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Review

Strategies for Biofouling Control: A Review from an Environmental Perspective of Innovation and Trends

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Abstract

Biofouling is the colonization and attachment of sessile organisms on submerged surfaces, whether natural or artificial. The presence of these communities compromises the structural integrity, operational efficiency, and durability of coastal structures, resulting in high economic and environmental costs, especially when conventional removal methods involve the use of toxic biocides. In this context, this article aimed to evaluate the scientific productivity of the literature related to sustainable antifouling strategies, with an emphasis on technologically and environmentally sustainable solutions, through a bibliometric analysis. We analyzed 160 research articles and 90 patents published between 2004 and 2024. It was observed that, since 2019, there has been an increase in publications about biofouling solutions, with a notable emphasis on China's leadership in both scientific production and patent filings. This topic has also attracted extensive international collaboration. The most promising strategies for controlling marine biofouling involve a combination of physical, chemical, and biological methods, integrated with sustainable coatings. The growing demand for low-environmental-impact solutions has driven the development of safer, more effective, and economically viable antifouling technologies. Therefore, the integration of traditional techniques with advances in biotechnology represents a strategic path to mitigating the impacts of biofouling in marine environments.

Keywords: sustainable antifouling; fouling-release technologies; patent analysis; marine biofilm; marine biotechnology

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1. Introduction

Biofouling is a complex community characterized by the accumulation and adhesion of organisms on submerged surfaces—especially on artificial substrata [1], where they find nutrients as well as protection against predators and adverse conditions [2]. This process occurs when bacteria and microalgae form a biofilm [3,4], which facilitates the recruitment of other organisms (e.g., barnacles, ascidians, mollusks, polychaetes, and bryozoans) [5]. Through this ecological process, a highly structured community emerges, creating a dynamic and diverse ecosystem [6].

The formation of biofouling is influenced by several environmental factors (e.g., temperature, salinity, nutrient availability, and hydrodynamics) [7,8]. In tropical zones, where biological growth rates are higher, biofouling tends to occur more intensely and rapidly compared to in colder regions, where growth is slower and less vigorous [9]. Also, the properties of the substrata surface (e.g., roughness, size, and even electrostatic charge) are important in the initial adhesion of organisms [10–12]. Additionally, pioneer organisms can influence recruitment through the release of chemical signals, attracting or repelling subsequent species [13–15].

Man-made structures in marine areas, such as ship hulls, harbors, water inlet systems, and oil platforms are highly susceptible to biofouling. Because of that, numerous efforts have been made to solve this problem, but control with antifouling paints is the most common [16] because it is very effective in managing biofouling. However, since they are toxic to non-target organisms and can affect biodiversity [17,18], their use could bring significant ecological costs. Various toxic substances, including copper, lead, mercury, and arsenic, were historically used as biocides in antifouling paints to control fouling organisms [19,20].

Many organisms, particularly benthic ones, are vulnerable to these toxic effects. As a result, environmental regulations are becoming increasingly stringent worldwide, encouraging research and development for substances capable of inhibiting the fouling community without causing environmental harm [6]. Some of these bioactive compounds can be extracted from marine animals and algae and included in paints or other substances for antifouling purposes (e.g., [21–24]). Moreover, natural products are becoming more attractive to industries due to greater environmental awareness [25–27].

Thus, this paper sought to assess the productivity and scientific impact of the literature on antifouling techniques in marine applications, particularly those employing modern and environmentally sustainable methods, using bibliometric analysis. Furthermore, this paper provides some discussions on the group of foulants and possible solutions to address the problems arising from biofouling on artificial surfaces, despite the limitations and shortcomings of current research and applications.

Given environmental constraints and the increasing interest in sustainable antifouling strategies, a key question emerges: which environmentally friendly antifouling methods show the greatest potential for effective biofouling control while reducing ecological impacts, and how has the scientific community examined these solutions in recent studies?

2. Integrative Bibliometric Review

In this study, an integrative bibliometric review was conducted using the SCOPUS database, renowned for its comprehensive coverage of peer-reviewed studies. Selecting it as the primary research platform ensured access to the most relevant and up-to-date academic articles aligned with the focus of this study. To refine the search and increase the precision of results, Boolean operators were employed. Specifically, the keywords (“marine” AND “fouling” AND “control” AND “strategies” AND “innovative”) were combined using the AND operator, which retrieves only those studies that include all the specified terms. This strategy allowed for a more targeted and comprehensive identification of literature related to innovative approaches in marine fouling control. To obtain a more up-to-date sample, only articles from the last twenty years were included. In addition, only articles written in English were included. After that, 183 documents were selected, but only the research and review papers were analyzed, for a total of 160 documents. To unravel the patterns within this extensive dataset, the tools of SCOPUS and VOSviewer software (version 1.6.20) were used for analysis, bibliometric mapping, and visualization. The SCOPUS database was selected for bibliometric analysis because of its extensive multidisciplinary coverage, which includes applied, technological, and environmental fields essential for research on biofouling and antifouling. Additionally, it offers robust tools for extracting indicators and developing knowledge networks.

Also, for the patent documents a systematic search was made in major national and international databases—the Brazilian National Institute of Industrial Property (INPI), the European Patent Office (EPO) and the World Intellectual Property Organization (WIPO)—aiming to identify documents related to the solutions for preventing or solving fouling recruitment in artificial structures. The Boolean operators used were "marine" AND "biofouling", considering publications from the last twenty years. Filters were applied based on the International Patent Classification (IPC), followed by manual screening of abstracts and claims to select the most relevant patents. The analysis of the selected documents allowed us to identify the state of the art and the technological applications for the prevention and control of marine biofouling.

Data Analysis and Visualization

The results provide a comprehensive overview of bibliographic statistics related to fouling strategies and control (Table 1). A total of 183 documents were found during the period of 2004 to 2024, which suggests a highly collaborative research community with a focus on review articles, synthesizing knowledge across multiple studies. Also, the open access rate (almost 33%) suggests the need for more publications to become openly accessible. Only 160 (reviews and research articles) were used in this study.

Table 1. Overview of statistics from bibliometric search.

Metrics	**Results**
Total number of publications	183
• Review articles	129
• Research articles	31
• Other documents *	23
Number of contributing authors	161
Number of open access publications	61
Sole-authored publications	4
Co-authored publications	179
Total number of citations	5981
Average citations per document	37

* Not used for further analysis.

Over the sampled period, there were annual trends in research output (Figure 1), and there was evolving interest and activity levels of researchers and academics on this topic. It is possible to see the growth of academic output on the topic, with a slight decrease in the year 2023 (14 publications) compared to the previous years (2020 = 17 publications; 2021 = 25 publications; 2022 = 25 publications). One of the main reasons for this decrease is likely to have been the slowdown in scientific research, in general, due to the COVID-19 pandemic. Also, the high number of review articles and citation impact (Table 1) align with this growth trend. A greater number of research fields often produce more reviews and gain traction in the academic community. Furthermore, the growing interest and research on the topic is related to the urgency of addressing environmental challenges and the global commitment to sustainable maritime practices, especially when it comes to antifouling solutions.

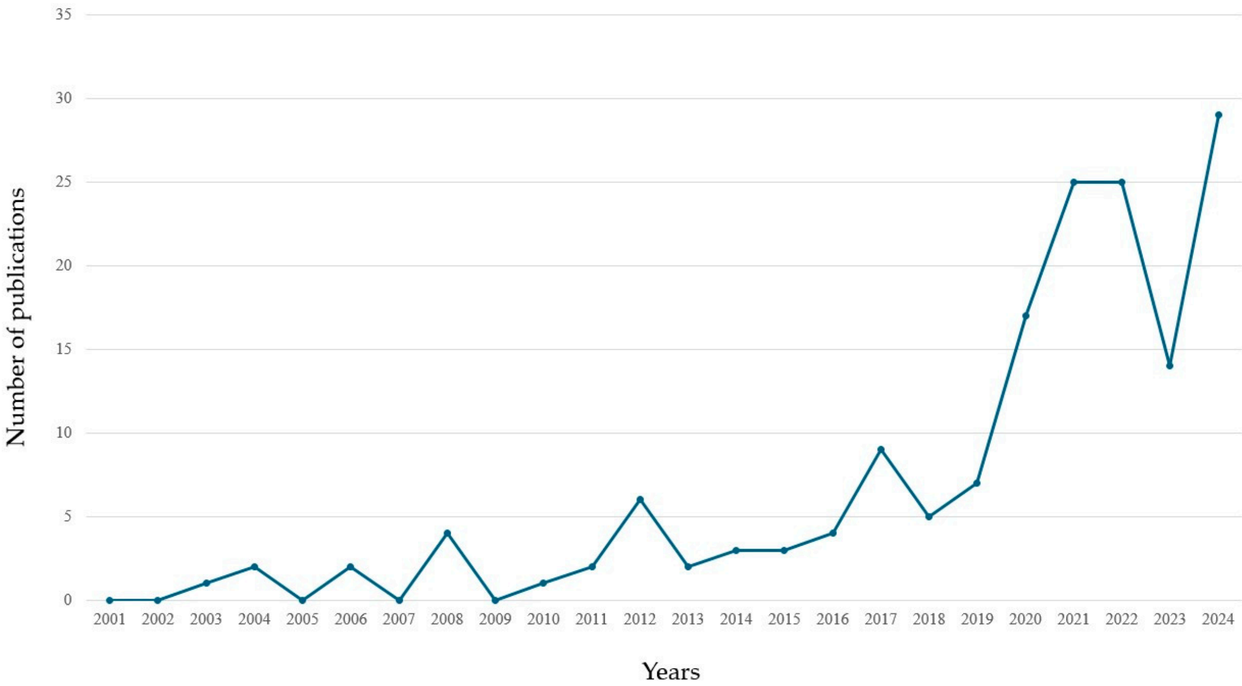

Figure 1. Yearly output of publications related to the selected keywords.

