Development and Application of Biomimetic Superwettable Materials

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Keywords: Biomimetic, Superinfiltration, Innovative Materials, Practical Applications.

Abstract: Wettability plays a crucial role in the self-cleaning properties of materials and has attracted significant scholarly interest. Since the development of superhydrophobicity theory, research has shifted from solely hydrophobic functionality to the integration of multiple functions. Early research produced materials that were difficult to adapt to complex working conditions. In recent years, researchers have introduced stimulus-responsive materials to build dynamic structures and developed adaptive intelligent super-immersion systems. This paper systematically reviews the research progress of bionic superwetting systems in multifunctional integration strategy in recent years, focusing on the synergistic principle between microstructure, chemical components, and external stimulus response. The article also analyzes the innovative applications of bionic super-impregnated systems in various fields, including energy harvesting, environmental protection, and coating innovation. Finally, the article proposes future research directions and solutions, including the development of novel stimulus-responsive materials, the optimization of micro- and nanostructure design, and the exploration of low-cost preparation processes, taking into account the current research trends and technical bottlenecks. The article aims to provide theoretical support and practical guidance for the further development of bionic superinfiltration systems and to promote their practical applications in more fields.

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1 INTRODUCTION

With the advancement of industrial technology and the growth of extreme environmental demands, the performance bottlenecks of traditional material surface interfaces in the fields of anti-icing, anti-fouling, and water harvesting are becoming more and more prominent. Bio-attachment on ship surfaces leads to increased energy loss, highway icing raises safety concerns, and inefficient access to fresh water in arid regions. In this context, biomimetic super-immersed materials have been developed. Bionic superwetting materials are a new class of materials designed and prepared by mimicking the special wettability of the surfaces of living organisms in nature. They show great potential for application in various fields such as material science, energy, environment, and biomedicine. By mimicking the microstructure and chemical composition of the surface of living organisms, materials with special wettability properties, such as superhydrophobic, superhydrophilic, or superbiphobic (superhydrophobic and superoleophobic at the same time), are realized. These materials can precisely modulate the behavior of liquids on their surfaces and exhibit unique physical and chemical properties.

Since the establishment of superhydrophobicity theory in the 1990s, biomimetic superimpregnation research has undergone a transition from single hydrophobic property to gradient-function fusion. Early research focused on micro- and nano-structural replicas and low surface energy modifications, which successfully realized stable superhydrophobic surfaces with contact angles > 150°. However, static super-immersed interfaces are difficult to adapt to complex working environments, and their mechanical durability and functional adaptability still have significant shortcomings. In recent years, researchers have developed intelligent superwetting systems with adaptive properties by introducing stimulus-responsive materials to construct multilevel dynamic structures and other strategies. For example, through the design of bionic octopus sucker structure, the underwater reversible adhesion-desorption intelligent regulation has been realized. It is worth noting that most of the current reviews focus on the optimal design of a single wetting state, and the research

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Qiao, N.
Development and Application of Biomimetic Superwettable Materials.
DOI: 10.5220/0013828100004708
Paper published under CC license (CC BY-NC-ND 4.0)
In *Proceedings of the 2nd International Conference on Innovations in Applied Mathematics, Physics, and Astronomy (IAMPA 2025)*, pages 487-492
ISBN: 978-989-758-774-0
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summary of cross-scale synergistic effect, environmental adaptive mechanism, and multi-physical field coupling is still insufficient.

This paper focuses on the multifunctional integration strategies of bionic super-immersed systems in recent years, elucidates the synergistic principles of microstructure design, chemical component regulation, and external stimulus response, and analyzes their innovative applications in the fields of energy harvesting, environmental protection, and biomedicine etc. Finally, it synthesizes the development trends and proposes future solutions. Finally, it synthesizes the development trend and proposes future development directions and solutions by combining the advantages and disadvantages.

2 BIONIC SUPERWETTABILITY MATERIALS

2.1 Bionic Superwettability Materials

Biomimetic Superwettability refers to the design and manufacture of artificial surfaces with specific wettability properties by mimicking the special wettability properties of biological surfaces in nature. Some biological surfaces in nature have special wettability properties. For example, lotus leaf superhydrophobicity, desert beetle directional water collection, and hogweed super slippery interface(Jiang et al., 2021). The principle of directional water harvesting in desert beetles (nanofabric desert beetles) is mainly based on the unique micro-nanostructure and wettability differences on their back, where water vapor in the mist condenses into small droplets at the top of the hydrophilic bumps. As the water droplets gradually increase in size, their weight exceeds the adsorption force of the hydrophilic region, and they roll down the hydrophobic "valley". These droplets eventually converge and flow towards the beetle's mouth for drinking.

