E3S Web of Conferences **715**, 01008 (2026) https://doi.org/10.1051/e3sconf/202671501008
EPEMR 2026

Superhydrophobic Materials for Green and Low-Carbon Technologies: A Review of Recent Progress and Applications

Gaoqiang Zuo, Shuangzhe Lu, Yuhao Xue*, Bingbing Hu, Zihan Chen

Xi'an Polytechnic University, Xi'an 710600, China

Abstract. With the increasing global demand for energy conservation and emission reduction, superhydrophobic materials have attracted significant attention due to their exceptional surface wettability. Based on the classical theories of Young, Wenzel, and Cassie-Baxter, these materials achieve extreme liquid repellency through micro-nano structures and low-surface-energy chemistry. This review systematically summarizes recent progress in the application of superhydrophobic materials in key energy-saving and emission-reduction fields, including automotive, aviation, marine, construction, and solar energy conversion. The analysis covers the core principles, functional mechanisms, and performance characteristics of representative studies, highlighting the multifunctional roles of superhydrophobic coatings in self-cleaning, anti-icing, corrosion resistance, drag reduction, and thermal insulation. The review provides a comprehensive reference for the development of high-performance, environmentally friendly superhydrophobic materials toward green and low-carbon technologies.

1 Introduction

With the sustained development of the global economy and the continuous growth of human demands, energy consumption continues to rise, and environmental degradation problems are becoming increasingly severe. The global strategy for energy saving and emission reduction is urgent, and the demand for new functional materials is becoming more pressing. Due to their excellent properties, superhydrophobic materials show broad application prospects in key areas of energy saving and emission reduction, such as surface self-cleaning [1], separation and treatment of waste sewage [2], anti-icing at low temperatures, corrosion resistance in special environments [3], and drag reduction in aviation and marine applications. This paper summarizes the research progress in the application of superhydrophobic materials in the field of energy saving and emission reduction.

2 Core Principles of Superhydrophobicity

Superhydrophobicity arises from low-surface-energy chemistry and micro/nanoscale roughness. Three classical models describe surface wettability [4].

Young's equation defines the intrinsic contact angle θ on a smooth surface:

$$\cos\,\theta = \frac{\gamma_{SV}-\gamma_{SL}}{\gamma_{LV}} \tag{1}$$

It provides the first design rule: to achieve θ > 90°, the surface must be modified with low-energy materials (e.g., fluorosilanes, PDMS). However, even the lowest-energy smooth surface reaches only ~120°, not superhydrophobic (>150°).

For rough surfaces, Wenzel introduced the roughness factor r (actual/projected area):

$$\cos\,\theta_W = r\cos\,\theta \tag{2}$$

This model shows that roughness amplifies the native wettability: hydrophobic surfaces become more hydrophobic. It guides the design of “fully wetted” superhydrophobic surfaces [4].

Cassie-Baxter described composite wetting where air is trapped in surface pores:

$$\cos\,\theta_{CB} = f(1+\cos\,\theta)-1 \tag{3}$$

Here f is the solid-liquid contact fraction. Minimizing f (e.g., via hierarchical or re-entrant structures) maximizes the contact angle and reduces droplet adhesion [5].

Wenzel–Cassie transition and stability. A Cassie-state surface can irreversibly transition to the Wenzel state under pressure, impact, or freezing. This transition destroys superhydrophobicity and increases ice adhesion. Stability depends on microstructure geometry: re-entrant and hierarchical structures raise the energy barrier, maintaining the Cassie state longer. Preventing this transition is critical for durable anti-icing and marine coatings. The following sections will refer to these principles when analyzing application performance.

As shown in Figure 1, these three models describe the wetting states on smooth surfaces, rough surfaces, and composite surfaces, respectively, while providing a direct visual comparison of the microscopic morphology differences among these three classical wetting models.

