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Research Progress on Lotus-Leaf-Inspired Self-Cleaning Coatings in Cultural Heritage Conservation

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Abstract: *Cultural heritage serves as the material carrier of human history and civilization. However, under the influence of both natural and anthropogenic factors, it faces multiple threats such as pollution, weathering, and biological erosion, among which moisture is a critical factor contributing to the aging and deterioration of heritage materials. Lotus-leaf-inspired self-cleaning coatings, based on the micro-nano hierarchical structure and low surface energy characteristics of lotus leaf surfaces, exhibit outstanding superhydrophobic and self-cleaning properties, thereby providing a novel solution for the preventive conservation of cultural heritage. This paper systematically reviews the hydrophobic principles and preparation processes of self-cleaning coatings, summarizes their current application status in stone, wood, paper, mural, and metal cultural relics, and analyzes the existing problems of this technology in terms of durability, construction adaptability, and other aspects. Finally, from the perspectives of material innovation, process optimization, and functional integration, the future development directions of biomimetic self-cleaning coatings in cultural heritage conservation are prospected, aiming to provide theoretical references for related research and practice.*

Keywords: *Biomimetic Coating; Self-Cleaning; Superhydrophobic Materials; Lotus Effect; Cultural Heritage Conservation*

1. Introduction

Cultural heritage is an important material carrier of human history and civilization. The conservation of cultural heritage entails not only the maintenance of physical remains, but also the continuation of historical memory and cultural inheritance. However, during long-term preservation, cultural heritage is frequently subject to damage from multiple factors such as moisture intrusion, microbial proliferation, and chemical corrosion, among which moisture often acts as a medium that exacerbates the occurrence and development of various deterioration processes[1]. Therefore, constructing a stable barrier between the heritage substrate and the external environment through effective technical measures has become an important approach to delaying the degradation of cultural relics.

In recent years, advances in biomimetic materials science have provided new perspectives for cultural heritage conservation. Lotus-leaf-inspired self-cleaning coating technology has been introduced into this field, demonstrating particular potential for the surface protection of ancient buildings and open-air stone cultural relics. Based on the micro-nano hierarchical structure and low surface energy characteristics of lotus leaf surfaces, this technology exhibits outstanding superhydrophobicity and self-cleaning capability. It can not only effectively prevent water adhesion and penetration, but also remove surface contaminants through water droplet rolling, thereby achieving the "self-cleaning" function[2]. Lotus-leaf-inspired self-cleaning coating technology offers an environmentally friendly, convenient-to-apply, and long-lasting solution for the preventive conservation of cultural heritage.

This paper systematically reviews the application and research progress of lotus-leaf-inspired self-cleaning coating technology in cultural heritage conservation. It first elaborates its biomimetic principles and preparation methods, then analyzes in detail its applicability and practical performance in the conservation of different types of cultural heritage, including stone, wood, paper, mural, and metal relics, and further discusses the current challenges facing this technology, such as durability, construction adaptability, and environmental compatibility. Finally, by integrating the needs of materials science and cultural heritage conservation, it looks ahead to the development trends in material innovation, process

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optimization, and functional integration, with the aim of providing theoretical reference and technical guidance for research and practice in related fields.

2. Technical Principles and Preparation Methods of Lotus-Leaf-Inspired Self-Cleaning Coatings

2.1. Lotus Effect and Its Superhydrophobic Mechanism

The lotus effect originates fundamentally from the unique microscopic structure and wetting behavior of the lotus leaf surface (Fig. 1A). Rather than being smooth, the lotus leaf surface is covered with microscale papillae, and the surface of each papilla is further coated with nanoscale wax crystals, forming a two-tier micro-nano hierarchical structure. This structure is capable of trapping air, drastically reducing the actual contact area between water droplets and the solid surface, thereby achieving a superhydrophobic state (with a contact angle typically greater than 150° and a sliding angle less than 10°) . As illustrated in Fig. 1, on an ideal smooth surface a droplet follows Young's wetting model (Fig. 1B), whereas the rough lotus leaf surface assumes a Cassie–Baxter composite wetting state (Fig. 1C). In this state, the droplet only contacts the tips of the solid protrusions, rolls off in a near-spherical shape, and during this process picks up and carries away contaminants such as dust and particles, ultimately achieving the self-cleaning function. The self-cleaning efficiency of superhydrophobic surfaces is significantly influenced by the tilt angle. Studies have shown that vertical or inclined surfaces facilitate the rapid roll-off of water droplets under gravity, thereby enhancing cleaning efficiency and water removal capability, which is particularly important for the conservation of cultural heritage such as stone carvings, murals, and buildings.

