll-off angle of less than 1°, signifying its potential for promoting rapid water droplet removal in building applications [156]. However, electrospinning also presents some limitations. The process can be time-consuming and labor-intensive, particularly when dealing with large surface areas. Additionally, the surface roughness generated by the electrospun fibers can degrade over time due to wear and tear, potentially leading to a decrease in the water contact angle [157]. Table 1 provides an overview of advanced approaches employed by researchers to address these challenges.

Table 1. Advanced techniques for generating the SH surfaces.

Method	**Application**	**CA°**	**Ref.**
Sol-gel	Flame-retardant, water-oil separating, and self-cleaning abilities	156	[127]
Convenient dip-coating	Self-cleaning	158 ± 2	[128]
The etching process Chemically	Long-term mechanical dependability, thermostability, and anti-icing properties	158.6 ± 1.3	[129]
Method of calcinations	Enduring, transparent, and highly thermally stable	163	[130]
The spray coating Sol-gel	Prolonged utilization in household and industrial environments	163 ± 2	[131]
Casting solutions	Water and oil separation	170 ± 2	[132]
The acid etching and grinding procedure	Hexadecane, the liquid's surface tension repellency due to its exceptionally low tension, and its behavior	162	[133]
Texturing with picoseconds laser	Antibacterial Adherence	161 ± 2.5	[134]
Thermoplastic synthesizing	Mechanically steadiness and corrosion resistance	156	[135]
Melting and hot pressing in a roll	Wrapping, Drag-reducing and self-cleaning feature	152 and 145	[136]
The process of electrodeposition	Outstanding corrosion resistance and self-cleaning properties	154	[137]
Combined chemical Enhancement and droplet etching	Thermostability, anti- corrosion, self-cleaning and anti-fouling	156	[138]
Process of solutions immersing	Cohesive capability and adaptability to both high and low temperatures	162 ± 5	[139]
Only a single-electrode Triboelectric nano-generator along with microstructures of cilia	Energy Reclamation	∼99.82°	[140]
Etching and polishing	In addition to mechanical and thermal stability, it has UV resistance	150	[141]

4. Applications for superhydrophobic surfaces

The unique and multifunctional properties of superhydrophobic surfaces, particularly their exceptional water and liquid repellency, have attracted significant global interest across various industries. Research efforts are directed towards the development of superhydrophobic materials with tailored properties for diverse applications. A wide range of materials, including metals, composites, polymers, glass, and micro/nanoparticles, are being explored and chemically modified using various techniques to achieve superhydrophobicity [14]. This has resulted in the creation of superhydrophobic surfaces with varying chemical compositions and surface structures, catering to a multitude of applications.
Due to their unique ability for repel water and other liquids; superhydrophobic surfaces have been emerged as a promising research area with applications across various scientific and engineering disciplines. These surfaces hold significant potential in diverse areas including drag reduction for improved fuel efficiency [158], anti-fogging for enhanced visibility [159], anti-fouling to reduce bio-adhesion [160], oil-water separation for environmental remediation [161], anti-icing to prevent ice formation [162], anti-corrosion for extended material lifespan [163], self-cleaning for effortless dirt removal [155], anti-bacterial applications in hygiene and healthcare [164], biomedical applications like implant coatings [165], and even water collection from fog or humidity in arid regions [166]. Figure 5 illustrates some of the possible uses for superhydrophobic surfaces that are summarized in the ensuing subsections.

4.1 Self-cleaning surfaces

Superhydrophobic surfaces exhibit a remarkable self-cleaning property, enabling them to repel dirt, stains, dust, organic matter, and other surface contaminants [11, 167]. Figures 6 (a) and (b), exhibit examples of superhydrophobic surfaces, which possess the property of self-cleaning. This self-cleaning mechanism harnesses gravity. As water droplets roll off the surface due to the superhydrophobicity, they capture and remove contaminants in their path. This phenomenon, observed in nature on gecko feet, water striders, and lotus leaves, is attributed to a complex interplay between surface morphology and chemical composition, creating a physiochemical process known as the lotus effect [26, 168]. The unique surface structure, characterized by micro- and nanometer-scale features, coupled with low surface energy chemistry, disrupts the adhesion of contaminants and promotes water droplet formation with minimal contact area. This minimal contact area allows water droplets to roll off easily, taking away dirt particles. Superhydrophobic self-cleaning surfaces hold promise for various applications across diverse sectors, including industry, agriculture, and even the military.
Nanotechnology-based coatings have emerged as a prominent strategy for creating self-cleaning surfaces, finding applications in everyday products like glass, cars, and electronic devices. These coatings typically introduce a roughness on the surface at the micro and nanoscale, hindering water adhesion and preventing dirt and grime from adhering to the surface. Rainwater collects on the treated surface, forming droplets with minimal contact area due to the superhydrophobicity. As these droplets roll off, they effectively