The lotus leaf effect is one of the best-known superhydrophobic phenomena in nature (Zhang, 2005). The surface of the lotus leaf is covered with tiny papillae structures, which have an average size of about 6-8 micrometers, an average height of about 11-13 micrometers, and an average spacing of about 19-21 micrometers. Distributed between these tiny papillae are also some larger papillae, which are composed of even smaller microprotrusions clustered together. These multiple nano- and micron-sized ultramicrostructures result in an extremely thin layer of air on the surface of the lotus leaf. When a water droplet falls on the lotus leaf, since the diameter of the droplet is much larger than the size of the papillae, the droplet can only form a few points of contact with the tips of the papillae on the leaf surface, and thus cannot infiltrate into the surface of the lotus leaf, thus obtaining the effect of superhydrophobicity. The various super-immersed structures in natural organisms give a template for super-immersed materials, enabling the development of bionic super-immersed materials research. Bionic super-immersed materials provide a wealth of ideas and methods for artificial material design through the inspiration of structure, function, material selection and modification, theoretical innovation, and intelligent response. This transformation from natural to artificial not only promotes the development of materials science but also shows broad application prospects in many fields and provides new ways to solve practical problems.

2.2 Fundamentals of Bionic Superwettability Materials

Young's equation and contact angle theory are important theoretical foundations for the study of bionic superimmersion. Young's equation, which was proposed by Thomas Young in 1805, describes the equilibrium relationship of interfacial tension at the gas-liquid-solid three-phase contact line at equilibrium. Its mathematical expression is:

$$\gamma SV = \gamma SL + \gamma LV \cdot cos\theta \quad (1)$$

Where γSV, γSL, and γLV represent the surface tension at the solid-gas, solid-liquid, and liquid-gas interfaces, respectively, and θ is the contact angle. The contact angle is the tangent line of the gas-liquid interface made at the intersection of gas, liquid, and solid phases, and the angle between the liquid side and the solid-liquid intersection line, which is an important parameter for measuring the wetting performance of liquid on a solid surface. According to the size of the contact angle, the wettability of the solid surface can be judged: when $\theta < 90°$, the solid surface is hydrophilic; when $\theta > 90°$, the solid surface is hydrophobic. Academician Jiang et al. (2002) discussed for the first time that the micro- and nano-multiscale structure of the surface is the key to the lotus leaf effect, and is an important reason for the simultaneous high surface contact angle and low adhesion. This phenomenon not only deepened the understanding of the relationship between surface roughness and wettability but also inspired materials scholars to draw inspiration from nature to construct diverse superhydrophobic surfaces.

3 BIONIC SUPERWETTABILITY MATERIALS AND PREPARATION METHODS

3.1 Binary Synergistic Interface Materials

Academician Lei Jiang proposed a binary synergistic design system for nanointerfacial materials, creatively combining biomimetic micro- and nano-composite structures with external-field responsive molecular design (Jiang, 2019). For example, in the preparation of superhydrophobic materials, not only are surfaces with specific micro- and nano-structures constructed to increase the roughness, but also the surfaces are chemically modified to reduce the surface energy so that it is difficult for water droplets to spread on the surfaces, thus realizing superhydrophobic properties. Different wettability of the upper and lower surfaces (e.g., superhydrophobic vs. superhydrophilic) can be used to achieve special functions, such as floating stably at the air/water interface and for oil-water separation. There are broad prospects in the fields of energy, health, environment, etc., such as concentration difference power generation in the energy field, medical catheters in the health field, and wastewater treatment in the environmental field. The design is flexible and can be generalized to other physical systems, providing a new method for the design of biomimetic intelligent multi-scale interface materials and expanding the range of material applications. Traditional materials may have limited performance in specific application scenarios. Binary synergistic interfacial materials can realize efficient interfacial regulation through the difference of surface wettability, which significantly improves the separation efficiency and selectivity. Superhydrophilic surfaces can quickly adsorb water, while superhydrophobic surfaces repel oil, resulting in efficient oil-water separation. Conventional materials have unstable performance in complex environments. Binary synergistic interface materials can adapt to a variety of complex environments and maintain stable performance through surface modification. Their superhydrophobic surface prevents oil adhesion and extends the service life of the materials.

