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Biomimetic antifouling coatings: Harnessing nature's strategies for sustainable marine protection

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ABSTRACT

Biofouling, the unwanted buildup of microorganisms, plants, algae, and animals on underwater structures, presents considerable difficulties in multiple sectors, especially in maritime activities. Conventional antifouling techniques, typically dependent on biocidal coatings, have proven successful but pose environmental issues because of their harmfulness. As a result, studies have increasingly focused on biomimetic antifouling coatings that take cues from the natural antifouling methods seen in marine life. These advanced coatings seek to imitate the natural physical and chemical protections, providing environmentally friendly options to traditional techniques. Recent research has emphasized the promise of micro-structured surfaces, like those resembling shark skin, and chemical repellents derived from marine organisms, in inhibiting biofouling. Although promising, the creation and widespread use of these biomimetic coatings pose challenges, such as difficulties in fabrication and worries about durability. Future studies aim to address these challenges, concentrating on the development of sustainable, efficient, and scalable antifouling strategies.

KEYWORDS

Biofouling; Antifouling coatings; Biomimetic materials; Marine biofouling; Surface engineering

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Introduction

Biofouling, also known as biological fouling, denotes the build-up of microorganisms, plants, algae, or tiny animals on moist surfaces that serve a mechanical purpose, leading to structural or other functional impairments. This occurrence presents considerable difficulties in numerous marine sectors [1].

In the shipping industry, biofouling raises hydrodynamic resistance on ship hulls, resulting in greater fuel usage and an uptick in greenhouse gas emissions. Offshore facilities, like oil platforms and wind turbines, undergo heightened corrosion and structural strain from biofouling, requiring regular upkeep and raising operational expenses. In aquaculture, biofouling impacts equipment and the wellbeing of stock, resulting in financial losses. Conventional antifouling techniques mainly consist of using biocidal coatings infused with harmful substances aimed at preventing or eliminating fouling organisms. Although effective, these coatings emit biocides into nearby waters, negatively affecting non-target organisms and jeopardizing ecosystems. Moreover, the persistence and bioaccumulation of these hazardous substances create worries regarding long-term ecological health [2,3].

To address these challenges, biomimetic antifouling methods have surfaced as environmentally friendly options. These strategies seek to inhibit the buildup of fouling organisms by mimicking the natural antifouling mechanisms seen in marine life, like the micro-structured surfaces of shark skin, without the use of harmful chemicals. This method not only provides a sustainable answer but also reduces ecological disturbance, harmonizing with worldwide initiatives to safeguard marine ecosystems. The creation of biomimetic antifouling coatings signifies a hopeful progression in marine technology, presenting the possibility to reduce the negative impacts of biofouling while maintaining ecological balance [4].

Biological Inspiration for Biomimetic Antifouling Coatings

Biomimetic antifouling coatings draw inspiration from various marine organisms that have evolved effective strategies to prevent biofouling. By emulating these natural mechanisms, researchers aim to develop environmentally friendly solutions to mitigate biofouling.

Shark skin microstructures

Shark skin is characterized by microscopic riblet patterns formed by dermal denticles, which reduce drag and inhibit the attachment of fouling organisms. These riblets create a surface that disrupts the formation of biofilms and the settlement of organisms. Studies have shown that surfaces mimicking these riblet patterns can significantly reduce microbial adhesion. For instance, biomimetic surfaces replicating shark skin microstructures have demonstrated a reduction in biofouling by up to 67% compared to smooth surfaces [5].

Diatom and algae-inspired surfaces

Diatoms and certain algae possess surfaces that remain clean due to their unique micro- and nano-structures combined with the secretion of slippery substances. These features prevent the settlement of fouling organisms by reducing surface energy and creating a slippery interface. Inspired by this, researchers have developed Slippery Liquid-Infused Porous Surfaces (SLIPS), which mimic the lubricated surfaces of these organisms. SLIPS have shown effectiveness in repelling a wide range of fouling agents, including bacteria and marine organisms [6,7].

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Mollusk shell and fish mucus adaptations

Mollusks and fish have evolved chemical defenses to deter fouling. Mollusk shells often contain natural biocides, while fish secrete mucus with antifouling properties. These chemical deterrents prevent the settlement and growth of fouling organisms. Researchers are exploring coatings that incorporate natural or synthetic analogues of these compounds to replicate these antifouling effects. Such biomimetic coatings aim to provide a non-toxic alternative to traditional antifouling paints [7,8].