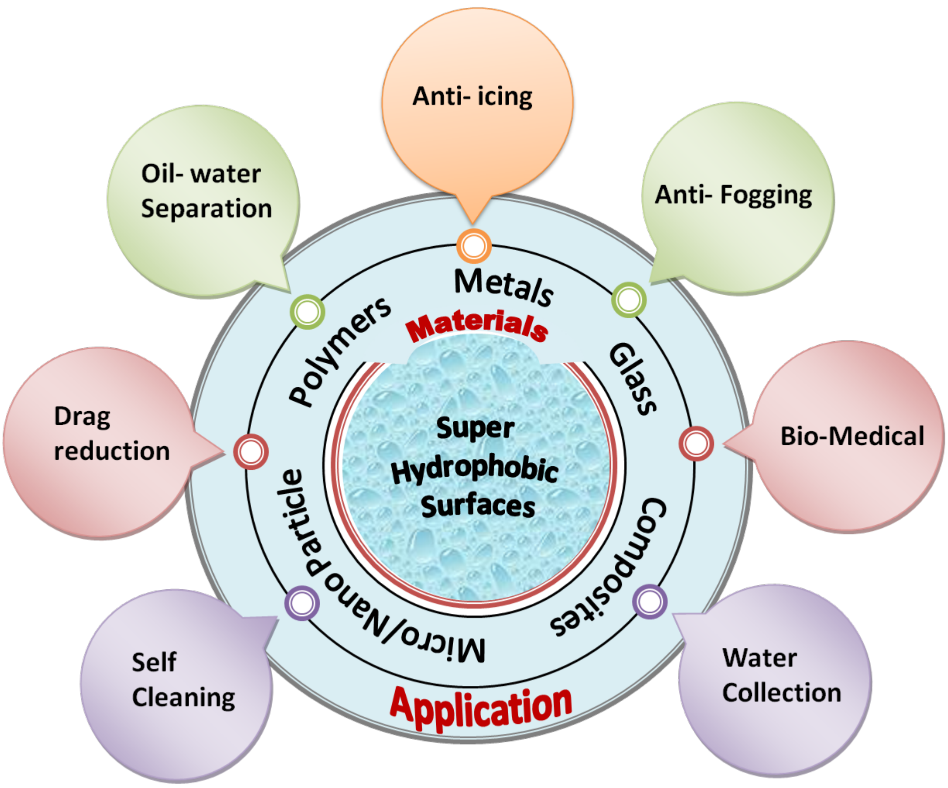

Figure 5. A look at the scope of the superhydrophobic surface applications.