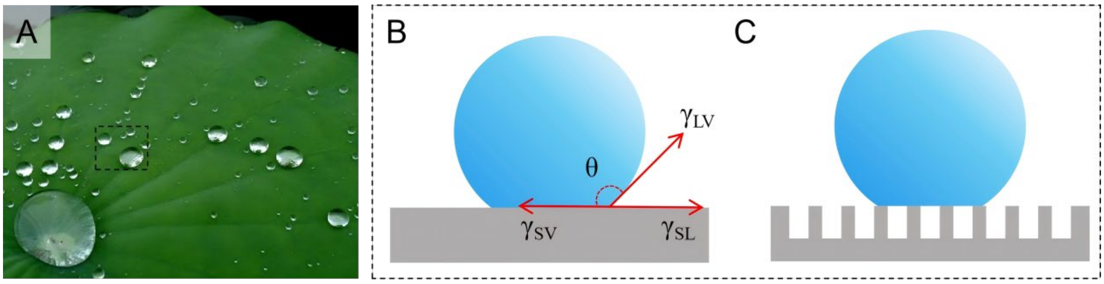

Figure 1: (A) Macroscopic superhydrophobic phenomenon on a lotus leaf surface (spherical water droplets rolling off); (B) Young's wetting model on an ideal smooth surface; (C) Cassie-Baxter composite wetting model on a micro-nano rough surface.

2.2. Major Preparation Methods for Lotus-Leaf-Inspired Self-Cleaning Coatings

2.2.1. Template Method

The template method is one of the approaches with relatively high controllability for preparing biomimetic superhydrophobic surfaces. Its principle is to use a substance possessing a specific micro-nano structure as a template and accurately transfer the template morphology onto the target substrate material through imprinting, casting, or chemical replication, thereby constructing the desired rough structure. For example, researchers have used fresh lotus leaves as the original template, performed a two-step replication with polydimethylsiloxane (PDMS), followed by fluorination treatment, yielding a coating with a contact angle exceeding 160° that causes minimal damage to the heritage substrate. However, this method suffers from high template preparation costs, difficulty in controlling structural uniformity during large-area replication, and poor adaptability to heritage substrates with complex shapes. It is therefore more suitable for laboratory research or the conservation treatment of small-area precious cultural relics.

2.2.2. Sol-Gel Method

The sol-gel method is one of the most widely used chemical methods for preparing organic–inorganic hybrid self-cleaning coatings and has attracted particular attention in the field of cultural heritage conservation. This method is based on the hydrolysis and condensation reactions of metal alkoxides or inorganic salts (e.g., silicon and titanium sources) under mild conditions to form a sol with a three-dimensional network structure. The sol is then applied to the substrate surface via dip coating, spin coating, or spray coating, and after drying and curing, a coating is formed. Its advantages include flexible composition control, mild reaction conditions, and ease of achieving large-area film formation.

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Furthermore, by introducing hydrophobic groups (such as long-chain alkyl or fluoroalkyl groups) or nanoparticles (such as hydrophobized SiO_2 or TiO_2), coatings that combine both micro-nano rough structures and low surface energy characteristics can be constructed in a one-pot process. Currently, the sol-gel method is considered to have good industrialization prospects and is the most promising for large-scale application in scenarios such as the conservation of open-air stone cultural relics and building exterior walls.