The evaluation of countries' productivities based on the quantity of academic papers provides a nuanced perspective on the global view of antifouling. China is the country with the most number of research papers published, totaling almost 28.9% of all publications (53 articles) in the period (Figure 2), followed by the United States (9.83%), the United Kingdom (8.74%), Portugal (8.19%), and India (7.65%). Furthermore, even though the vast scientific output was concentrated in a few countries, there was international collaboration in many regions of the world, which contributed to collective knowledge in the field. This shows the collaborative nature of research efforts to advance understanding and solutions in antifouling practices.

Additionally, Table 2 lists the 20 most-highly cited documents on fouling strategies and control, offering a comprehensive view of authors, titles, years of publication, source titles, document types, and total citations. It is important to say that recent research did not have enough time to accumulate citations and great impact [28]. The top-cited document was "*The impact and control of biofouling in marine aquaculture: A review*" [3], published in *Biofouling*, totaling 598 citations. This review paper discusses the impacts of biofouling on marine aquaculture, the costs and damages on infrastructure, and the best control methods and innovative eco-friendly strategies to mitigate its effects. Being a fairly comprehensive review, it has probably been used more in other research and studies.

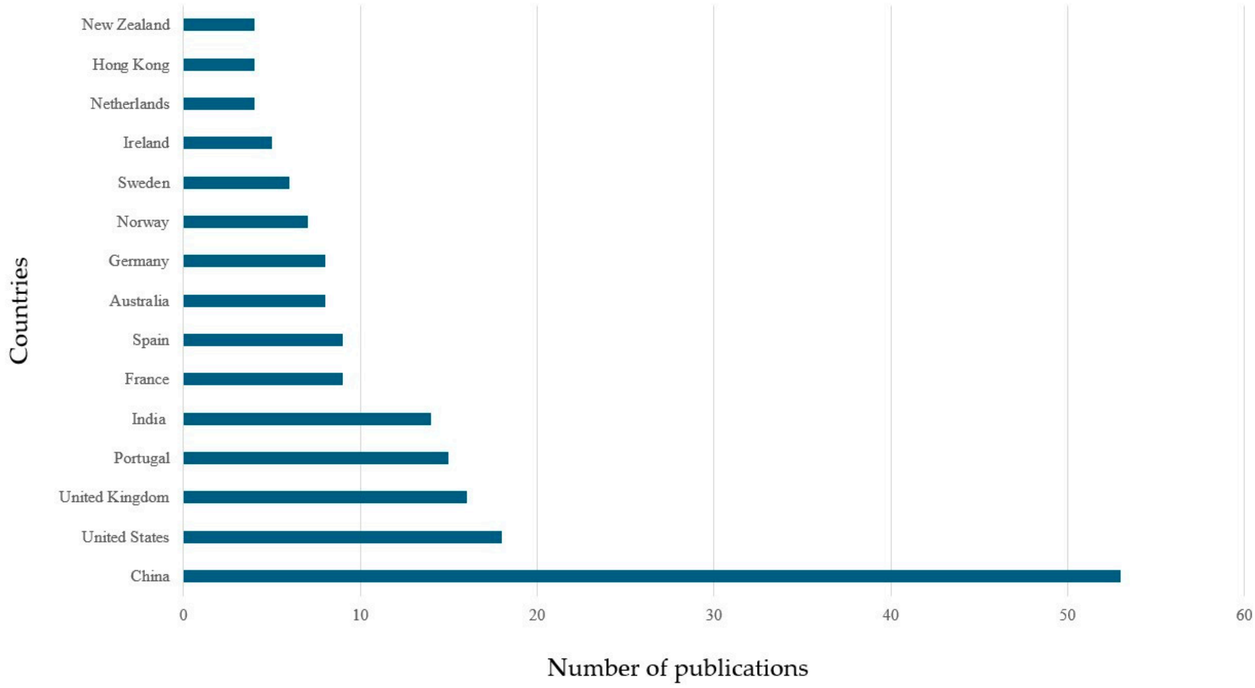

Figure 2. Number of publications by country.

In an overview of the 10 areas with the highest publications on fouling strategies and control, "Environmental science" tops the list with 54 publications (Figure 3), followed by "*Chemistry*" (53), "*Biochemistry, Genetics and Molecular Biology*" (45), "*Materials Science*" (45), "*Chemical Engineering*" (35), "*Agricultural and Biological Sciences*" (30), "*Engineering*" (25), "*Immunology and Microbiology*" (25), "*Physics and Astronomy*" (24), and "*Pharmacology, Toxicology and Pharmaceutics*" (17). It is worth noting that one article can be published in journals covering more than one area.

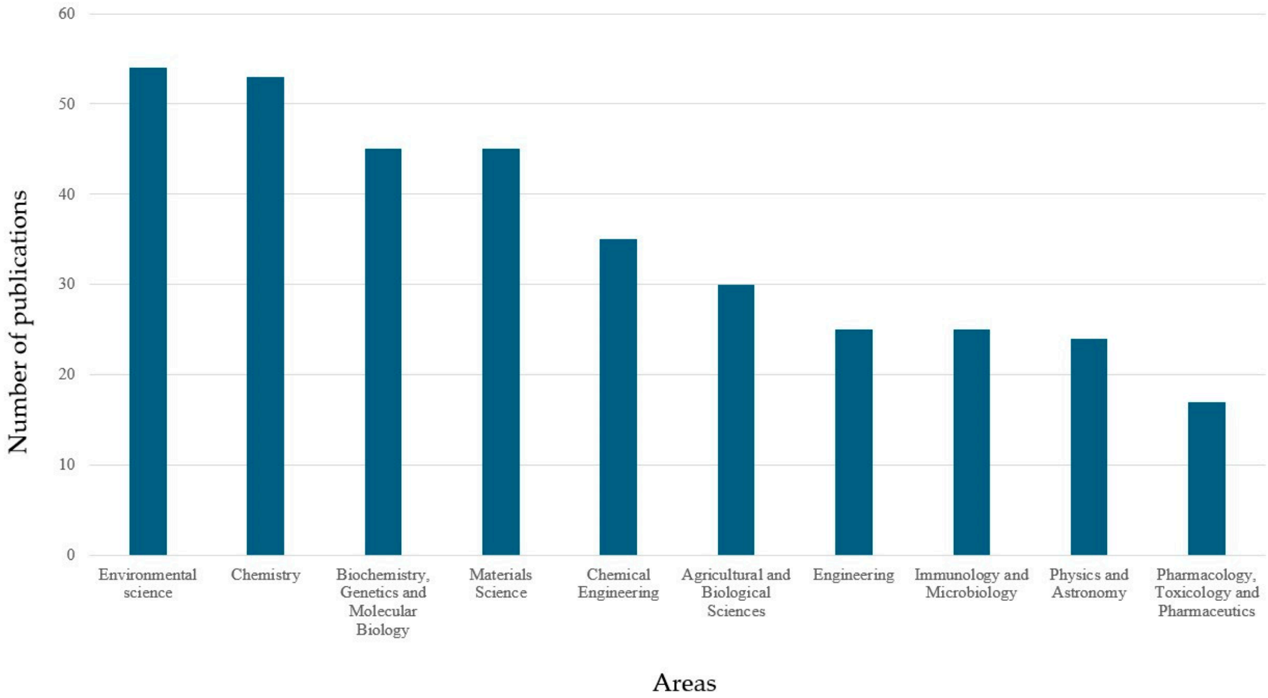

Figure 3. List of the 10 areas of study with the greatest number of publications.

Table 2. The 20 most-highly cited documents on fouling strategies and control according to SCOPUS Platform.

Title	Article Type	Total Citations	Reference
The impact and control of biofouling in marine aquaculture: A review	Research article *	598	[3]
Preventing mussel adhesion using lubricant-infused materials	Research article *	407	[29]
Slippery liquid-infused porous surfaces showing marine antibiofouling properties	Research article	274	[30]
Biofouling in marine aquaculture: a review of recent research and developments	Research article *	206	[31]
Bacterial Biofilm Inhibition: A Focused Review on Recent Therapeutic Strategies for Combating the Biofilm Mediated Infections	Review *	194	[32]
The influence of natural surface microtopographies on fouling	Research article	185	[21]
Research strategies to develop environmentally friendly marine antifouling coatings	Review *	165	[27]
Marine biofouling on fish farms and its remediation	Research article	163	[33]
Fabrication of slippery lubricant-infused porous surface with high underwater transparency for the control of marine biofouling	Research article	160	[34]
Biomimetic surface coatings for marine antifouling: Natural antifoulants, synthetic polymers and surface microtopography	Review	152	[35]
Current and emerging environmentally-friendly systems for fouling control in the marine environment	Review	151	[25]
Polymer-based marine antifouling and fouling release surfaces: Strategies for synthesis and modification	Review	147	[36]
Superhydrophobic surfaces for applications in seawater	Review	137	[37]
Mini-review: The role of redox in Dopa-mediated marine adhesion	Research article *	117	[38]
Eco-friendly non-biocide-release coatings for marine biofouling prevention	Research article	105	[26]
Antifouling strategies for marine and riverine sensors	Review	103	[39]
Superhydrophilicity and strong salt-affinity: Zwitterionic polymer grafted surfaces with significant potentials particularly in biological systems	Review	95	[40]
Advanced nanostructures for the control of biofouling: The FP6 EU integrated project AMBIO	Review *	76	[41]
Marine invasive macroalgae: Turning a real threat into a major opportunity—the biotechnological potential of *Sargassum muticum* and *Asparagopsis armata*	Review	69	[42]
Amidoxime Group-Anchored Single Cobalt Atoms for Anti-Biofouling during Uranium Extraction from Seawater	Research article *	65	[43]

* Open access publications.