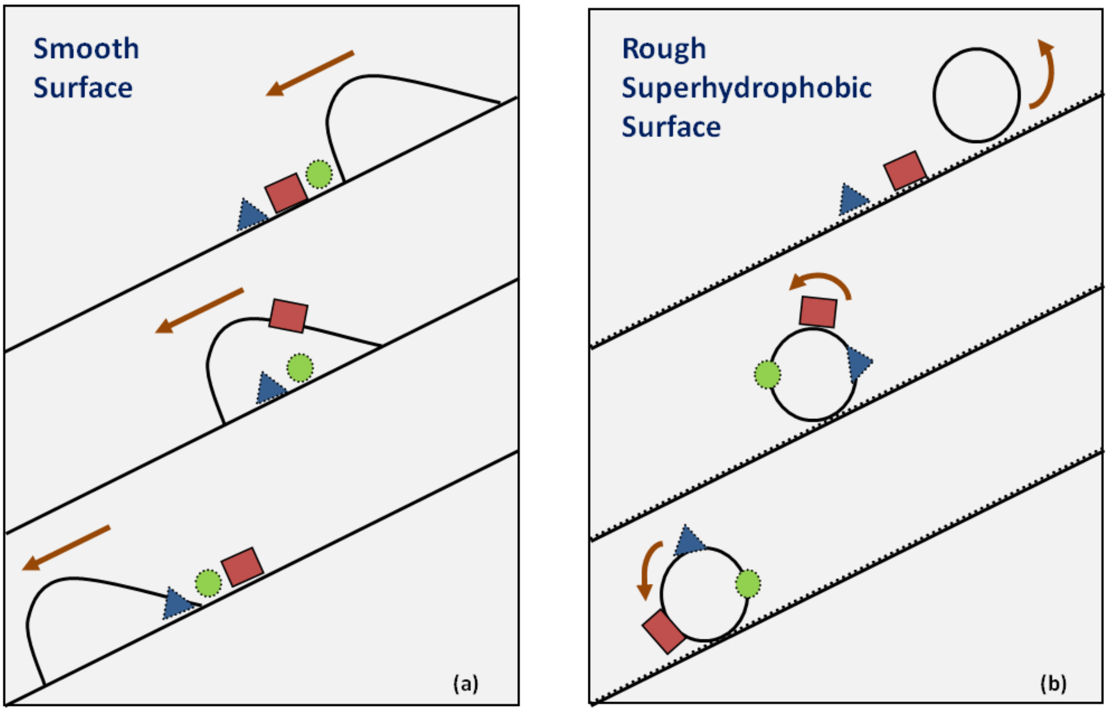

Figure 6. The animation depicts the self-cleaning properties of the water droplets within the lotus petal. They gather and eliminate dust particles from hydrophobic surfaces that are inclined, while they slide over rough surfaces as, (a) shows how a drop via a low contact angle leaves the surface unclean, while (b) shows how a drop with an exceptionally high interaction angle removes contaminants.

capture and remove contaminants, leaving the surface clean. This phenomenon, exemplified by self-cleaning glass, offers a compelling real-world application of superhydrophobic surfaces. Buildings equipped with self-cleaning glass benefit from reduced maintenance requirements, as rainwater becomes a natural cleaning agent, minimizing the need for manual cleaning.

Research efforts are ongoing to explore the development and application of self-cleaning coatings, particularly superhydrophobic coatings, for various surfaces including solar cells. A study by Wang et al. [169] delves into the development and use of these coatings. For applications where surfaces are exposed to dirt and debris, self-cleaning properties offer significant advantages. Numerous methods and techniques have been explored recently to achieve self-cleaning functionality [71, 170]. Significantly, Liu et al. demonstrated the development of a superhydrophobic Ni-Cu coating using a combination of electrodeposition and myristic acid modification. The resulting surface exhibited a low surface energy and a hierarchical structure, facilitating easy contaminant removal and showcasing exceptional self-cleaning properties [14, 16, 171].

4.2 Drag reduction

Superhydrophobic surfaces offer a promising approach for drag reduction by minimizing frictional forces between a flowing liquid and the surface. These surfaces are typically engineered composites that incorporate a significant amount of trapped air at the interface. This trapped air layer plays a crucial role in promoting a phenomenon known as boundary region slippage. Boundary region slippage refers to a reduction in shear stress near the solid-liquid interface due to the presence of the air layer. This essentially creates a shear-free gap between the air-water interface and the substrate or liquid interface, effectively reducing overall drag [179].

Superhydrophobic surfaces are emerging as a revolutionary technology for drag reduction across various sectors. Their ability to repel water and minimize surface-to-fluid contact offers significant advantages in marine [180], aviation [181], and automotive applications [182]. While the benefits for everyday life may be less immediately apparent, the potential for underwater drag reduction in areas like underwater vehicles, oil pipelines, and aquaculture is attracting considerable research interest. A compelling real-world example is the application of superhydrophobic coatings on aircraft wings. These coatings can improve fuel efficiency by repelling water droplets, thereby minimizing drag and reducing carbon emissions, with positive environmental and economic impacts [183]. Nature provides valuable inspiration for drag-reduction strategies. Studies by Bhushan's group on shark skin-inspired surface textures offer insights into how natural and biomimetic surfaces can achieve functionalities like superhydrophobicity and drag reduction [184]. Their work on "Design and application of sharkskin-inspired surface textures" explores this concept in detail. The mechanism behind drag reduction with superhydrophobic surfaces lies in their ability to minimize the contact area between the surface and the fluid. This minimized contact area leads to improved system efficiency. The wettability of the surface plays a crucial role in this process. Studies by Fukagata et al. investigating turbulent flows have demonstrated that superhydrophobic surfaces can significantly reduce fluid drag [185]. Table 2 summarizes recent research on superhydrophobic surfaces in drag reduction applications.