2.2.3. Layer-by-Layer (LbL) Assembly Method

The layer-by-layer (LbL) assembly method is a precisely controllable technique for preparing self-cleaning coatings based on the alternating deposition of oppositely charged species to construct multilayer films. Typically, positively charged polymers (e.g., poly(diallyldimethylammonium chloride), PDDA) and negatively charged nanoparticles (e.g., silica, titania, clay platelets) are alternately deposited, driven by electrostatic attraction, hydrogen bonding, or van der Waals forces, to build layer-by-layer on the substrate surface a composite film with controllable thickness, roughness, and porosity. After assembly, post-treatment (such as mild calcination or modification with low-surface-energy substances) is often required to form a stable superhydrophobic structure. The advantages of the LbL method lie in its high controllability and universality. Researchers can precisely tailor the micro-morphology, transparency, and wettability of the coating by adjusting the number of deposition cycles, nanoparticle size, and solution ionic strength, thereby meeting the conservation requirements of different materials (paper, textiles, wood, stone, etc.) and shapes. Although the procedure is relatively tedious and time-consuming, its strong structural designability and minimal damage to the heritage substrate endow it with unique value in fundamental research and high-precision conservation.

3. Application Status of Lotus-Leaf-Inspired Self-Cleaning Coatings in Cultural Heritage Conservation

3.1. Conservation of Stone Cultural Heritage

Stone cultural heritage, including grottoes, stone carvings, ancient building stone, and gypsum, is exposed outdoors for long periods and is susceptible to rain erosion, microbial adhesion, and freeze-thaw cycles, leading to surface pulverization, spalling, dissolution, and contaminant accumulation. Water is the primary medium for stone weathering; it penetrates into the interior of the stone, dissolves soluble salts, and generates crystallization pressure during wet-dry cycles, thereby exacerbating the structural damage of the heritage object. Therefore, constructing surface coatings with hydrophobic and self-cleaning functions is of great significance for retarding stone weathering and preserving its original appearance.

In recent years, lotus-leaf-inspired self-cleaning coatings have been studied for application in stone cultural heritage conservation. To address the challenge that protective coatings for sandstone relics struggle to balance superhydrophobicity, transparency, interfacial adhesion, and mechanical strength, and that hydrophobic SiO_2 nanoparticles tend to agglomerate, impairing coating performance and large-scale application, a team from Shaanxi University of Science and Technology prepared a SiO_2-based superhydrophobic coating with high transparency, good interfacial adhesion, and excellent mechanical properties. By tuning the mass ratio of amino-modified SiO_2 (A-SiO_2) and fluorinated SiO_2(P-SiO_2)/PDMS, and improving dispersibility through hydrogen bonding between A-SiO_2 and P-SiO_2, the aggregation problem of SiO_2 was solved. The coating exhibited a contact angle of 154.3°-155.0° and a transmitted color difference $\Delta E = 1.74$, while also improving interfacial adhesion and mechanical properties. This coating is suitable for the conservation of sandstone relics [3]. C. Esposito Corcione et al. from the University of Salento, Italy, prepared a solvent-free UV-curable organic–inorganic hybrid methacrylate coating via a sol–gel method. By optimizing the coating amount and conducting a comprehensive comparison with commercial solvent-based and water-based stone protection products, they addressed the problems of toxic solvents, poor breathability, and harsh curing conditions (high temperature/long time) in existing protective coatings, which affect the long-term preservation of cultural relics. After curing, the coating achieved a contact angle of over 120° and remained stable after 6 months of testing. It exhibited moderate breathability (70 $g/m^2 \cdot day$), superior protective performance to commercial solvent-based coatings, a water absorption inhibition rate for travertine exceeding 80%, rapid curing, and little influence from the environment [4].

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3.2. Conservation of Wooden Cultural Heritage

Wooden cultural relics, mainly composed of cellulose and lignin, are susceptible to microbial erosion, insect infestation, and environmental humidity. After absorbing moisture, wood is prone to swelling, cracking, mildew, and decay; paper, when absorbing water, can undergo hydrolysis, acidification, and blurring of writings. Moisture is the primary inducer of degradation in fiber-based cultural relics. Therefore, developing lotus-inspired coatings that combine transparency, moisture resistance, and self-cleaning functions, while complying with the principles of minimal intervention and reversibility, holds promise for the long-term preservation of cultural relics.