Biofouling, a specific journal on fouling covering studies, methods, and solutions for fouling in marine activities, has the highest rate of citations (Table 2). When analyzed by VOSviewer, it seems to be a central source with an emerging role in research related to fouling, biomaterials, and environmental impact (Figure 4). Also, according to the same tool, the red cluster also includes journals like *ACS Applied Materials & Interfaces*, indicating strong relationships with materials science and surface interactions related to biofouling studies. The green cluster includes journals such as *Marine Drugs* and *International Biodeterioration & Biodegradation*, suggesting an integration of research on marine biotechnology and degradation. The blue cluster, including *Marine Pollution Bulletin*, covers studies on marine pollution, marine ecology, and sustainable chemistry. And finally, the yellow cluster is centered around *Advance of Colloid and Interface Science*, which focuses on colloid chemistry, surface science, and material interfaces.

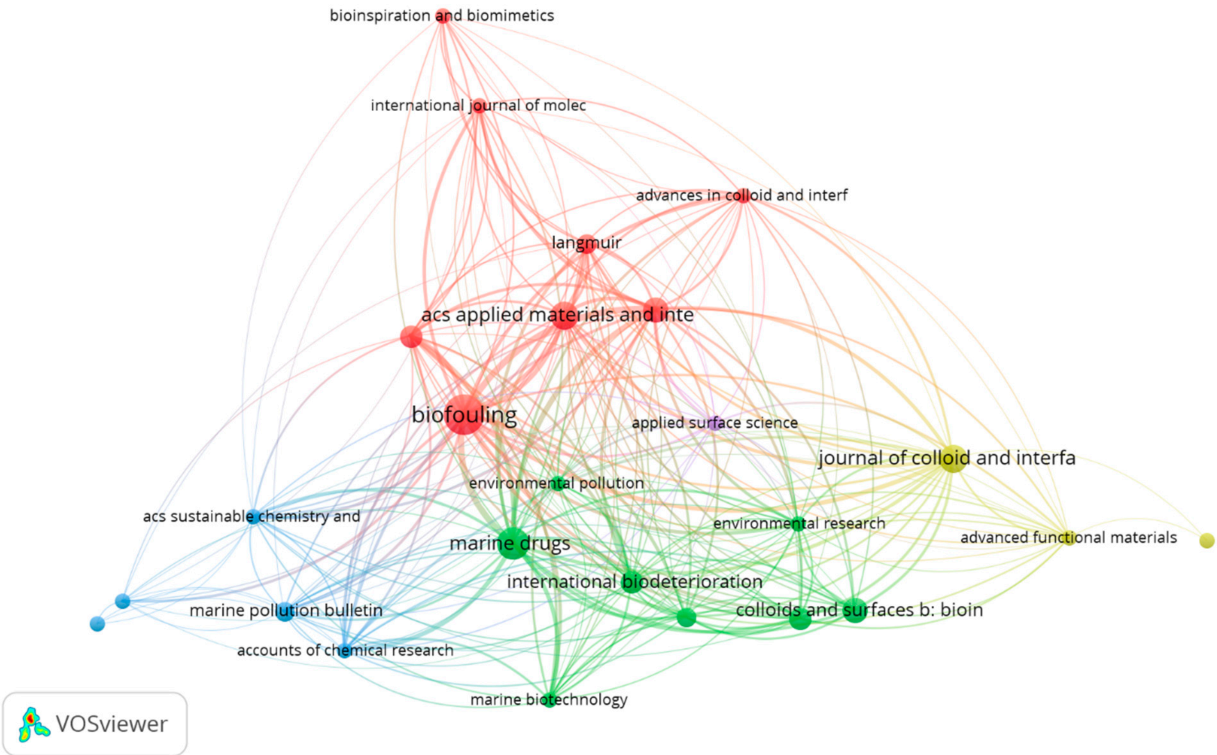

Figure 4. Cluster visualization obtained by VOSviewer representing the network of journals related to studies on the topic of biofouling.

When analyzed by keywords coupling, the publications' network map formed three groups (Figure 5): a red cluster, focused on materials and technologies used to prevent biofouling; a green cluster, related to a microbiological and ecological perspective; and a blue cluster, which connects with practical applications and industry-related discussions on antifouling. It is possible to notice highly connected terms from different groups, like "Antifouling performance" (red), "Biofilm" (green), and "Marine Research" (blue), whose studies are mainly focused on evaluating the effectiveness of antifouling strategies, with a strong connection with biological aspects and fouling formation in a maritime context.

The network view map of authors and co-citations (Figure 6) shows three larger groups (red, green, and blue) and two smaller ones (yellow and purple). The red group represents pioneers in the study of antifouling strategies and coatings with frequent co-citations, which include European researchers such as Callow M.E., Clare A.S., Rosenhahn A., Rittschof D., and Dobretsov S. The green cluster is dominated by Chinese researchers, such as Wang Y., Liu Y., Zhang Y., and Wang J., whose research is focused on materials science and biofilm control. The blue cluster, which has as its central figures the authors Qian P.Y., Hellio C., and Xu Y. from different countries, seems to be focused on marine biofouling and biological antifouling methods, sharing strong connections to the red cluster. The smaller yellow and purple clusters, less prominent and with less connections, gather contributions in antifouling research. Also, the high number of co-authored publications (179 of 183; Table 1) here shows a highly collaborative research field.

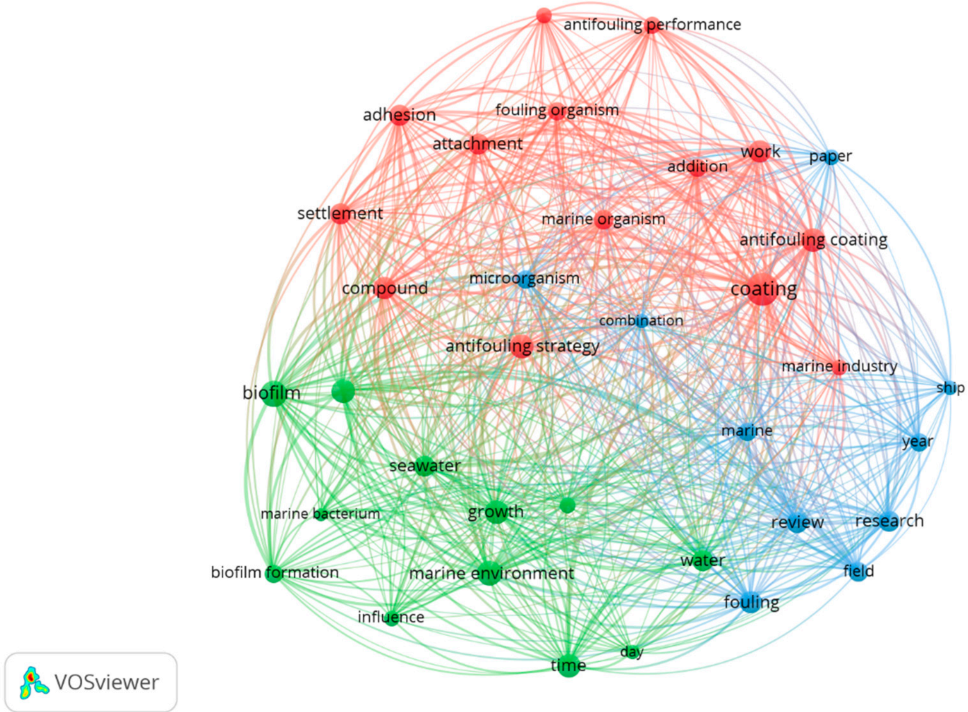

Figure 5. Network map of publications obtained through keyword coupling analysis, highlighting three main groups ("Antifouling performance" (red), "Biofilm" (green), and "Marine Research" (blue)), generated by VOSviewer.