---

*Corresponding author's e-mail: 42304040406@stu.xpu.edu.cn

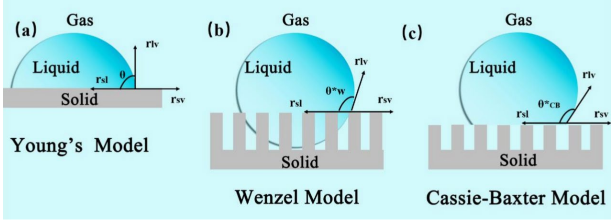

Figure 1. caption: (a) Schematic of Young's equation, (b) Schematic of Wenzel model, (c) Schematic of Cassie-Baxter model [5]

3 Summary of the Applications of Superhydrophobic Materials in the Field of Energy Conservation and Emission Reduction

In the transportation sector, superhydrophobic coating technology provides multifaceted support for achieving energy saving and emission reduction goals. Firstly, in the automotive industry, corrosion resistance, anti-fogging, optical transmittance, and self-cleaning are the most important properties for coatings. Superhydrophobic windshields with anti-fog and self-cleaning functions have attracted significant attention in recent years [6]. Lyu et al. [7] developed a novel environmentally friendly self-assembly strategy that endows glass surfaces with superhydrophobicity while maintaining 94.2% high transmittance. This not only enhances visual clarity but also significantly reduces the frequency of wiper and cleaning fluid use, thereby reducing indirect energy consumption and chemical pollution during maintenance. Microscopically, such coatings achieve extremely low surface energy through their micro-nano secondary structures, effectively inhibiting water droplet adhesion and enabling self-cleaning aided by airflow during driving. Notably, these coatings can also withstand water jet impact at 8.6 m/s for up to 6 minutes(As shown in Figure 2)[7], demonstrating excellent mechanical stability and ensuring their long-term application in complex driving environments.

In the field of automotive metal protection, superhydrophobic coatings form stable gaseous film barriers on the surfaces of steel, aluminum, and magnesium alloys by constructing micro-nano composite structures, effectively blocking moisture and corrosive media to extend component service life. Specifically, Du et al. [8] demonstrated that a superhydrophobic surface on Q235 carbon steel, achieved through chemical etching and fluorination treatment, exhibits a water contact angle as high as 161.6°, showcasing excellent corrosion resistance and fundamentally reducing resource consumption and environmental load associated with material replacement. Meanwhile, G et al.[9]incorporated modified nano-SiO_2 and VTES into polyurethane (PU) automotive clear coatings (PU-NS, PU-NS-V1-1), enhancing scratch resistance, gloss retention, and metal adhesion. They successfully developed a prototype superhydrophobic coating with self-cleaning potential (as shown in Figure 3: PU-NS-V1-1 contact angle of 111°). The energy-saving benefits are reflected in extended coating lifespan, reduced maintenance requirements, and decreased energy consumption by inhibiting corrosion and UV degradation.