4.3 Water separation from oil

The ever-increasing frequency of industrial oily effluent production and oil spill disasters has propelled oil-water separation to a critical global challenge [186]. Marine oil spills and the substantial volumes of oil released by various industries worldwide pose a significant threat to ecosystems. Effective oil removal from contaminated water is paramount. Conventional methods for spilled oil cleanup often rely on expensive, laborious, and sometimes environmentally hazardous chemical, physical, or biological approaches [187, 188]. Recent advancements in innovative materials, such as superhydrophobic surfaces, have been offered a more eco-friendly and cost-effective approach to separating oil from water.

Superhydrophobic surfaces hold promise for diverse oil-water separation applications, including spill cleanup and industrial wastewater treatment. Their ability to repel water while attracting oil facilitates efficient separation of the two immiscible liquids. Superhydrophobic-superoleophobic sponges are gaining traction in oil-water separation processes, particularly for environmental protection and valuable oil recovery [189]. Researchers have addressed scalability challenges associated with superhydrophobic surfaces by developing a fluorine-free, brush-dip- or spray-applicable coating termed MSHOs (modified silica hyperbranched organosilanes). These MSHOs exhibit remarkable self-cleaning properties, maintain water repellency after abrasion, and demonstrate high oil-water separation efficiency exceeding 93 %. Coated meshes showcased sustained high separation effectiveness (>95 %) over 20 cycles, signifying a straightforward and scalable approach for producing multidimensional surfaces with practical applications in self-cleaning oil-water separation [190]. Various materials, including fabrics, membranes, foams, and sorbents, have been explored for oil-water separation using diverse techniques [71, 191]. A compelling real-world example is the Oleo Sponge, a revolutionary development in oil spill cleanup technology by researchers at Argonne National Laboratory. This innovative material addresses the critical challenge of effectively removing oil from water surfaces during oil spills, which pose severe environmental risks to coastal areas and marine ecosystems [192].

4.4 Anti-icing

Ice accumulation on exposed surfaces presents a significant hazard, leading to numerous safety incidents with the potential for financial losses and even fatalities [49]. Icing disrupts daily life and hinders various economic activities, impacting diverse sectors like transportation, aviation, maritime structures (ships), satellites, wind turbines, energy-harvesting equipment, underwater oil and gas production facilities, and communication infrastructure [11, 49]. Consequently, the development of icephobic surfaces or anti-icing coatings is crucial.

Traditional methods for ice mitigation often involve physically or chemically removing ice after formation, which can be environmentally detrimental and energy-intensive. Fortunately, the unique properties of superhydrophobic surfaces offer promise for ice-phobic applications [71, 198]. Researchers typically evaluate anti-icing effectiveness using two primary approaches: "deicing" and "anti-icing." Deicing allows ice formation to occur initially and then focuses on removing it using electrical, physical, or thermal methods. Anti-icing, on the other hand, aims to prevent ice formation altogether [199]. Studies by Bharathidasan et al. [200] have shown that smooth hydrophobic silicone coatings exhibit weaker ice adhesion compared to rough superhydrophobic surfaces. While surface roughness may not be a critical factor, very low surface energy has been demonstrated to hinder ice nucleation [68, 201]. Table 3 summarizes recent research on the application of superhydrophobic surfaces in anti-icing technologies.

4.5 Anti-fogging

Fogging, the condensation of humid air into microscopic water droplets on transparent or solid reflective surfaces, arises due to temperature differences between the surface and the surrounding humid environment [202]. Light scattering by these water droplets reduces light transmission or reflection, hindering visibility [203]. Fog accumulation on surfaces can have detrimental consequences beyond mere inconvenience,

Table 2. An overview of the most current research on SHS within drag reduction appliances.