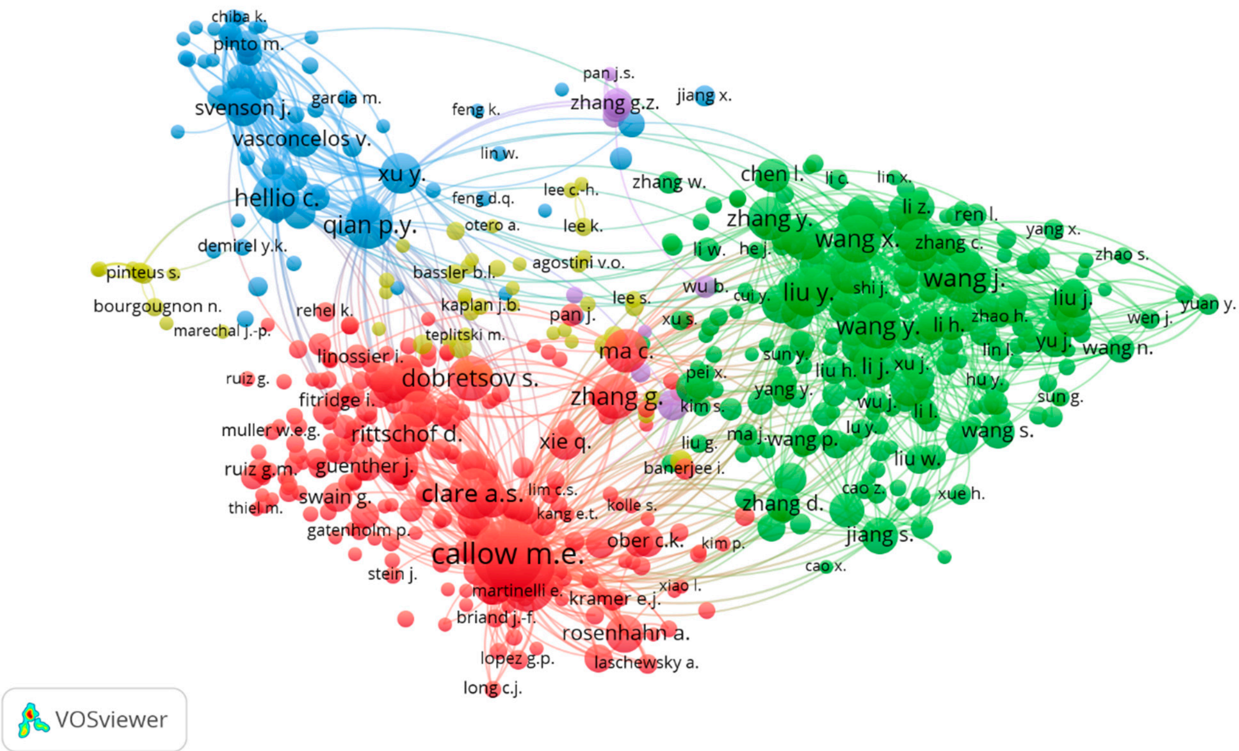

Figure 6. Author and co-citation network map, highlighting five clusters on the topic of biofouling, generated from VOSviewer analyses.

Notably, China emerges as a prominent player (green group; Figure 6) with a substantial contribution to research in this area. The size of each circle correlates with the number of publications originating from each country, providing a visual representation of scientific production in antifouling solutions with an emphasis on larval attachment and interaction with different substrates. This visualization highlights the global distribution of research efforts and reveals the networks of scientific collaboration that have been consolidating around addressing the challenges of biofouling.

The prominence of Chinese researchers in the scientific literature on biofouling control is driven by a combination of strategic, economic, and scientific factors. China's vast coastline, along with its rapidly growing shipbuilding and aquaculture industries, underscores the critical importance of biofouling management for both operational efficiency and environmental sustainability [44]. He et al. [45] highlight the pressing need for biofouling mitigation in marine aquaculture, calling attention to the demand for effective and environmentally friendly solutions. Concurrently, significant government investments in research and development have established a solid foundation for innovation in antifouling technologies. This is exemplified by Wang et al. [46], who detail advancements in the use of antifouling biocoatings.

Collaboration among universities, research centers, and industry has further accelerated progress, resulting in integrated strategies to control biofouling in marine and freshwater systems [6]. Zhang et al. [47], for example, review approaches to managing *Limnoperna fortunei*, highlighting research advances and emphasizing the importance of interdisciplinary and applied perspectives. These efforts have led to concrete innovations, such as silicone-based antifouling coatings, which show superior performance in marine conditions. Tian et al. [48] note that these initiatives collectively demonstrate how industrial demand, government incentives, and coordinated research agendas come together to position China as a global leader in biofouling control technologies.

At the same time, national strategies, including Made in China 2025, prioritize sectors affected by biofouling, while vertically integrated financing structures ensure that academic research rapidly converts into industrial applications [49]. This synergy contrasts with situations where fragmented financing and slower commercialization processes hinder the pace of innovation [50]. However, China's trajectory also reflects the global challenges in this field, especially the difficulty of balancing industrial efficiency with ecological safety under the regulatory frameworks set by the International Maritime Organization [51].

Furthermore, new technologies like artificial intelligence (AI) are being explored as potential accelerators for progress in antifouling research. This includes predictive modeling that incorporates hydrodynamic and ecological variables, as well as identifying combinations of material properties and toxin-release mechanisms that would be difficult to discover through traditional experiments [44]. However, these advances face ongoing challenges such as the limited availability of large, reliable datasets, difficulties in obtaining real-time environmental data, and regulatory hurdles [52]. Therefore, although AI shows promise, its effective use still needs proper evaluation.

The concentration of academic publications in East Asian countries like China reflects their leadership in knowledge production and correlation with technological innovation. This phenomenon is evident in the significant increase in the volume of publications in this region of the world, surpassing traditional leaders like the United States [53]. Moreover, the relationship between scientific research and patent applications serves as a strategic indicator of how academic advances translate into practical applications, particularly in the development of technologies to prevent biofouling on submerged surfaces [54,55].

3. The Most Common Organisms on Marine Structures and Their Effects

Materials submerged in seawater typically develop various layers before fouling formation, some of which are abiotic (i.e., detritus, organic secretions, etc.) and some biotic, such as fouling communities. Knowing the organisms that are part of these communities is important in the management process, as they may require specific solutions. This is especially because the composition of fouling communities and their interactions and effects on marine artificial surfaces are the key for understanding protection and control of biofouling [3,31,56]. Fouling biological communities are commonly classified into two groups: microfouling and macrofouling [57].

Microfouling, also known as biofilm, is the result of the growth of initial colonizers such as bacteria and microalgae, which can occur within a few hours after the submersion of hard substrata in the sea and prepare surfaces for macrofouling [58–62]. Its development occurs in at least four stages [63,64] (Figure 7). Although the attachment of initial microfouling organisms is often relatively fast, the development and evolution of the microbial biofilm is a much slower process and may take hours or even days [65].

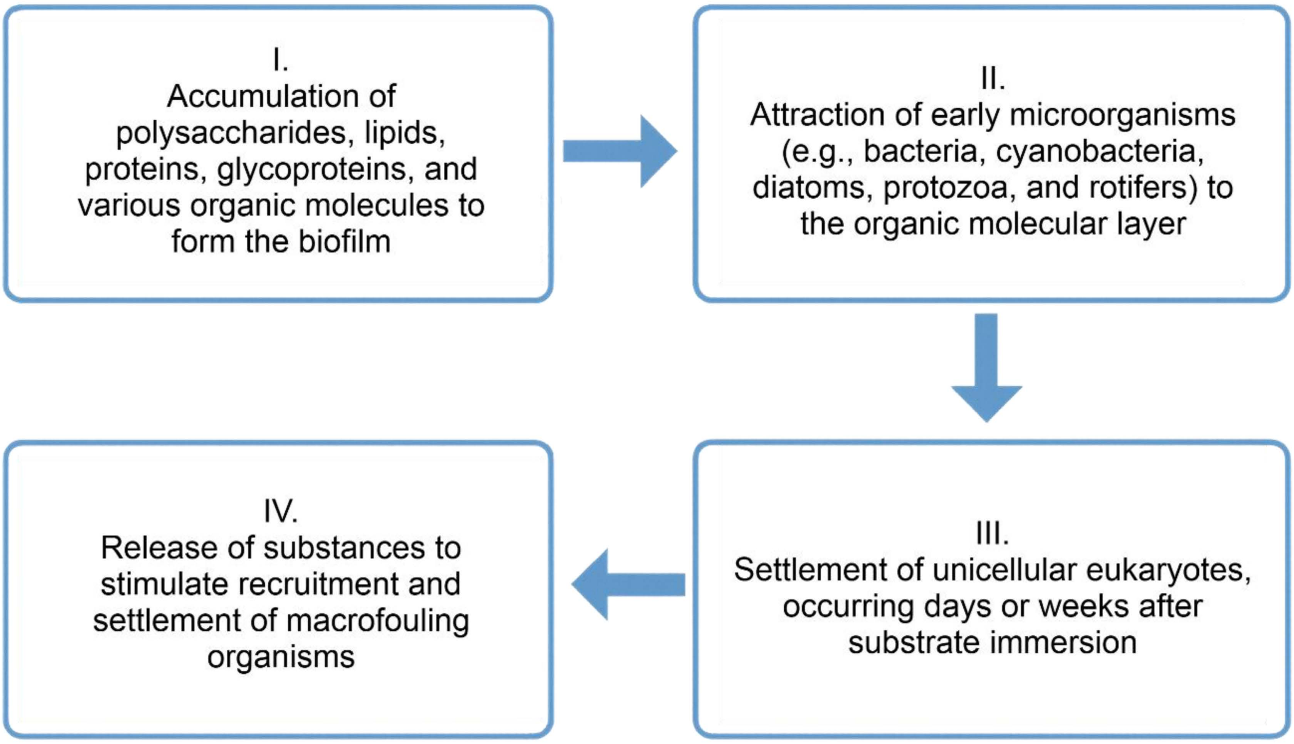

Figure 7. Steps of microfouling development [53].

Microfouling development generally consists of the formation of a conditioning film and the settlement of simple microorganisms and phytoplankton [63,66]. This conditioning film is composed mainly of dissolved organic environmental materials, such as proteins and carbohydrates, and enables the attachment of other microorganisms (i.e., bacteria, protozoa, and even microalgae; Figure 8) [66]. Its formation also allows the creation of specific conditions (e.g., pH, humidity, temperature, and substrate chemical composition) for the development of microfouling community [67]. Also, during their growth, microorganisms produce extracellular polymeric substances, which are inserted into the biofilm and act as a glue for firm attachment on surfaces [68]. Thereafter, photosynthetic organisms, particularly diatoms, which are the secondary colonizers on surfaces in the sea [69,70], are considered the earliest photoautotrophs to, along with cyanobacteria, provide energy to biofilms [71–73].