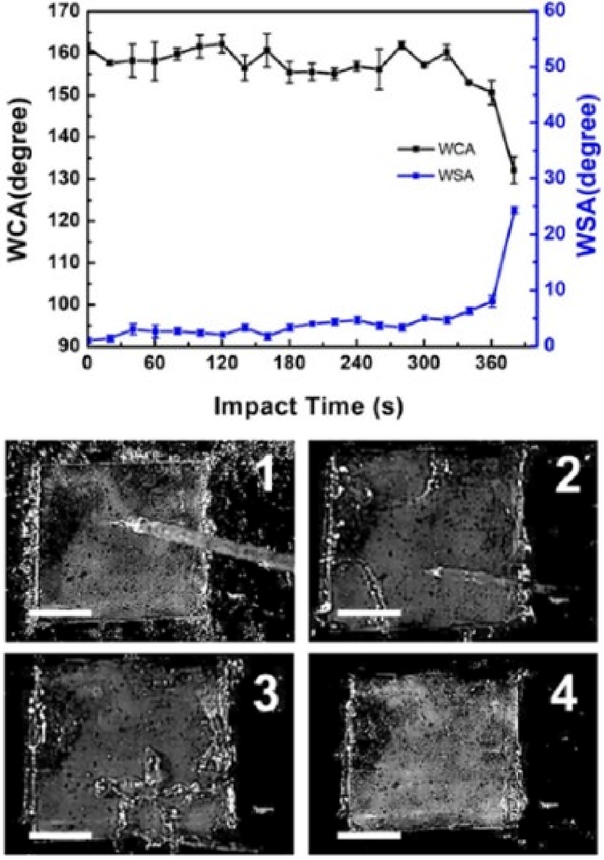

Figure 2. Superhydrophobic properties of the coating after water jet impact at a speed of 8.6 m/s. And captured images of the water jet impact process at a speed of 8.6 m/s; the scale bar is 1 cm[7].

In automotive applications, transparent self-cleaning coatings (Lyu et al.) and metal-protective coatings (Du et al.; Ghamarpoor et al.) prioritize optical clarity versus mechanical/chemical durability, respectively, revealing a clear transparency–durability trade-off. An integrated solution that combines high transparency, high abrasion resistance, and long-term self-cleaning performance is still lacking.

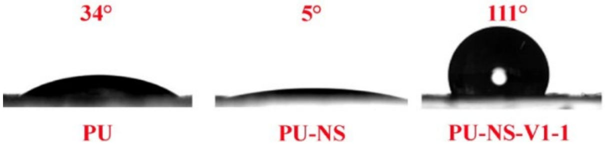

Figure 3. WCA of PU, PU-NS and PU-NS-V1-1[9]

The aviation industry imposes extremely high requirements on anti-icing and deicing technologies. Superhydrophobic coatings have emerged as an effective alternative to traditional energy-intensive thermal deicing methods, leveraging their ability to delay ice formation, reduce ice adhesion strength, and suppress the freezing of supercooled droplets. The anti-icing mechanism primarily involves three aspects: prolonging the retention time of liquid water at low temperatures, lowering the ice nucleation temperature, and reducing ice adhesion strength to less than one-fifth of that on conventional surfaces. For instance, Zhao et al. [10] designed a flexible–flexible synergistic superhydrophobic structure (FFSSS), formed by tightly integrating near-zero-shrinkage flexible silica aerogel with nickel-copper-coated polyurethane sponge (NCCPS), which combines electrothermal deicing and passive anti-icing capabilities. The energy-saving effects are demonstrated by the structure's ability to achieve a long ice-formation delay time of 1500 s at −20°C (as shown in Figure 4), along with low-power electrothermal deicing (melting ice within 152 s at a current density of only 0.10 W/cm²). This significantly reduces energy consumption during deicing under extreme conditions, making it particularly suitable for energy-limited humid and cold environments.

In comparison, passive anti-icing (FFSSS) offers zero energy consumption and is suitable for mild icing or energy-limited platforms (e.g., drones), but its durability under repeated icing cycles remains limited. Active photothermal de-icing (PDMS/Fe/CS) is more reliable under severe conditions but depends on sunlight availability. How to intelligently integrate both strategies, and the Cassie-state stability under long-term icing–de-icing cycles, are current knowledge gaps.

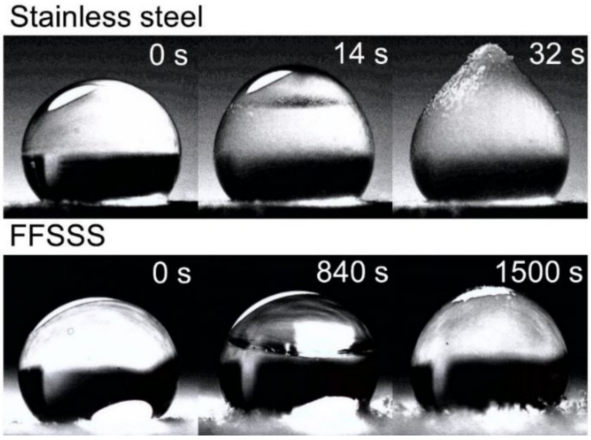

Figure 4. Icing delay process of a droplet on stainless steel and FFSSS surfaces (water drop: 10 μL).[10]