The protection of wooden cultural relics must balance hydrophobicity, breathability, and mechanical durability to prevent the coating from hindering the wood' s breathing or causing surface cracking. The team from Jiangsu University of Technology used Paraloid B72 as the matrix, composited with hydrophobic SiO_2 nanoparticles (optimal ratio 2 wt%), and prepared a transparent superhydrophobic coating via one-step spray coating [5]. This coating formed a continuous porous network structure on the wood surface, with a water contact angle reaching 165°, a sliding angle of only 6°, visible light transmittance of 72.57%, and a color difference $\Delta E < 1.02$, hardly altering the original appearance of the artifact. It also exhibited good breathability (air permeability decay rate < 10%), could withstand acid and alkali erosion at pH 1–13, sand impact, and 30 days of outdoor exposure, and maintained a contact angle > 150° after 5 days of hygrothermal aging (60 °C, 85-90% RH), effectively inhibiting wood moisture absorption and mold growth. Furthermore, the team from the University of Campinas, Brazil, used elephant grass biomass as raw material to extract cellulose nanofibrils (CNFs), cellulose nanocrystals (CNCs), and lignin nanoparticles (LNPs) to prepare a water-based nanocomposite coating. The hydrophobicity could be tuned by adding carnauba wax nanoparticles (CWNPs), achieving a maximum water contact angle of 113° on wood surfaces [6]. After hygrothermal aging, the wood color difference ΔE was <2, with discoloration barely perceptible to the naked eye. Moreover, the coating exhibited excellent reversibility and could be removed by hydrogel cleaning, meeting the reversibility requirement of cultural heritage conservation. This coating, through a dual mechanism of penetration and film formation, blocks moisture ingress without damaging the natural grain and breathability of the wood, and has already shown application potential in the conservation of ancient building wooden components and archaeological wooden artifacts.

3.3. Conservation of Mural Cultural Heritage

Mural cultural heritage is frequently affected by humidity fluctuations, salt crystallization, microbial growth, and visitor touching, leading to flaking, detachment, soiling, and mold growth of the paint layer. Moisture is particularly critical in mural conservation. On one hand, high-humidity environments easily trigger salt migration and crystallization; on the other hand, water participates in microbial metabolism and accelerates the degradation of organic binding materials. Therefore, developing surface coatings that do not affect the appearance of murals and combine breathability with self-cleaning functions is an important direction for the preventive conservation of murals.

In mural conservation, the application of lotus-inspired self-cleaning coatings also possesses unique potential. To address the problems that murals in humid environments are prone to dampness-induced powdering, lifting, and detachment, while traditional Paraloid B72 coatings suffer from poor breathability and yellowing, the team from Jiangsu University of Technology employed a one-step spray method to prepare a translucent superhydrophobic coating (BSP-3). This coating used B72 as the matrix, hydrophobic nano-SiO_2 as the building blocks for micro-nano roughness, and polydimethylsiloxane (PDMS) as the low-surface-energy modifier and toughening component. The coating achieved a contact angle of 165.5°, a sliding angle of 7°, a visible light transmittance of 60.17% (translucent, ΔE=1.69), and a breathability decay rate of only 13%. It could withstand 5 cycles of high–low temperature cycling, 196 h of UV exposure, and 7 sand impacts. The moisture absorption rate of the mural decreased from 53% to 5%, largely solving the problem of moisture-induced degradation of murals [7]. Additionally, ancient architectural murals are susceptible to water erosion, UV aging, and mold damage. Existing coatings (epoxy, acrylic) exhibit poor UV resistance, weak antibacterial properties, and insufficient mechanical strength, readily leading to the peeling of polychrome paintings. The team from Shaanxi University of Science and Technology used fluorocarbon vinyl ether (FEVE) resin as the matrix, modified nano-SiO_2 with silane coupling agent KH550, and compounded with nano-TiO_2 to construct a multifunctional protective coating, which was successfully applied to the conservation of the polychrome paintings in the Yuhua Pavilion of the Forbidden City. This coating achieved high color fidelity with $\Delta E < 3$, maintained stable performance after 480 h of accelerated UV aging, strongly inhibited common pathogenic fungi of polychrome paintings, and exhibited good water vapor permeability. It integrated waterproofing, UV resistance, antibacterial properties, and mechanical reinforcement, providing an efficient and feasible new material and solution for the multifunctional integrated protection of outdoor ancient architectural polychrome paintings [8].