Various marine organisms exhibit hydrophobic and self-cleaning surfaces that prevent biofouling. For example, the lotus leaf effect, characterized by super hydrophobicity, leads to water droplets rolling off the surface, carrying away dirt and microorganisms. This phenomenon has inspired the development of superhydrophobic coatings that mimic these self-cleaning properties. Such coatings have been shown to reduce biofouling by minimizing the adhesion strength of organisms, making it easier for them to be removed by water flow [9].

Design and Fabrication of Biomimetic Antifouling Coatings

The development of biomimetic antifouling coatings involves innovative design and fabrication techniques that emulate natural antifouling mechanisms. This section explores various approaches, including micro/nanostructured surfaces, Slippery Liquid-Infused Porous Surfaces (SLIPS), superhydrophobic and omni phobic coatings, and hybrid coatings with smart properties [10].

Micro/nanostructured surfaces

Micro/nanostructured surfaces are engineered to mimic the intricate patterns found in nature, such as the riblet structures on shark skin, which have been shown to reduce drag and inhibit biofouling. Fabrication techniques for these surfaces include:

3D Printing: Advanced additive manufacturing allows for the precise creation of complex microstructures. For instance, 3D printing has been utilized to fabricate surfaces with specific topographies that deter microbial adhesion [11].

Lithography: Techniques like photolithography and electron-beam lithography enable the patterning of surfaces at the micro and nanoscale. These methods have been employed to create antifouling surfaces with defined geometries that replicate natural antifouling patterns [9].

Nanoimprinting: This technique involves pressing a mould with nanoscale features into a substrate to create patterned surfaces. Nanoimprinting has been used to produce surfaces that mimic the hierarchical structures found in natural antifouling surfaces [10,11].

These fabrication methods have been instrumental in developing surfaces that reduce biofouling by inhibiting the initial adhesion of organisms.

Slippery liquid-infused porous surfaces (SLIPS)

Inspired by the pitcher plant, SLIPS are designed by infusing a lubricating liquid into a micro/nanostructured porous substrate, creating a slippery surface that prevents the attachment of fouling organisms. The mechanism relies on the stability of the infused liquid, which repels contaminants and allows for self-healing properties. Studies have demonstrated that SLIPS can effectively resist biofouling in marine environments, maintaining their performance over extended periods [12].

Superhydrophobic and Omniphobic coatings

Superhydrophobic coatings, characterized by water contact angles greater than 150°, mimic surfaces like lotus leaves, which exhibit self-cleaning properties. Advances in material science have led to the development of durable superhydrophobic surfaces through the creation of binary structures that combine micro and nanoscale features. These structures have been shown to provide self-cleaning, antireflection, and drag-reduction properties, making them suitable for antifouling applications [13].

Omniphobic coatings extend this concept by repelling both water and oil-based substances. By designing surfaces with re-entrant curvature and appropriate chemical modifications, researchers have developed omniphobic surfaces that resist a wide range of contaminants, offering potential for antifouling applications in diverse environments [14].

Hybrid coatings with smart properties

Hybrid coatings combine multiple antifouling strategies to enhance performance. For example, integrating superhydrophobic properties with photocatalytic materials can result in surfaces that not only repel water but also degrade organic contaminants under light exposure. Stimuli-responsive coatings, which change their properties in response to environmental triggers such as temperature, pH, or light, have also been explored. These coatings can release antifouling agents on-demand or alter their surface characteristics to prevent biofouling [15,16].

Performance Testing and Evaluation

Evaluating the performance of biomimetic antifouling coatings is essential to ensure their effectiveness, durability, and environmental compatibility. This evaluation encompasses laboratory-based testing, field testing in marine environments, and comparative studies with conventional coatings [17].

Laboratory-based testing methods

Laboratory assays are fundamental for assessing the antifouling efficacy of coatings under controlled conditions. Settlement assays involve exposing coated substrates to marine organisms, such as barnacle larvae, to observe settlement rates. Adhesion assays measure the strength of attachment of fouling organisms to the coated surfaces, often using calibrated water jets or shear stress tests. For example, a study designed a laboratory test with a flow-through system to evaluate antifouling paints, investigating the applicability of this method for testing paints of varying efficacies [18].