Compared to passive anti-icing strategies often limited by mechanical durability, active de-icing technology performs more reliably under various icing conditions and has been widely applied. Huang's team [11] compounded PDMS, iron powder (Fe), and candle soot (CS) to develop a superhydrophobic coating system integrating passive anti-icing and active photothermal de-icing functions, tested under simulated sunlight (Figure 5A). It can be seen that the ice on the superhydrophobic coating surface completely melted within 237 seconds of illumination (Figure 5B). Simultaneously, this photothermal-superhydrophobic composite coating exhibited a 4.7 times longer ice delay time compared to ordinary surfaces, greatly reducing the energy input required to maintain aircraft operation in cold environments, providing a novel solution for aviation safety and energy saving under extreme climate conditions.

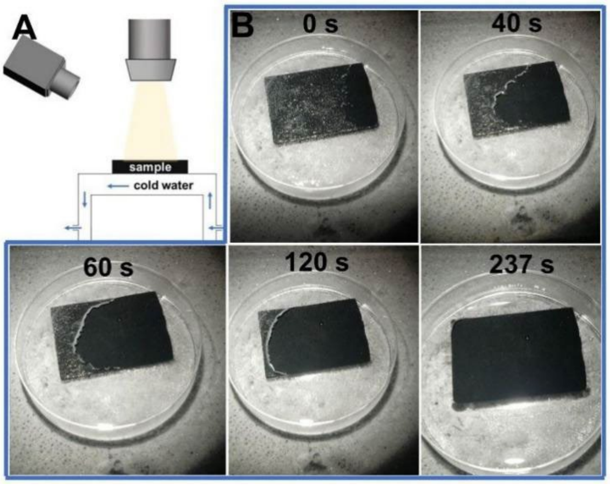

Figure 5. caption: (A) Schematic diagram of the photothermal de-icing device. (B) Photothermal de-icing process of a thin ice layer (1 mm thick) on the superhydrophobic coating under solar irradiation. The diameter of the Petri dish is 3.2 cm [11].

In the marine and offshore engineering field, superhydrophobic coatings are widely used to enhance hull corrosion resistance, anti-biofouling, and drag reduction performance. Salt corrosion and biofouling in the marine environment have long been key factors restricting ship service life and energy efficiency. Superhydrophobic technology can address both issues simultaneously by forming a stable air film barrier. For instance, surfaces mimicking the pitcher plant mechanism, such as liquid-infused slippery surfaces (SLIPS) with pecan-like and hyacinth-like structures (Figure 6d: B-SLIPS, Figure 6e: H-SLIPS), and superhydrophobic surfaces (SHS) with different morphologies (torreya and hyacinth-like structures) prepared by electrodeposition (Figure 6b: B-SHS, Figure 6c: H-SHS), can inhibit microalgae adhesion by over 95% and Bacillus sp. adhesion by 97% compared to bare 5083 aluminum alloy (as shown in Figure 6f) [12], significantly reducing ship maintenance frequency and the use of chemical antifouling agents.

Furthermore, Hu et al. [13] designed a microscopic morphology with alternating superhydrophobic and hydrophilic regions. This drag-reducing design facilitates the formation of continuous and uniform air rings, which can induce a stable air film on the hull surface, effectively reducing navigation resistance and thereby achieving fuel savings and reduction of exhaust emissions. Wang et al. [14] constructed micro-structured superhydrophobic PDMS/HSS surfaces and superoleophobic PDMS/HSS-PZS surfaces with sustained regenerative capacity by mimicking the superhydrophobicity of lotus leaves, the anti-adhesion properties of shark skin, and the "brick-and-mortar" structure of nacre. These surfaces reduce biofouling and contact with corrosive media. Specifically, the PDMS/HSS coating demonstrated an antibacterial efficiency of 37.8% compared to bare aluminum, while the superoleophobic PDMS/HSS-PZS coating showed a higher antibacterial efficiency than PDMS/HSS (81.1%) (as shown in the figure7). This significantly reduces the energy consumption and maintenance demands of marine equipment caused by biofouling and corrosion, indirectly achieving energy savings by extending equipment service life and reducing cleaning frequency.