	CA°	Reduction rate in drag	Ref.
Acid perfluorotetradecanoic	160	20–30	[172]
Normal dodecanethiol	159.7	38.5	[173]
Perfluorooctyltriethoxysilane	163	13	[174]
Superhydrophobic coating for business purposes	165.8	20	[175]
Perfluorooctyltriethoxysilane	163	31.6	[176]
Biomimetic- polydimethylsiloxane	151.74	19.2	[177]
A mixture consisting of FAS17, lauric acid, and stearic acid	< 161	67	[178]

Table 3. A summary of the most recent studies on the use of SH surfaces within anti-icing equipment.

	CA°	**Ref.**
Micro- and nanostructures and Groups of organosilane	159	[56]
Micro cubic array-based hierarchies	149.61	[193]
Composite of graphene	155–165	[194]
Polydimethylsiloxane	155	[195]
The concrete overlaying	160 ± 1	[196]
Polydimethylsiloxane	< 161	[197]

posing safety concerns and hindering performance across various applications. Anti-fogging is crucial for surfaces used in diverse fields, from electrical power transmission and telecommunications to photography. In a critical example, fogging of endoscopic lenses during surgery can impair vision and compromise surgical outcomes [202, 204]. During the COVID-19 pandemic, fogging of goggles emerged as a life-threatening issue for healthcare professionals [205]. Fortunately, various approaches exist to prevent fogging by modifying surface wettability, offering solutions to these societal challenges [205, 206]. Fortunately, various approaches exist to prevent fogging by modifying surface wettability, offering solutions to these societal challenges.
Superhydrophobic coatings, characterized by a high contact angle (>150°) and low contact angle hysteresis (<5°), are highly desirable for achieving anti-fogging properties due to their unique wetting behavior [11, 50]. While condensation may still occur on superhydrophobic surfaces, these surfaces can impede fog formation by promoting faster evaporation [207]. Chen et al. demonstrated this concept by fabricating a superhydrophobic surface using silica capsule nanostructures via dip coating. This highly transparent surface exhibited a high contact angle of nearly 152° and a low sliding angle of around 8°. Furthermore, this surface facilitated rapid fog evaporation, leading to the disappearance of condensed droplets [204].

4.6 Biomedical applications

Superhydrophobic surfaces, characterized by a unique combination of high surface roughness and extremely low surface energy, exhibit a non-wetting state. This property, along with their biocompatible and anti-corrosive characteristics, makes them potentially valuable in various biomedical fields, including drug delivery and tissue engineering [208, 209]. These properties differentiate superhydrophobic surfaces from traditional biomedical implants. Furthermore, these characteristics set them apart from other biomedical implants. For instance, superhydrophobic coatings can act as protective barriers, reducing the risk of implant rejection by the human body. Additionally, they hold promise for controlled drug delivery systems, enabling sustained and targeted release of medications over extended periods [210]. The growing demand for such advanced materials in biomedicine has spurred the development of transparent superhydrophobic and biomimetic coatings [211]. These innovative coatings offer a diverse range of potential applications, including plasma separators, stents designed to prevent cell adhesion and thrombosis, hemostatic bandages, and surfaces with reduced bacterial adhesion during interaction with blood and human fluids [49, 212]. A real-world example of superhydrophobic surfaces in biomedicine is their utilization in medical devices to prevent biofouling, enhance biocompatibility [213], and facilitate controlled drug delivery [214]. A comprehensive review by Falde et al. [208] delves into the design and applications of superhydrophobic surfaces within the biomedical field.
Superhydrophobic surfaces (SHSs) represent a burgeoning technology with immense potential to revolutionize the field of biomedical implants. Their unique properties offer a compelling solution to current challenges in implant technology, paving the way for improved patient outcomes and healthcare delivery [215, 216]. The integration of SHSs into biomedical implants holds significant promise for overcoming existing limitations. By repelling water and biomolecules, SHSs offer a two-pronged attack: reducing the risk of infection and mitigating biofouling, a critical concern during implant surgery [217, 218]. This not only enhances biocompatibility but also minimizes the likelihood of foreign body reactions, fostering better integration with surrounding tissues and lowering the risk of rejection or adverse reactions, ultimately leading to improved patient outcomes. SHSs further contribute by enhancing implant durability and functionality. Their inherent ability to repel biological fluids and water protects implant materials from degradation and erosion, thereby extending their lifespan and maintaining structural integrity over time [219, 220]. Moreover, SHSs open new avenues in tissue engineering and drug delivery by enabling the controlled release of growth factors or therapeutic agents near the implant site. This capability unlocks possibilities for regenerative medicine and personalized treatment strategies. Furthermore, SHSs can contribute to reduced friction and wear between the implant and surrounding tissues. This translates to a lower risk of mechanical failure or loosening, ultimately enhancing patient comfort [221, 222]. In general, the incorporation of SHSs into biomedical implants has the potential to transform the medical implant industry by offering safer, more efficacious, and ultimately, more

patient-centric healthcare solutions.