3.4. Conservation of Metallic Cultural Heritage

Metallic cultural heritage (with bronze as the core representative, also including ironware, gold and silver ware, etc.) is an important material carrier of ancient civilizations. However, during long-term burial or outdoor display, it is susceptible to erosion by corrosive media such as chloride ions (Cl^-), oxygen (O_2), and water vapor (H_2O), leading to deterioration phenomena such as electrochemical corrosion, pitting, and "bronze disease," which cause surface rusting, exfoliation of mineralized layers, and structural loosening, seriously threatening the integrity of the artifacts. Moreover, the transition from an anoxic environment to an oxygen-rich environment after excavation accelerates the corrosion process. Protective coatings must adhere to the conservation principles of "reversibility" and "minimal intervention," achieving long-term corrosion protection without altering the original color and appearance of the artifacts, which imposes stringent requirements on coating performance. Lotus-inspired self-cleaning coatings, with their superhydrophobicity, physical barrier effect, high transparency, and environmental compatibility, have become an important technical means for the anti-corrosion protection of metallic cultural heritage.

Based on the organic–inorganic hybridization theory, the team from Shaanxi University of Science and Technology composited the metal–organic framework ZIF-8 with two-dimensional MXene material $Ti_3C_3T_x$, and after fluorination modification with 1H,1H,2H,2H-perfluorodecyltriethoxysilane (PFDTES), successfully prepared an F-WPU@ZIF-8/$Ti_3C_3T_x$ composite anti-corrosion coating for bronze [9]. The coating exhibited a water contact angle of 154.1°, demonstrating a superhydrophobic state and excellent self-cleaning performance. Electrochemical tests showed that its corrosion current density was as low as 3.344×10^{-6} A cm^{-2}, two orders of magnitude lower than those of F-WPU@ZIF-8 and F-WPU@$Ti_3C_3T_x$ coatings. After 15 days of UV irradiation at 365 nm, the contact angle remained at 146.5°, indicating outstanding aging resistance. Meanwhile, the coating surface color difference ΔE was < 3, not affecting the appearance of the bronze artifacts, and it could be reversibly removed by ultrasonic cleaning in ethanol, fully conforming to the principles of cultural heritage conservation. To address the problems that bronze artifacts are easily corroded by chloride ions, moisture, and UV radiation, while traditional Paraloid B72 coatings have strong hydrophilicity, insufficient aging resistance and anti-corrosion performance, and commonly used protective agents containing benzotriazole (BTA) pose environmental toxicity, the same team further optimized the coating system by incorporating fluorinated $Ti_3C_3T_x$ (F-$Ti_3C_3T_x$) nanosheets and polypyrrole (PPy) nanoparticles into the Paraloid B72 matrix, constructing an F-$Ti_3C_3T_x$/PPy/B72 composite protective coating for bronze that combines superhydrophobicity and long-term durability [10]. The coating achieved a static water contact angle of 152.6° and excellent self-cleaning ability. After 21 days of UV aging and temperature-humidity cycling tests, high hydrophobic angles of 149.5° and 146.3°, respectively, were maintained. In 3.5 wt% NaCl solution, the corrosion current density was as low as 5.15×10^{-8} A cm^{-2}, with a corrosion protection efficiency of approximately 98%. Moreover, the coating surface color difference ΔE was < 3, preserving the appearance of the bronze artifacts. Synergistic protection was achieved through the physical labyrinth barrier effect of F-$Ti_3C_3T_x$, the anodic passivation of PPy, and the mechanical support of B72, providing a novel, non-toxic, and highly effective solution for the long-term anti-corrosion protection of bronze artifacts in harsh environments.

4. Existing Problems and Challenges

Although lotus-leaf-inspired self-cleaning coatings have shown promising prospects in cultural heritage conservation, they still face the following problems in practical applications.

4.1. Insufficient Durability

At present, the long-term weatherability of most lotus-inspired coatings remains unsatisfactory. In particular, under outdoor conditions characterized by temperature–humidity cycling, large diurnal temperature differences, and ultraviolet radiation, the coatings are prone to aging, cracking, or a decline in hydrophobic performance. For instance, some silicon-based coatings are susceptible to hydrolysis in hot and humid environments, leading to the loss of protective function.

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4.2. Limited Construction Adaptability and Controllability

It is difficult for the coating to form a uniform film on complex surfaces (such as sculptural textures and mortise-and-tenon joints). Excessive spraying may cover the surface details of cultural relics or lead to material accumulation, thereby affecting the original appearance. Moreover, the control of coating penetration depth and film thickness requires further optimization.