Field testing in marine environments

Field testing provides insights into the real-world performance of antifouling coatings. Long-term exposure studies involve immersing coated substrates in marine environments for extended periods, ranging from several months to over a year, to

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monitor biofouling accumulation and coating degradation. Such studies have demonstrated that certain coatings can effectively inhibit marine bacteria and maintain antifouling ability for more than three months [19].

Comparative studies are crucial for evaluating the performance of biomimetic coatings against traditional antifouling methods. These studies assess factors such as antifouling efficiency, coating durability, and cost-effectiveness. For instance, research has shown that certain biomimetic coatings exhibit excellent antifouling properties, with 99.8% resistance to algae and 100% resistance to mussels, outperforming conventional coatings in specific applications [20].

Environmental and Economic Impact

Biomimetic antifouling coatings, inspired by natural mechanisms, offer promising solutions to mitigate the environmental and economic challenges posed by traditional antifouling methods. These coatings not only reduce toxic leaching but also present long-term cost benefits for marine industries. However, their adoption involves navigating regulatory considerations and addressing certain challenges [21].

Eco-friendly nature of biomimetic coatings

Traditional antifouling coatings often rely on biocidal substances, such as tributyltin (TBT) compounds, which leach into marine environments, causing significant ecological harm. In contrast, biomimetic coatings are designed to prevent biofouling through physical structures or non-toxic chemical properties, thereby minimizing or eliminating toxic leaching. For instance, coatings inspired by shark skin microstructures reduce microfouling settlement by 77% compared to smooth surfaces, without the need for toxic substances [22].

Long-term cost benefits for marine industries

The adoption of biomimetic antifouling coatings can lead to substantial long-term cost savings for marine industries. By reducing the frequency of maintenance and repainting required due to biofouling, these coatings can lower operational costs. Additionally, the enhanced fuel efficiency resulting from decreased drag can lead to significant savings over time. A study analyzing a biocide-free antifouling coating demonstrated its potential to reduce fuel consumption and CO_2 emissions, highlighting its economic sustainability [23].

Regulatory considerations and adoption challenges

Despite their advantages, the adoption of biomimetic antifouling coatings faces several challenges. Regulatory bodies require comprehensive data on the performance, durability, and environmental impact of these coatings before approval. Additionally, the initial cost of developing and implementing these coatings can be higher than traditional methods, potentially hindering widespread adoption. However, as the global market for marine coatings is projected to exceed USD 15 billion by 2024, the economic incentives for adopting environmentally friendly alternatives are substantial [24].

Future Perspectives and Challenges

Biomimetic antifouling coatings, inspired by natural mechanisms, are advancing rapidly, offering sustainable solutions to marine biofouling. Emerging trends, challenges in large-scale application, and the potential for interdisciplinary research are pivotal in shaping the future of these coatings. Recent developments in biomimetic antifouling materials have introduced innovative strategies such as micro/nanostructured surfaces, slippery liquid-infused porous surfaces (SLIPS), and bioinspired hydrogels. Micro/nanostructured surfaces, inspired by shark skin, significantly reduce microfouling by disrupting organism attachment. SLIPS create a slippery interface that prevents biofouling, mimicking natural surfaces. Bioinspired hydrogels, incorporating self-lubricating polymers, offer antifouling properties suitable for applications like marine coatings and medical devices [25,26].

Interdisciplinary research plays a crucial role in advancing biomimetic antifouling coatings. Material science and nanotechnology drive innovations for enhanced durability and effectiveness. Marine biology aids in designing coatings that deter fouling while minimizing ecological harm. Environmental science ensures that these coatings align with sustainability goals by assessing their long-term ecological impact. By integrating these fields, biomimetic antifouling solutions hold promise for revolutionizing marine industries with environmentally friendly, high-performance alternatives [27].

Conclusions

Biomimetic antifouling coatings, inspired by nature's strategies, have shown promising potential in mitigating the challenges posed by biofouling. Key findings indicate that coatings based on shark skin microstructures, slippery surfaces, and bioinspired hydrogels effectively reduce organism attachment and minimize environmental harm. While these coatings offer long-term cost benefits, challenges related to scalability, regulatory approval, and durability remain. Nonetheless, with ongoing advancements in material science and interdisciplinary research, biomimetic coatings represent a sustainable, eco-friendly alternative for the marine industry, with significant potential for widespread adoption and innovation.

Disclosure statement

No potential conflict of interest was reported by the authors.

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