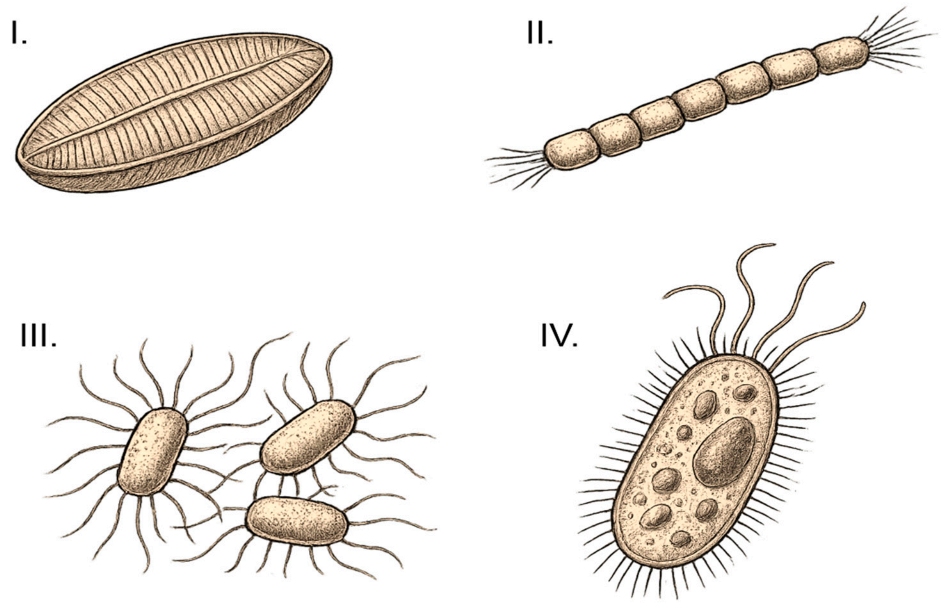

Figure 8. Common microbial groups found in marine microfouling: diatoms (**I**), cyanobacteria (**II**), bacteria (**III**), and protozoa (**IV**).

The formation of biofilms on hard marine substrata, including natural or artificial surfaces, holds great ecological importance because they can play multiple roles in coastal ecosystems [74]. Among these, their contribution to the recruitment of benthic organisms is particularly important, since they facilitate larval settlement and metamorphosis (e.g., [60,61,75,76]). Biofilms are also a key source of primary production and play an essential role in delivering ecosystem services such as nutrient recycling and pollutant degradation [77,78]. Their development can be influenced by physical, chemical, and biotic factors in the aquatic environment, with nutrient availability being considered one of the most important [79–81]. Therefore, biofouling-management measures could be more successful if focused on this stage.

This stimulation by microfouling starts macrofouling recruitment, a relatively rapid and dynamic biological fouling process that occurs over various scales of time and size, forming a complex system [56,63,82,83]. The term macrofouling is applied to multicellular sessile organisms attached to hard substrata and visible to the naked eye [84–86]. For the macrofouling colonization process, secretions through chemical bonding, electrostatic interactions, and other comprehensive effects ensure the adhesion of organisms, especially those represented by calcareous-shell species [87–89].

Fouling microorganisms are highly successful in colonizing substrata, especially the artificial ones, due to favorable conditions such as adequate oxygen and nutrient availability, protection of hydrodynamics, and absence of light and predators [57,90]. This process leads to the formation of an "enclosed layer" of macrofouling that can cause significant damage and accelerate corrosion, posing serious challenges to artificial structures (e.g., [91–95]). Studies have demonstrated that macrofouling organisms are responsible for substantial losses in operational efficiency, particularly on ship hulls, offshore platforms, subsea equipment, piping systems, and port structures (e.g., [96–101]). Therefore, the economic implications of marine biofouling are considerable, severely impacting various maritime industries and activities.

Macrofouling composition and growth is heavily influenced by environmental factors, but macroalgae and larger invertebrates dominate the settlement on hard substrata. Commonly, macrofouling (Figure 9) comprises soft-fouling noncalcareous organisms and hard-fouling organisms, which have a more rigid or calcareous body [102–104]. Soft-fouling organisms comprise macroalgae (e.g., algae species introduced by ship hulls; [105] and a few invertebrates, such as soft corals and anemones (e.g., [106,107]), sponges (e.g., on artificial structures or being the substrata; [108,109]), ascidians (commonly found in artificial substrata, especially in mussel farms; [110,111]), and hydroids (e.g., especially on artificial structures; [112–114]). On the other hand, hard-fouling organisms comprise invertebrates such as barnacles (e.g., *Amphibalanus amphitrite*, prevalent in artificial environments along the South Atlantic coasts; [104,115]), mollusks (e.g., *Crassostrea gigas* and *Limnoperna fortunei*, which dominate natural reefs and artificial structures in South Atlantic coastal regions; [114–117]), and tubeworms (e.g., *Hydroides elegans*, a common species on fouling; [118,119]). Also, bryozoans can be part of soft- or hard-fouling and are commonly found on both natural and artificial substrata, especially plastic debris (e.g., [12,57,120]).

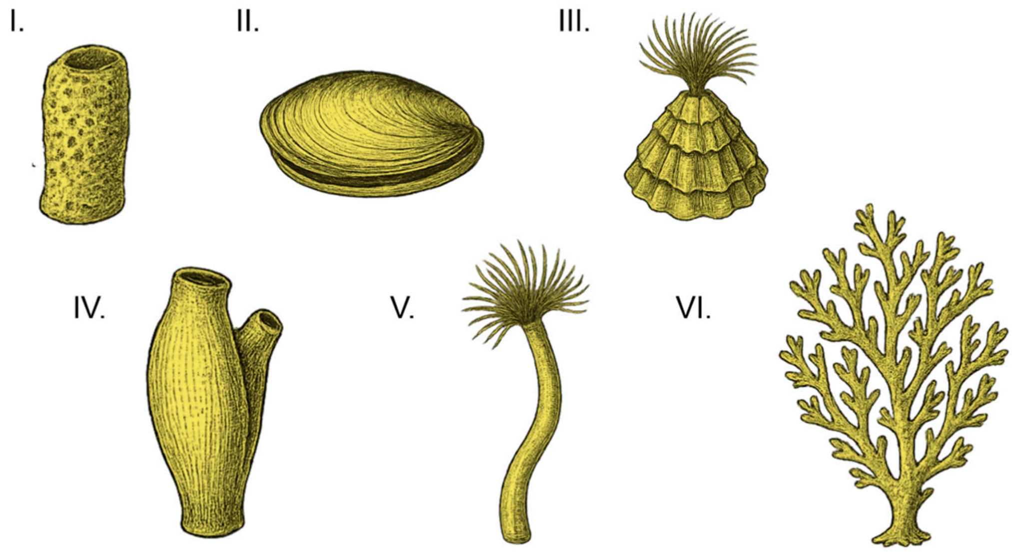

Figure 9. Illustrations of common groups of species found in marine macrofouling: sponges (**I**), mollusks (**II**), barnacles (**III**), ascidians (**IV**), polychaetes (**V**), and bryozoans (**VI**).

Colonization of different substrata by micro- and macro-fouling communities occurs during larval propagation phases, where organisms settle, grow, compete for space, and reproduce [121,122]. This process is influenced by the physical properties (i.e., marine flow, pressure, light, roughness, form, and even color) and chemical composition (i.e., substances secreted by microfouling) [12,123–126].

Fouling communities have widespread impacts on artificial structures and surrounding environments. Various industrial sectors are affected by the economic costs associated with the accumulation of organisms on submerged or water-contact surfaces [127,128]. Commonly observed on vessels, oil platforms, pipelines, and other artificial structures, fouling results in increased weight and friction, structural corrosion, high fuel consumption, and reduced operational efficiency [129–132]. These impacts necessitate frequent cleaning and application of antifouling coatings [133].

Another significant negative impact of biofouling is the alteration of local biological communities, potentially leading to competition for space and resources and causing substantial biodiversity loss [134,135]. This phenomenon, known as bioinvasion, is a global problem linked to fouling communities (e.g., [136,137]). Organisms are often transported—intentionally or accidentally—from one environment to another via ship hulls, oil platforms, and even marine debris [138]. On the other hand, while fouling organisms can disrupt ecosystems, they may also increase habitat complexity, potentially benefiting certain native species.

4. Effective Strategies and Methods for Managing Biofouling

The development of innovative solutions for biofouling control and mitigation has established itself as a strategic area within applied research, which is strongly associated with patent protection [139]. Several countries, through specialized institutions such as the INPI, the EPO, and the WIPO, have registered a growing number of patents related to antifouling technologies. These innovations range from new functional coatings and surfaces with micro-textures inspired by marine biology to sustainable, low-environmental-impact control strategies and automated cleaning systems (Tables 3 and S1).

The integration of bibliometric data with patent analysis is a strategic approach to guide both public policy and the development of industrial innovation. While bibliometric studies help map the scientific state of the art, identify emerging trends, knowledge gaps, and collaboration networks between researchers and institutions, patent analysis offers a complementary perspective focused on the practical application and intellectual property protection of technologies. It reveals the pace of innovation, the most dynamic sectors, and potential commercial opportunities [140].