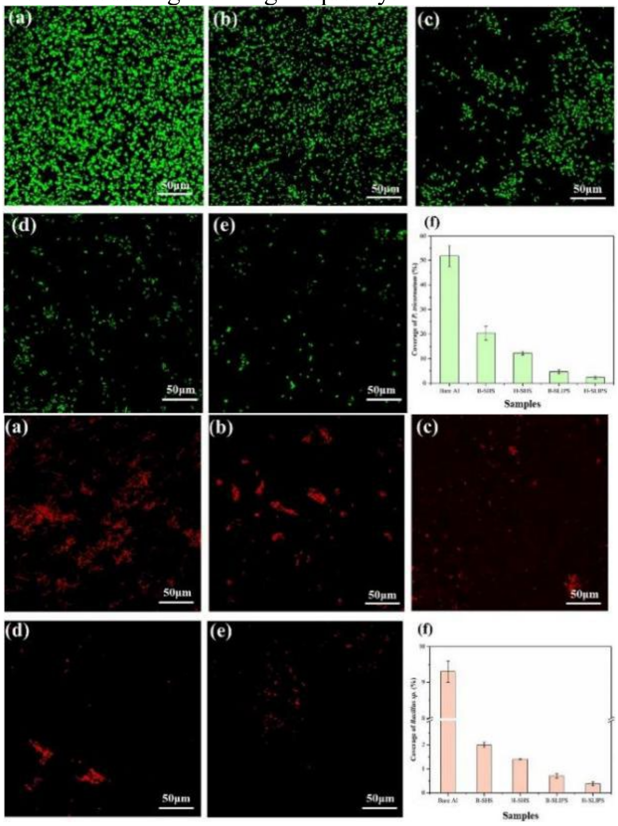

Figure 6. caption: CLSM images of microalgae and Bacillus sp. adhesion on bare 5083 Al (a), B-SHS (b), H-SHS (c), B-SLIPS (d), H-SLIPS (e), and statistical analysis of coverage rates on the original sample (f) [12].

Both SHS (air-trapping) and SLIPS (lubricant-infused) achieve high antifouling efficiency, but SHS suffer from the Cassie-to-Wenzel transition risk, while SLIPS face lubricant depletion over time. Hybrid strategies or bio-inspired durable structures are promising directions, yet their long-term performance under real marine dynamic conditions remains unevaluated.

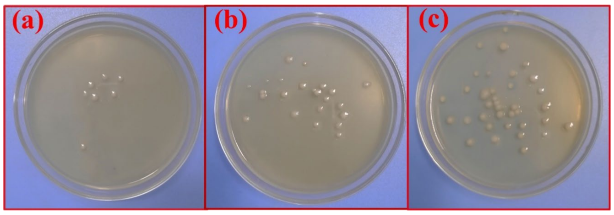

Figure 7. Growth status of Pseudomonas sp. colonies on different coating specimens after 3 d culture: (a) PDMS/HSS-PZS; (b) PDMS/HSS; (c) bare Al.[14]