5. Future outlook

Superhydrophobic surfaces (SHSs) have revolutionized numerous industries, but significant hurdles remain. A critical challenge lies in maintaining their water-repelling properties over time, especially under harsh conditions or mechanical stress. Addressing this necessitates the development of novel, robust materials, and innovative fabrication techniques. These advancements would ensure the sustained effectiveness of SHSs in real-world applications. Furthermore, the high cost and limited scalability of current SHS production methods hinder widespread adoption. Research efforts should focus on exploring cost-effective and scalable manufacturing approaches, such as scalable Nano structuring or roll-to-roll processing, to bridge the gap between promising research and practical implementation.

Beyond durability concerns, further research is necessary to endow SHSs with additional functionalities without compromising their water-repellency. This necessitates exploring novel hybrid materials and surface engineering techniques to create multifunctional self-healing surfaces. The focus should be on incorporating features like antibacterial properties or self-healing capabilities while maintaining the delicate balance for specific applications like medical implants or marine coatings. Furthermore, a thorough investigation into the environmental impact and biocompatibility of SHSs is crucial for their responsible development and application. To ensure the responsible and sustainable application of superhydrophobic technologies, future research should prioritize the development of environmentally friendly and biocompatible materials, safeguarding human health and the environment. Additionally, research should explore methods to improve the dynamic responsiveness and adaptive behavior of SHSs. Many current SHSs are static, lacking the ability to adjust to changing environmental conditions or stimuli. This limits their functionality and necessitates further investigation into smart materials that can dynamically adapt for optimal performance in various scenarios. Despite the advancements in superhydrophobic surfaces (SHSs), challenges remain. A key focus should be on developing durable, cost-effective coatings. While various fabrication techniques exist, concerns regarding raw material costs and mechanical durability persist. The ideal SHS would be semi-permanent or permanent, possessing a suite of functionalities like self-cleaning, anti-biofouling, optical clarity, and superoleophobicity, all while being environmentally friendly. To achieve this, interdisciplinary collaboration between material scientists, chemists, engineers, and biologists is paramount. Overcoming large-scale manufacturing hurdles and achieving these advancements will be crucial for unlocking the full potential of SHSs and their real-world utilization. Furthermore, future research should prioritize the development of environmentally benign and biocompatible materials for sustainable and responsible use of SHSs. Additionally, exploring stimuli-responsive materials and smart surface designs that can adapt their wetting behavior based on external cues holds promise for enhanced functionality and broader applicability of SHSs.

6. Conclusions

This review article explores superhydrophobic surfaces, drawing inspiration from their intricate natural counterparts. Following a brief overview of the fundamental concepts and background, the article delves into various fabrication processes for superhydrophobic coatings. It then highlights a multitude of potential applications and explores the diverse approaches to surface energy manipulation for achieving superhydrophobicity. The review concludes by summarizing recent research advancements in this field. Superhydrophobicity, a property observed in nature, can be replicated artificially to create highly water-repellent surfaces. These surfaces offer not only water resistance but also a range of additional advantages, making them valuable across various industries and extending their service life. Researchers have successfully produced superhydrophobic surfaces for a broad spectrum of applications, including drag reduction, anti-fogging, anti-fouling, self-cleaning, anti-icing, anti-corrosion, anti-bacterial properties, oil-water separation, ice-repellency, biomedical applications, and more. The article provides a concise overview of several fabrication methods, such as lithography, plasma etching, chemical etching, laser ablation, template-assisted assembly, sol-gel, layer-by-layer deposition, PVD, CVD, and electrospinning. These methods, guided by principles that relate a substrate's micro- and nanostructure to its chemical composition, are designed to mimic naturally occurring superhydrophobic surfaces.

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Authors Contributions

All authors have contributed equally to prepare the paper.

Availability of Data and Materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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