Patent protection is an institutional instrument for fostering technological innovation by guaranteeing the intellectual property rights necessary to enable investment in research and development [141]. In this context, the results of the systematic search for patent documents are presented in Table 3 and in Table S1. Although the search covered the last 20 years, for the purposes of analysis and synthesis of the information in the main body of this work, only patents filed in the last five years were considered, as they more accurately reflect the current state of technology. The complete table, with all results referring to the last two decades, is available for consultation as Table S1.

Table 3. Patents involving strategies for preventing marine biofouling filed in the last 5 years.

Patent Title	Patent Number	Locality	Reference
System and method for cleaning of biofouling and pathogens and use of the system	WO2024151170	NO *	[142]
Membrane treatment method and biofouling suppression method	WO2024128050	JP *	[143]
Biofouling prevention system for vessel	WO2024117880	KR *	[144]
Reduction of biofouling on watercraft	WO2024094622	SE *	[145]
Mixed metal oxide coatings for protecting titanium alloys from biofouling	WO2024079222	ES *	[146]
Photocatalytic surfaces for anti-biofouling	WO2024044665	USA *	[147]
Roof coating resistant to biofouling	EP4519372	EP *	[148]
Controlling biofouling in water purification	WO2023028503	USA *	[149]
Biofouling preventing device for ships and method for manufacturing same	WO2022255578	KR *	[150]
Underwater robot for removing marine biofouling from hulls of floating units, with system for containing and capturing waste	WO2022140831	BR *	[151]
A marine system comprising an anti-biofouling light arrangement that includes a polarizing device	EP4103468	EP *	[152]
Anti-biofouling in marine applications using uv light source	WO2021055500	USA *	[153]
Marine biofouling prevention apparatus for seawater battery	WO2020013378	KR *	[154]
Compositions for antifouling protection	JP2023126913	JP *	[155]
Stainless steel coating with marine organism fouling resistance function and preparation method thereof	CN114150306	CN *	[156]

Table 3. *Cont.*

Patent Title	Patent Number	Locality	Reference
Environment-friendly marine antifouling coating and preparation method thereof	CN112876984	CN *	[157]
Integrated system for removing and treating marine biofouling on submerged metal surfaces	NZ802311	NZ *	[158]
High-transmittance ultraviolet antifouling coating system with embedded ultraviolet led lamp beads and preparation method thereof	CN111117477	CN *	[159]
Modular system for treating effluent from cleaning hulls of floating units	CA3203772	CA *	[160]
Transparent nanowire architectures for marine anti-fouling	US20210262089	USA *	[161]
Environment-friendly antifouling slow-release material as well as preparation method and application thereof	CN118085433	CN *	[162]
Device and method for preventing biofouling of marine propellers	CN111498071	CN *	[163]
Stratified poly dimethyl siloxane-epoxy coating possessing anticorrosive & foul release properties in a single coat and their method of preparation thereof	IN202111011420	IN *	[164]
Antibacterial polytitanilazane coating composition and preparation method thereof	CN115558323	CN *	[165]
Light emitting unit configured to be applied to surface area of marine object	CN112771309	CN *	[166]
Apparatus and methods to prevent biofouling	US20210138519	USA *	[167]
Process for biofouling cohibition in marine environments	US20210395900	USA *	[168]
Biofouling prevention device for marine instrument	CN210146517	CN *	[169]
Ocean system comprising device for preventing biofouling light comprising polarizing device	CN115087592	CN *	[170]
Marine plastic pipeline with high impact resistance, high biofouling resistance and high wear resistance and preparation method thereof	CN112480520	CN *	[171]
Biofouling prevention device	JP2024121088	JP *	[172]
Sensor device	WO/2024/09499	EP *	[173]
Method for producing a coating with low surface energy against biofouling	RU0002760600	RU *	[174]
Biofouling prevention film structure formed on surface of ship structure	KR1020230066865	KR *	[175]
A system for mitigating biofouling	SE2350663	SE *	[176]
Biological fouling prevention coating as well as preparation method and application thereof	CN115521709	CN *	[177]
Anti-fouling robot	WO/2022/268300	WO *	[178]
960 mpa grade ultrahigh-strength steel plate with marine fouling resistance and manufacturing method therefor	WO/2023/240850	WO *	[18]
An apparatus for vessel drag reduction and planetary cooling	AU2023204574	AU *	[179]
Preparation method of photocatalytic material composite micro-texture anti-microbial attachment surface	CN114985937	CN *	[180]
Antifouling polymer and composition, polymerizable monomer, article, method for producing a medetomidine monomer and an antifouling polymer	BR1120230074541 A2	BR *	[181]

Table 3. *Cont.*

Patent Title	Patent Number	Locality	Reference
Wet and dry synthesis process of lysoglycerophosphocholine compounds and their o-alkylated derivatives as biocidal additives in antifouling coatings	BR1020200200453 A2	BR *	[182]
Antifouling composition and its use, antifouling paint and method for inhibiting marine biofouling	BR112021009728 7 A2	BR *	[183]

* Localities: USA—United States of America; NO—Norway; JP—Japan; KR—Republic of Korea; RU—Russia; IN—India; EP—European Union; CN—China; AU—Australia; NZ—New Zealand; CA—Canada; SE—Sweden; ES—Spain; BR—Brazil; WO—International patent.

As observed in Tables 3 and S1, China has gained prominence as the leading patent filer in the biofouling field. This can be attributed to the country's significant investments in research and development focused on marine biotechnology [184], especially in technological strategies for the industrial sector, which leads to discoveries of sustainable antifouling tactics [24,185], corroborating the cloud of co-citations and authors presented in Figure 6. Furthermore, national incentive policies contribute to the high number of patent filings in the country, as they reward researchers and companies for registering new technologies, regardless of their actual technical impact [185,186]. This scenario is reinforced by studies [186] which highlight that certification as a high-tech company stimulates innovation, especially in small companies, even though the quality of the resulting innovations can be quite variable.

Although China has stood out, other countries have also demonstrated significant advances, especially in research into alternative methods and materials. The United States, Spain, and global publications follow China in the spotlight [187,188] (Table 3). This competitive landscape has the potential to foster innovation and influence global trends in the development of new technologies and patents [31]. Fewer registrations are noted for South Korea, Russia, and Brazil, with similar levels of activity in these areas. These data reveal a series of structural, economic, and institutional factors that directly influence the dynamics of technological innovation and intellectual property protection in these countries.

In Brazil, although there is a consolidated scientific base, bottlenecks related to continuous investment in Research, Development, and Innovation (RD&I), as well as limited technology transfer infrastructure, still represent obstacles to the conversion of scientific knowledge into intellectual property assets [181–189]. In addition, the patenting process in the country is bureaucratic and costly, which can discourage the national and international registration of innovations [190–192].

Russia has a strong scientific tradition, especially in areas such as advanced materials and naval engineering [193]. However, the focus of its applied research is often directed towards strategic defense and energy sectors, which may reduce the number of filings specifically focused on biofouling control in the civil sector [194]. Furthermore, economic sanctions and restrictions on access to international markets may limit the incentive for the global patenting of its technologies [195].

South Korea, while highly developed technologically, may have a lower specific representation in the field of antifouling solutions due to the direction of its innovation investments toward priority sectors such as semiconductors, electronics, information technology, and urban mobility [196]. Nevertheless, its presence in Table 3 indicates the potential for expanding maritime and naval applications within the context of its industrialized and highly export-oriented economy. Therefore, the limited number of patent applications filed by this country, as well as others, does not necessarily reflect a lack of innovative capacity, but rather differences in investment priorities, mechanisms for encouraging intellectual property protection, and the structure of collaboration between universities, research institutions, and productive sectors.

Many recent effective and promising strategies and methods to address fouling aim to be low-cost and non-toxic [25–27], as noted in patents EP-4519372 [148] and CN-112876984 [131]. However, fouling treatment methods can be divided into physical, chemical, and biological approaches, with the first category including mechanical processes such as brushing and sandblasting. Other methods are the development of robotic equipment used in the removal of marine biofouling, described in patents CA 3203772 [160] and WO/2022/268300 [178], as well as thermal methods that use temperature variations to remove deposits [197,198].

Other physical-mechanical techniques, such as brushing, high-pressure water jets, and abrasive blasting, are commonly used to remove surface deposits (e.g., [199–202]), and are particularly effective in removing all fouling. Mechanical cleaning is widely used due to its simplicity and efficiency, while thermal cleaning is particularly used for removing biofilms and scale formed by soluble salts, reducing the need for aggressive chemical agents [40,199].

Another type of cleaning that can be mentioned uses lasers that deliver radiation to render biological and/or pathogen fouling harmless, as described in patent WO 2024151170 [142]. Furthermore, high-frequency vibrations or UV-based treatment has been shown to be another effective method in preventing particle adhesion to surfaces (e.g., [203–207]), which can prevent fouling. This treatment is described in patent WO 2024044665 [147], in which the authors address the plurality of photocatalytic particles, where the UV-ray source activates this plurality to prevent biofouling of plates on maritime vessels.

Chemical methods involve the use of various agents to dissolve or disperse deposited contaminants, which are commonly applied in the cleaning of membranes and heat exchangers [202]. Acids, such as citric and sulfuric acids, are effective in dissolving carbonates and metal oxides, while surfactants and dispersants are used to remove biofilms and organic materials [35,197,208–210], as described in the patent US 20170275473 [200]. To reduce particle adhesion or larval attachment, fouling inhibitors can be introduced into the process fluid [29,30,32,38,41], as well as pharmacological substances that counteract dopamine and prevent biofilm release and the attachment of fouling larvae, as described in patent US 20060045864 [211]. Other chemical methods involve the use of chemical agents to dissolve or disperse deposited contaminants, which are widely applied in the cleaning of membranes and heat exchangers [199]. Additionally, Surfactants, as described in the patent US 20170275473 [200], and other components, such as medetomidine, can also be used as antifouling agents, as described by [212] in patent WO 2015011178.