In construction and energy-saving equipment, superhydrophobic coatings provide innovative pathways for building energy efficiency and efficient resource utilization. For example, ultrafast laser technology can be used to prepare highly transparent, superhydrophobic glass surfaces whose self-cleaning performance can be maintained for over 30 days [15], significantly reducing the use of cleaning water and chemicals. The introduction of ultrafast laser processing enables superhydrophobic glass to possess both ultra-high transparency and durable hydrophobicity, offering an ideal energy-saving solution for modern building curtain wall systems. On the other hand, Thai et al. [16] prepared superhydrophobic aerogels from waste tires, achieving solid waste recycling while exhibiting excellent thermal insulation performance (average thermal conductivity of 0.035–0.047 $W\cdot m^{-1}\cdot K^{-1}$) and good sound absorption (noise reduction coefficient up to 0.41)(Figure 8). Used in building exteriors and roofs, they can significantly improve thermal insulation performance and reduce HVAC energy consumption. Their high solar reflectance also helps mitigate the urban heat island effect, further reducing electricity load during cooling stages. These materials not only surpass the acoustic performance of commercial sound-absorbing foams but also possess flame retardancy and environmental friendliness, meeting the sustainable development requirements of green building materials.

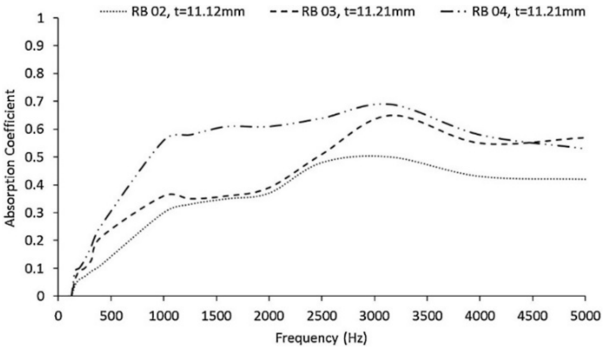

Figure 8. The sound absorption coefficient curves of the rubber aerogels (11.2 mm-thickness) at different RCTF concentration (3.0–5.0 wt.%). [16]

Table 1 below systematically summarizes the key trade-offs of the representative superhydrophobic strategies discussed above, allowing readers to quickly compare the selection criteria for different application scenarios.

Table 1. Key trade-offs of representative superhydrophobic strategies

Application	Strategy Comparison	Advantage	Limitation
Aviation anti-icing	Passive (FFSSS) vs. Active (photothermal)	Zero energy vs. high reliability	Durability vs. light dependence
Automotive glass	Transparent superhydrophobic coating	Visual clarity, self-cleaning	Moderate abrasion resistance
Automotive metal	Anti-corrosion superhydrophobic coating	Extended lifespan, corrosion protection	Poor transparency, complex processing
Marine antifouling	SHS (air-trapping) vs. SLIPS (lubricant-infused)	No consumable vs. stable interface	Cassie transition vs. lubricant depletion

It can be seen from Table 1 that current technologies cannot simultaneously satisfy all performance requirements; therefore, targeted optimization based on operating conditions (such as mechanical wear, lighting conditions, maintenance cycles, etc.) is necessary in practical applications.

4 Summary and Outlook

Superhydrophobic materials offer significant benefits for energy-saving and emission-reduction applications, including self-cleaning, anti-icing, corrosion resistance, and drag reduction. However, practical deployment is limited by mechanical fragility, environmental instability, and high fabrication costs.

Based on the comparative analysis in this review, three knowledge gaps are identified:

Lack of standardized durability assessment – most studies report short-term lab tests without simulating real-service conditions (UV, salt spray, thermal cycling), hindering cross-study comparison.

Poor understanding of passive–active synergy – integrating passive anti-icing with active de-icing (or SHS with SLIPS in marine applications) remains unexplored.

Absence of life-cycle carbon assessment – quantitative net emission reduction data from synthesis to disposal are missing.

Future research should prioritize self-healing and bio-inspired durable surfaces, passive–active integrated systems, scalable fabrication, and life-cycle assessment with standardized protocols. Addressing these gaps will accelerate industrial deployment of superhydrophobic technologies for global energy-saving and emission-reduction strategies.