3.2 Preparation Methods and Applications

Academician Jiang Lei's team has invented a variety of methods for the preparation of superhydrophobic interfacial materials with practical value, including the template method, the phase separation method, the self-assembly method, and the electrospinning method (Jiang, 2019). The template method can precisely control the micro-nano structure of the material surface, thus realizing the regulation of wettability. Based on the design concept of binary synergistic interface materials, Jiang Lei's team successfully prepared a variety of biomimetic superhydrophobic interface materials with special functions. The researchers have prepared Janus copper sheets with superhydrophobic upper surfaces and superhydrophilic lower surfaces, which can float stably on the air/water interface and can be used in the fields of oil-water separation and interfacial catalysis. The study of such binary synergistic interfacial materials enriches materials science theories and provides new perspectives for understanding the special wettability of biological surfaces. By mimicking the structure and function of biological surfaces, the mechanism of superhydrophobicity formation is revealed, which shows broad application prospects, such as concentration power generation and efficient heat transfer in the energy field, cancer detection and medical catheters in the health field, and oil-water separation and wastewater treatment in the environmental field. In addition, the design concept can be generalized to other physical systems, providing a new approach for the design of biomimetic smart multi-scale interfacial materials.

4 PRACTICAL APPLICATIONS OF SUPERWETTABILITY MATERIALS

4.1 Condensation Performance and Mist Collection

Condensation is a common phenomenon in which liquid droplets are formed on the cold surface of a gas, and is divided into the less efficient membrane condensation (liquid film attachment) and the efficient droplet condensation (droplet shedding by gravity or fusion) (Zhang, 2019). The efficiency of droplet condensation is significantly improved by utilizing biomimetic super-wetting materials to construct surfaces such as TiO_2 nanostructures, which mimic the special wetting properties of desert beetles, cacti, and other organisms (Zhang, 2019). Breakthroughs have been made in the applications of enhanced heat transfer, anti-icing, and fog water collection, providing new strategies for water resource acquisition in extreme environments .

Aiming at the problem of water scarcity, a variety of water harvesting materials with special wettability have been designed, and the efficiency of condensate droplet self-dispersal and fog water harvesting has been significantly improved by modulating the surface microstructure. In terms of technology, titanium-based nanotube arrays, aluminum-based rod-hole composite structures, and aluminum-coated PET groove/Kirigami patterned surfaces were constructed by constant/variable voltage anodizing, water bath, and cutting methods, which were combined with low-surface-energy modifications to achieve superhydrophobicity (contact angle >150°) and low-adhesion properties (rolling angle <10°).

The nano-graded structures are characterized by high roughness, multiple hydrophilic nucleation sites acting synergistically with the hydrophobic regions to enable the droplets to bounce off the surface quickly after fusion, and the groove structure (200 μm spacing) to achieve directional transport of droplets through the infiltration anisotropy, which improves the water collection efficiency by 35%.

Structural aspects were also optimized, with a hydrophobic-hydrophilic heterogeneous design for optimal droplet capture and transport, and a triangular Kirigami pattern (2.8 mm wide) combined with a 90° inclination to increase mist collection efficiency by 42% compared to conventional structures. The triangular Kirigami pattern (2.8 mm wide) combined with the 90° inclination design provides a new material design strategy for efficient water harvesting in arid regions (Wei et al., 2019).

4.2 Anti-Icing Coatings

In cold natural environments, rainwater tends to freeze on surfaces below freezing. Surface icing is very damaging to infrastructure facilities such as airports, highways, and ships. Traditional de-icing methods are too cumbersome and time-consuming. In recent years, the bionic super-impregnation system has led to a considerable improvement in the de-icing method.

Superhydrophobic surfaces (SHS) combine micro- and nano-rough structures with low surface energy to form Cassie-like air cushion structures for liquid droplets, which reduces the liquid/solid contact area and shortens the three-phase line, significantly reduces the adhesion force and inhibits the heat transfer, and its air cushion thermal insulation effect delays the icing, realizing highly efficient anti-icing (Cao et al., 2025). Another strategy is the lubricant-infused surface (SLIPS), which injects a lubricant layer of perfluorinated liquid or silicone oil, vegetable oil, etc., into the microporous substrate to form a super-smooth interface (hysteresis angle < 5°), blocking direct contact between the ice and the substrate, and combining both anti-icing and low-adhesion ice-sparing properties. Both types of materials provide a new direction for anti-fog, anti-frost, and extreme environment applications by reducing solid-liquid/ice interactions.

4.3 Efficient Water Harvesting

Collecting airborne fog can improve the utilization of water resources and effectively alleviate water stress. In recent years, bionic super-impregnated materials for fog and water collection have gained more attention (Zhou & Guo, 2022). The morphology, structure, and chemical composition of spider silk have received much attention.