Furthermore, biocides such as chlorine and glutaraldehyde are widely used in water treatment industries to control biofilms, particularly in membranes and cooling systems, inhibiting microbial growth and reducing biofouling [43,201,213–215]. These chemical approaches offer versatile solutions for managing inorganic fouling and biofilm formation. However, traditional biocides contained in antifouling paints, although effective, are sources of persistent marine pollution, as the accumulation of heavy metals, such as copper, zinc, and lead, and toxic compounds such as diuron, igarol, chlorothalonil, tributyltin (TBT), etc., can negatively affect entire ecosystems [216–218].

Biological treatment methods, including the use of enzymes and microorganisms, have also been explored as alternatives for the degradation of organic deposits, particularly biofilms. These methods are considered environmentally friendly and have potential for low-impact applications [42,197,207]. These methods can be observed in the research of patent 101564050 [219], regarding the preparation of a biofouling inhibitor from an extract of the species *Ulva pertusa*, as well as the composition of an antibacterial polytitanazane coating, considered in the research of Tang et al. [165] under patent 115558323.

Specific enzymes, as observed by Characklis [220] long ago, can degrade biofilms and organic deposits without damaging surfaces. Furthermore, competitive microorganisms [221–223] and some substances of microbial origin [21] have been proposed as strategies to inhibit the growth of unwanted biofilms. These biological approaches offer a promising and environmentally friendly solution for the management of biofouling and organic contaminants.

The combined application of different methods has proven to be an effective approach for fouling control. Studies indicate that the integration of chemical and mechanical cleaning can optimize scale removal and increase operational efficiency [224–226]. Furthermore, modifying surfaces with antifouling coatings is a promising strategy for preventing scale formation [35,36,227]. An electrochemical approach used low-dose antibiotics combined with a weak electric field to disrupt the formation of biofilms or mature biofilms [32]. Other innovative solutions, such as hydrophobic and infused porous surfaces and the use of nanoparticles and superhydrophobic coatings have also demonstrated efficiency in reducing fouling formation [34,37,228,229]. In a method mentioned in patent US8309625 [230], nanoparticles are provided in a water-soluble polymer to prevent the accumulation of marine organisms.

Another crucial aspect of fouling mitigation is optimizing the operating conditions of industrial processes. Controlling the temperature, fluid velocity, and chemical composition of processed media can significantly reduce contaminant deposition rates [231–233]. Technological advances, such as smart sensors and real-time monitoring systems, enable early detection of fouling and efficient application of preventive measures [39]. This technology is described in patent WO2022255578 [150], which refers to an electrode placed on the surface area of a ship's hull, where it receives a trigger signal, delivering an electromagnetic wave to prevent biofouling.

The integration of science and technology in biofouling control needs stronger partnerships among research institutions, the production sector, and regulatory agencies to develop innovative and sustainable solutions. In applied research, it is important to invest in studies that include field testing in real conditions, material durability modeling, and life cycle assessment. This approach speeds up the transfer of promising technologies to industrial scales and helps meet new regulatory requirements [234]. Running pilot projects at an industrial scale to test solutions in real environments, and creating protocols for scaling up the production of new materials or coatings is also key to proving feasibility [235]. Modeling studies show the potential of these technologies by emphasizing economic and operational benefits, such as lower fuel use and greenhouse gas emissions on ships, longer service life for aquaculture equipment, heat exchangers, and piping, and less frequent cleaning and maintenance. These advantages make investing in new solutions more appealing to the industrial sector [6].

Studies [236,237] demonstrated that the use of artificial intelligence to predict deposit formation has great potential for reducing costs and extending equipment lifespan; therefore, it could be the next step in management. Moreover, integrating monitoring and modeling is important to reducing biofouling management costs and increase the effectiveness of control measures [27,31,33]. The most effective approaches combine prevention and treatment strategies.

5. Sustainable Approaches to Biofouling Control

The composition of antifouling paints has historically been based on the use of toxic chemical biocides, which has raised growing concerns about their environmental impacts.

TBT, or tributyltin, an organic compound used as a biocide in antifouling coatings since the 20th century, emerged as one of the most effective compounds for controlling biofouling in submerged structures due to its excellent antifouling properties [238]. However, subsequent studies classified it as the most harmful anthropogenic contaminant among those intentionally introduced into aquatic environments, due to its high toxicity compared to other chemicals used at that time [239]. This compound accumulates in the tissues of aquatic organisms, compromises the immune systems of marine mammals, and alters the balance of coastal ecosystems [20,240,241].

As a result, its use was progressively restricted until it was formally banned in 2008 by the International Marine Organization (IMO) [238]. Following this ban, there was an increase in the use of alternatives based on metal oxides, such as compounds containing copper, zinc, and other heavy metals [231]. Although they have lower toxicity compared to TBT, these substances still pose a risk to environmental quality as the accumulation of heavy metals in sediments and chronic exposure of aquatic species to them can generate sublethal effects, behavioral changes, bioaccumulation, and potential adverse effects on human health [231].

Research has been conducted in a wide range of fields to assess the impact of toxic biocides from antifouling paints. Most of these studies involve chemical determinations to quantify the presence of these biocides in water, sediments, and biota [242–244]. Research conducted to assess their toxicity on various marine organisms demonstrated that many of them affect non-target species [245].

Therefore, growing concern about the contamination of aquatic ecosystems has driven the strengthening of regulatory policies at the international level. Since the United Nations Conference on Environment and Development (Rio-92), measures to protect marine and coastal environments have been taken, and the IMO has instituted resolutions A.774(18) [246] and A.868(20) [247], which seek to control and manage ballast water to minimize the transfer of harmful aquatic fouling organisms. In addition, international legislation, such as the International Convention for the Prevention of Pollution from Ships (MARPOL), has progressively restricted the use and discharge of biocidal substances in the marine environment [248]. For example, the updated guidelines of the International Convention on the Control of Harmful Anti-fouling Systems on Ships (AFS Convention) also prohibit the application of antifouling systems that release toxic compounds above internationally established limits [249].

In this context, several types of coatings have been developed as sustainable alternatives for biofouling control. Polymeric coatings emerge as alternatives because they are affordable, non-toxic, biocompatible, and easy to produce [250]. Among them, amphiphilic coatings stand out because they combine hydrophobic and hydrophilic domains, which reduce the likelihood of bacterial biofilm formation through surface heterogeneity and microphase segregation [251,252]. Coatings based on polydimethylsiloxane (PDMS) modified with polyethylene glycol (PEG) or polyglycerol, as well as amphiphilic copolymers obtained by Reversible Addition–Fragmentation Chain Transfer (RAFT), also demonstrated high antifouling efficacy [253–255].

Some approaches include hydrolyzable coatings, which are degraded in seawater, promoting continuous self-cleaning, and the use of nanomaterials with reduced graphene oxide/silver nanoparticles (rGO/AgNPs) and 3 wt% poly(N-isopropyl acrylamide)–thiol (PNIPAM-SH) in an epoxy-silicon resin matrix with rGO/AgNPs, with antimicrobial and anticorrosive action [256]. Photocatalysis with graphitic carbon nitride (g-C_3N_4) has also been shown to be efficient in destroying microorganisms under visible light without toxic effects [257]. Furthermore, zwitterionic polymers, PEG, or peptoid coatings, which form hydration layers that hinder the initial adhesion of organisms [250], and self-repairing systems based on PU-silicon have been shown to increase the durability and resistance of materials in aggressive marine environments [258].

Another sustainable solution aimed at reducing hydrodynamic drag and biofouling on vessels was the development of a spontaneous and fast-acting air film based on superhydrophobic surfaces with a serial brachistochrone pattern [259], which enables the formation of a stable film that reduces frictional resistance by up to 27% and achieves up to 80% antifouling efficiency. Furthermore, this solution can serve as a tool for minimizing energy consumption and carbon emissions, standing out as a promising alternative for advancing sustainable navigation on a global scale [260,261].

The search for more sustainable antifouling strategies has also shifted towards biomimetic solutions, which replicate mechanisms found in nature to prevent biofouling without relying on biocides. These approaches are mainly based on two principles: creating low-adhesion surfaces inspired by the microstructure of shark skin that prevents organism attachment [262,263], and developing dynamic, self-cleaning materials such as lubricated impregnated porous surfaces (SLIPS) [257,264,265]. The effectiveness of these strategies stems from their non-biocidal physicochemical actions, replacing toxicity with surfaces designed with intelligent properties [228,266].

Lichens and their symbiotic microorganisms have emerged as sources of bioactive compounds with potential application in biofouling control. These symbionts produce compounds capable of inhibiting the formation and growth of biofilms, enabling their use in the development of antifouling coatings [267]. Among these compounds, natural phenols, which contain hydroxyl groups and aromatic rings, exhibit antibacterial activity, acting as free radical scavengers and hydrogen donors, characteristics that contribute to the inhibition of microbial colonization on submerged surfaces [268].