References

1. Li X L. Construction of Functionalized Superhydrophobic Composite Materials and Their Performance in Clean Water Production[D]. Liaocheng University, 2024. DOI: 10.27214/d.cnki.glcsu.2024.000515.
2. Cui C C. Preparation of Functional Superhydrophobic Materials and Their Application in Water Purification[D]. Hubei University, 2024. DOI: 10.27130/d.cnki.ghubu.2024.000271.
3. Dong S T. Research Progress in the Preparation and Application of Environmentally Friendly Superhydrophobic Materials[J]. Chemical Engineer, 2024, 38(04): 76-80. DOI: 10.16247/j.cnki.23-1171/tq.20240476.
4. Li Y G. Design and Construction of Clean and Sustainable Biomimetic Superhydrophobic Materials for Oil-Water Separation[D]. Changchun University of Technology, 2024. DOI: 10.27805/d.cnki.gccgy.2024.000292.
5. Liao C C. Construction and Properties of Bio-based Superhydrophobic High-performance Fabrics[D]. Changchun University of Technology, 2022. DOI: 10.27805/d.cnki.gccgy.2022.000762.
6. Syafiq A , Vengadaesvaran B , Ahmed U ,et al.Facile synthesize of transparent hydrophobic nano- CaCO3 based coatings for self-cleaning and anti-fogging[J].Materials Chemistry and Physics, 2019, 239:121913.DOI:10.1016/j.matchemphys.2019.121913.
7. Lyu J , Wu B , Wu N ,et al.Green preparation of transparent superhydrophobic coatings with persistent dynamic impact resistance for outdoor applications[J].Chemical Engineering Journal, 2020:126456.DOI:10.1016/j.cej.2020.126456.
8. Liang Z T Y .Preparation of superhydrophobic and anti-resin-adhesive surfaces with micro/nanoscale structures on high-speed steel via laser processing[J].Surface & Coatings Technology, 2019, 357.DOI:10.1016/j.surfcoat.2018.10.001.
9. Ghamarpoor R , Jamshidi M , Joshaghani M .Hydrophobic silanes-modified nano-SiO reinforced polyurethane nanocoatings with superior scratch resistance, gloss retention, and metal adhesion[J].Scientific Reports[2025-10-30].DOI:10.1038/s41598-025-16829-1.
10. Zhao Z , Yang M , Li L ,et al.A robust flexible-flexible synergistic superhydrophobic structure for deicing/long icing delay and microwave absorption[J].Chemical Engineering Journal, 2025, 510.DOI:10.1016/j.cej.2025.161654.
11. A W Z , A L T , A Y L ,et al.Magnetic Responsive and Flexible Composite Superhydrophobic Photothermal Film for Passive Anti-icing/Active Deicing - ScienceDirect[J].Chemical Engineering Journal, 2021.DOI:10.1016/j.cej.2021.130922.
12. Yang Z , He X , Chang J ,et al.Facile fabrication of fluorine-free slippery lubricant-infused cerium stearate surfaces for marine antifouling and anticorrosion application[J].Surface&Coatings Technology;, 2021, 415(000).DOI:10.1016/j.surfcoat.2021.127136.
13. Hu H , Wen J , Bao L ,et al.Significant and stable drag reduction with air rings confined by alternated superhydrophobic and hydrophilic strips[J].Science Advances, 2017, 3(9):e1603288.DOI:10.1126/sciadv.1603288.
14. Wang J , Bing W , Jin H ,et al.Bionic sustainable superhydrophobic coating featuring high durability, antifouling, and anticorrosion properties[J].Progress in Organic Coatings, 2025, 204.DOI:10.1016/j.porgcoat.2025.109264.
15. Barthwal S , Lim S H .Rapid fabrication of a dual-scale micro-nanostructured superhydrophobic aluminum surface with delayed condensation and ice formation properties[J].Soft Matter, 2019, 15.DOI:10.1039/C9SM01256G.
16. Thai Q B , Siang T E , Le D K ,et al.Advanced fabrication and multi-properties of rubber aerogels from car tire waste[J].Colloids and Surfaces A: Physicochemical and Engineering Aspects, 2019, 577(000):7.DOI:10.1016/j.colsurfa.2019.06.029.