4.3. Environmental Adaptability and Long-Term Safety to Be Verified

Climatic conditions in different regions significantly influence coating performance; for example, freeze–thaw resistance is required in alpine regions, while mildew prevention is necessary in hot and humid regions. According to the Law of the People's Republic of China on the Protection of Cultural Relics and related conservation guidelines, cultural heritage conservation should adhere to the principles of "minimal intervention," "reversibility," "compatibility," and "legibility." Currently, lotus-inspired coatings still face challenges regarding "reversibility." Some coatings bond too strongly to the substrate and are difficult to remove without damaging the cultural relics. In addition, the long-term chemical stability of the coatings and the potential impact of degradation products on the heritage substrate remain unclear, necessitating further safety assessments and standardized testing.

4.4. The Problem of Balancing Cost and Process

The raw materials and preparation processes for high-performance lotus-inspired coatings are relatively costly. Given the limited funding for cultural heritage conservation, balancing coating performance, construction efficiency, and economic cost to promote the transition from laboratory-scale to large-scale and standardized application is key to achieving technology dissemination.

5. Future Development Trends and Prospects

5.1. Material Innovation and Functional Integration

Future coating materials will develop towards multifunctional composites, integrating antibacterial, anti-ultraviolet, corrosion-inhibiting, and self-healing functions on the basis of superhydrophobicity. For example, natural antibacterial components or light stabilizers can be introduced to enhance the biological tolerance and weatherability of the coatings; intelligent stimuli-responsive coatings can be developed to adjust surface properties according to ambient humidity or pollutant concentration.

5.2. Optimization of Construction Processes

In view of the complex topography of cultural heritage, precise construction techniques such as directional spraying, atomized deposition, and 3D printing coating should be developed to achieve uniform construction and controllable thickness of the coating. Simultaneously, green processes such as low-temperature curing and solvent-free methods should be developed to reduce the impact of the construction process on the cultural relics themselves and the environment.

5.3. Standardization and Evaluation System

Performance evaluation standards for superhydrophobic coatings applicable to cultural heritage conservation should be established, including indicators such as hydrophobicity, durability, breathability, reversibility, and environmental safety. Through a combination of indoor accelerated aging and long-term on-site monitoring, the actual protective effects and failure mechanisms of the coatings should be systematically assessed to provide a basis for material selection and process optimization.

5.4. Interdisciplinary Cooperation and Regulatory Policy Support

The cross-disciplinary integration of materials science, chemistry, and cultural heritage conservation should be promoted, and customized coating research targeting specific cultural heritage materials and deterioration types should be carried out. At the same time, the connection between cultural heritage protection regulations and industry standards should be strengthened, clarifying the applicable scope of coating materials in cultural heritage conservation, thus promoting the scientific and standardized

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application of this technology.

6. Conclusion

By simulating the micro-nano hierarchical structure and low surface energy characteristics of natural lotus leaf surfaces, lotus-leaf-inspired self-cleaning coatings provide a protective barrier with superhydrophobic and self-cleaning functions for cultural heritage, demonstrating application value and potential in preventing moisture erosion, inhibiting contaminant adhesion, and resisting biological attack. This paper has systematically reviewed the research progress and application status of this technology in the conservation of cultural heritage made of different materials, including stone, wood, murals, and metals. Superhydrophobic coatings can be functionally customized for specific heritage substrates without affecting the original appearance of the relics, while significantly enhancing their durability. However, the transition of this technology from laboratory research to practical application in heritage conservation still faces problems such as insufficient durability, poor controllability of construction on complex surfaces, long-term environmental safety to be verified, and the balance between cost and process. In particular, in terms of coating reversibility and compatibility, the core principles of “minimal intervention” and “reversibility” in heritage conservation still need to be further satisfied. In the future, relevant research should focus on the development of multifunctional integrated coatings, the optimization of construction processes, and the establishment of a standardized evaluation system tailored to the specific needs of cultural heritage. Through the interdisciplinary integration of materials science, cultural heritage conservation, and other fields, lotus-leaf-inspired self-cleaning coatings are expected to play a more critical role in the preventive conservation of cultural heritage, providing technical support for extending the vitality of cultural heritage.

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