Liu et al. (2020) studied bionic spider silk and designed spindle junction microfibers with homogeneous roughness, and found that the surface morphology directly affects the water collection efficiency, and the larger the roughness gradient is, the higher the water collection efficiency is. The structural morphology of the fibers can be optimized by regulating the fluid flow rate and component content during preparation to obtain the best spindle junction fibers. During fog water collection, the surface of spindle junction microfibers captures fog droplets, which grow and aggregate, then move toward the center of the spindle junction, and finally overcome the adhesion force to fall off. The higher the height of the spindle junction, the larger the suspension volume of droplets at the instant of droplet shedding; spindle junctions with larger widths have larger droplet suspension volumes due to longer three-phase contact lines when the lengths are the same, all of which affect the fog water collection effect. Shi et al. (2023)also designed spindle junction fibers in the shape of a cobweb, which increases the three-phase area and effectively improves fog water collection. Inspired by the spider web, they further designed a biomimetic 3D fiber network to increase the specific surface area for fog water collection, and formed a hydrophilic nanocone-like morphology on the 3D mesh surface, which is more attractive to water molecules, by preparing a layer of ZnO crystalline seeds and growing it hydrothermally. Compared with the traditional method, this 3D network has a more complete water collection mechanism, which can rapidly capture fog droplets, promote coalescence, and decompose into dropletlike transport after forming a water film, realizing rapid and continuous water flow and greatly improving the fog water collection efficiency. The spiny microstructure of dragon fruit leaves can reduce the deviation of fog flow, and its hydrophilicity can make the fog water accumulate in the form of droplets, and the water supply capacity is 100 times faster than that of a 2D plane. Inspired by this, it developed a 3D fog catcher composed of 1D fine copper wires, which mimics the structure of dragon fruit, and the copper wires are arranged regularly to collect fog water, and the base material discharges the collected water. The efficiency of fog water collection is improved.

4.4 Oil Recovery Wastewater Treatment

Walnut shell filter media is a renewable resource with many advantages, such as strong adsorption capacity, oil immersion resistance, high hardness, good abrasion resistance, strong adsorption and dirt interception capacity, etc., and it is easy to regenerate and recycle. It is widely used in water treatment and is a new generation of filter media that replaces quartz sand filter media, improves water quality, and reduces the cost of water treatment. However, after some time, the adsorbed oil will adhere to the surface of the filter media, resulting in the adhesion of the filter media, reducing the rate of oil removal, easily leading to a dense bed, reducing the filtration channel, reducing the filter's dirt trapping capacity and filtration effect, while the backwashing effect deteriorates, and the filter media is easy to agglomerate, which will damage the internal structural parts of the filter and the phenomenon of running material. Therefore, modification and optimization of walnut shell filter media is a necessary way to improve the effect of the filter.

With the rapid development of the discipline of bionic superwetting, more and more materials with special wettability have been applied to oily wastewater treatment, and many new functional interfacial nanomaterials have been widely used in industry. Yang, Wang & Jing (2018) et al. used magnesium bisulfite steaming to modify the surface of walnut shell material, which made the surface of walnut shells from hydrophobicity to super hydrophilicity, which was used for the filtration of oily wastewater, and the oil removal rate was stabilized between 78% and 81%, which was 25% to 28% higher than that of the unmodified agent. Inspired by the coating method for the preparation of oily wastewater filter media, walnut shell filter media with different wettability were obtained by modifying the surface of walnut shell. Subsequently, the preparation was selected by filtering experimental studies and analyzed to select the suitable filter media. The superhydrophilic walnut shell filter media produced by bionic superwetting technology is characterized by a simple process, an economically and environmentally friendly formulation, and has a good development potential for application in oil recovery filters.

5 CONCLUSION

This paper systematically reviews the research progress of biomimetic super-immersed interfacial materials in recent years, and elaborates the complete development path from bio-inspiration to interface design, mechanism analysis, material synthesis, and application expansion. By their unique interfacial properties, these materials have demonstrated significant application potential in the fields of environmental governance and functional coating development. This paper also focuses on analyzing the technological breakthrough of biomimetic superwettability materials. The researchers not only revealed the self-cleaning effect of micrometer papillae and waxy layer on the surface of lotus leaves, but also deeply analyzed the synergistic enhancement mechanism of its surface dendritic nanostructures on superhydrophobic performance. Based on these findings, the design principles, preparation processes, and practical applications of bionic superhydrophobic surfaces have been systematically explored. For example, the applications of bionic materials in the fields of fog water collection, anti-ice coating development, and oil recovery wastewater treatment have fully verified their technical advantages in solving practical problems. This paper also provides an outlook on the future research direction of superwettability materials.

Although important progress has been made in this field, as a cutting-edge discipline, its research still needs to focus on enhancing the durability and multifunctionality of materials. The main challenges facing current research include the long-term stability of materials, their adaptability to complex environments, and the cost of large-scale preparation. Future research needs to further optimize material properties, reduce costs, and expand their applications in energy, environment, and biomedicine through interdisciplinary collaborations and technological innovations to fully unleash the enormous potential of biomimetic superwettability materials.

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