In addition to chemical compounds, enzymes produced by bacteria and fungi act by degrading the natural adhesives produced by fouling organisms, hindering their attachment to submerged surfaces [250]. These include proteases, lipases, cellulases, amylases, oxidoreductases, hydrolases, and AHL-acylases, the last being involved in the degradation of N-acyl homoserine lactones, which are signaling molecules essential for microbial communication and biofilm formation. Proteases, in particular, have been identified as the main active agents in enzymatic formulations due to their high efficacy in breaking down protein adhesion structures. Studies on serine proteases, such as Alcalase®, have demonstrated significant inhibition of *Ulva* sp. spore adhesion and of *Balanus amphitrite* larvae attachment both in laboratory and field tests, thereby demonstrating its practical potential as a component in antifouling coatings [267,269–271].

Another approach involves using nanotechnology to create coatings with antifouling properties. Nanomaterials can be designed with hydrophobic surfaces able to prevent microorganisms from adhering, or with nanobiocides capable of eliminating organisms on contact [272]. Materials such as silicone nanocomposites with graphene oxide or zinc oxide (ZnO) form effective physical barriers and simultaneously exhibit antimicrobial properties, expanding their applicability in marine environments [273,274].

Among the most promising strategies is the use of secondary metabolites produced by terrestrial or marine organisms [275,276]. These metabolites, although not essential for the survival of organisms, confer adaptive advantages and act through natural mechanisms to inhibit the attachment of encrusting microorganisms and larvae [185]. Compounds such as triterpene glycosides, halogenated furanones, low-molecular-weight brominated molecules, proteins, and polysaccharides with antiadhesive properties have been identified in different groups, including bacteria, algae, sponges, cnidarians, echinoderms, tunicates, and bryozoans [277].

An example of these strategies is the use of microorganisms of the genus *Pseudoalteromonas*, which produce a wide range of compounds with antibiofilm and antifouling activity, including protein antibiotics, pigments, small brominated compounds, and toxins such as neurotoxins and tetratoxins, which have been shown to be specific targets of biofouling groups [278–280]. These bacteria synthesize high-molecular-weight (100–200 kDa) proteins, bioactive polysaccharides, and thermostable and thermosensitive compounds with molecular weights ranging from <500 Da to 10 kDa. Such compounds have demonstrated efficacy in inhibiting the adhesion of bacteria, algal spores, and barnacle larvae such as those of *B. amphitrite*, both in laboratory and field tests, especially when incorporated into paint matrices or hydrogels [281].

The use of secondary metabolites produced by the species *Azadirachta indica* (Neem) and *Pongamia pinnata* (Karanjin) has demonstrated antifouling potential with lower environmental toxicity and favorable biodegradability [217,282]. These compounds represent a promising line of research for the development of more sustainable antifouling coatings, aligned with international environmental protection guidelines and the transition to a low-environmental-impact economy [276].

Additionally, the development of natural coatings and green paints is gaining ground, combining natural compounds with less toxic metals. One example is the combination of quebracho tannins with copper, which reduces the copper concentration in formulations by up to 40 times while maintaining antifouling efficacy and reducing environmental impacts. These coatings also explore the controlled release of bioactive compounds and the use of polymeric matrices to immobilize natural ingredients [185,267].

The role of biotechnology and combinatorial chemistry has become increasingly relevant in expanding the use of natural product antifoulants (NPAs). By characterizing the structure of natural compounds, it is possible to synthesize more stable and potent analogs, as well as express genes responsible for the production of antifouling metabolites in heterologous organisms. This advance contributes to scaled production, with economic viability and reduced environmental impact, consolidating the microbial approach as a sustainable and promising solution for marine fouling control [185].

Recent studies show that coatings based on copper selenide (CuSe) nanoparticles, embedded into polymer matrices, can release ions in a controlled manner for up to 80 days, providing sustainable antifouling properties [283]. However, large-scale production of these materials requires carefully controlled manufacturing processes to ensure uniformity and long-lasting antifouling effects. Additionally, economic viability depends on optimizing these processes, lowering raw material costs, and developing application methods suitable for various substrate types and the shapes of offshore structures like ship hulls and platforms [275].

From a regulatory perspective, replacing traditional biocidal coatings faces challenges related to the approval process for new materials, especially regarding environmental impacts and toxicity. Environmental agencies require thorough data on the ecotoxicological effects of nanomaterials or functionalized surfaces, which involves standardized short- and long-term testing, as well as the monitoring of secondary effects on non-target organisms [284,285]. Additionally, international standards for navigation and maritime structures establish performance criteria that must be met, potentially delaying the commercial deployment of innovative technologies [44,286].

Advancement in this field requires an interdisciplinary approach that combines microbiology, materials science, surface engineering, computational modeling, and data science. Microbiology is key to understanding initial microbial colonization and how biofilm communities interact with different textures or chemical compositions [287,288]. Materials science helps design surfaces with mechanical and chemical properties suitable for real-world applications. Data science and predictive modeling enable the analysis of large amounts of performance data under various environmental conditions, forecast durability, and guide modifications to coating designs [289]. This interdisciplinary approach is vital for creating effective, safe, economically feasible, and scalable antifouling solutions, supporting a gradual shift from traditional technologies to sustainable, high-performance alternatives [289–292].

In this scenario, there is a clear need for closer collaboration among academia, industry, and regulatory agencies to accelerate technology transfer and ensure that these scientific advances turn into practical and environmentally competitive solutions [293]. Therefore, the convergence of science and industrial innovation points to a future where biofouling control not only cuts operational costs and emissions related to maritime transport but also helps protect biodiversity and supports the shift toward sustainable maritime practices [275].

6. Conclusions

This study highlighted a rise in scientific production on marine biofouling control strategies since 2019, with China leading in publications and patent filings. However, the concentration of patents and publications in just a few countries underscores global disparities in investment, innovation policies, and technology transfer. Despite the progress, many solutions still lack full-scale validation and comparative analyses of durability and long-term ecological effects.

Given the complexity of fouling processes, most research still concentrates on laboratory-scale studies, and there is a lack of comparative analyses on the durability, long-term effectiveness, and ecological impacts of new materials such as nanostructured coatings, biomimetic surfaces, and natural composites. The complexity of biofilm–substrate interactions and the effects of environmental variables like temperature, salinity, and hydrological dynamics are also insufficiently studied. This calls for ongoing research and innovation efforts focused both on a deeper understanding of fouling mechanisms and on developing new materials and technologies with reduced environmental impact.

In the future, it is important to prioritize long-term field studies, systematically evaluate environmental impacts, and incorporate hybrid technologies, such as antifouling surfaces combined with controlled enzyme release. Using artificial intelligence for predictive modeling and encouraging multidisciplinary international collaborations are crucial for developing effective, scalable solutions that meet regulatory and sustainability standards for marine ecosystems.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/coatings15101185/s1, Table S1: Patents involving strategies for preventing marine biofouling filed in the last 20 years. References [294–335] are cited in the Supplementary Materials.

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Abbreviations

The following abbreviations are used in this manuscript:

AFS Convention	International Convention on the Control of Harmful Anti-fouling Systems on Ships
EPO	European Patent Office
INPI	Brazilian National Institute of Industrial Property
IPC	International Patent Classification
IMO	International Marine Organization
MARPOL	International Convention for the Prevention of Pollution from Ships
NPAs	Natural Product Antifoulants
TBT	Tributyltin
PDMS	Polydimethylsiloxane
PEG	Polyethylene glycol
RAFT	Reversible Addition–Fragmentation Chain Transfer
WIPO	World Intellectual Property Organization

References

1. Agostini, V.O.; Macedo, A.J.; Muxagata, E. O papel do biofilme bacteriano no acoplamento bentopelágico, durante o processo de bioincrustação. *Rev. Lib.* **2018**, *19*, 23–42. [CrossRef]
2. Bae, S.; Ubagan, M.D.; Shin, S.; Kim, D.G. Comparison of recruitment patterns of sessile marine invertebrates according to substrate characteristics. *Int. J. Environ. Res. Public Health* **2022**, *19*, 1083. [CrossRef] [PubMed]
3. Fitridge, I.; Dempster, T.; Guenther, J.; De Nys, R. The impact and control of biofouling in marine aquaculture: A review. *Biofouling* **2012**, *28*, 649–669. [CrossRef]
4. Bagheri, M.; Mirbagheri, S.A. Critical review of fouling mitigation strategies in membrane bioreactors treating water and wastewater. *Bioresour. Technol.* **2018**, *258*, 318–334. [CrossRef]
5. Dobretsov, S.; Rittschof, D. Biofouling and Antifouling: Interactions between Microbes and Larvae of Invertebrates. *Int. J. Mol. Sci.* **2023**, *24*, 6531. [CrossRef]
6. Romeu, M.J.; Mergulhão, F. Development of Antifouling Strategies for Marine Applications. *Microorganisms* **2023**, *11*, 1568. [CrossRef]
7. Tyrrel, M.C.; Byers, J.E. Do artificial substrate favor nonindigenous fouling species over native species? *J. Exp. Mar. Biol. Ecol.* **2007**, *342*, 54–60. [CrossRef]
8. Cunha, J.L.O.; Silva, S.L.; Batista, R.O.; Marques, B.C.D.; Coelho, D.C.L.; Silva, K.B. Monitoramento da bioincrustação em fitas gotejadoras aplicando água com distintas temperaturas e salinidades. *Irriga* **2020**, *25*, 1–13. [CrossRef]
9. Lum, W.M.; Sakamoto, S.; Yuasa, K.; Takahashi, K.; Kuwata, K.; Kodama, T.; Katayama, T.; Leaw, C.P.; Lim, P.T.; Iwataki, M. Comparative effects of temperature and salinity on growth of four harmful *Chattonella* spp. (Raphidophyceae) from tropical Asian waters. *Front. Mar. Sci.* **2023**, *10*, 1–16. [CrossRef]
10. Araújo, E.A.; Andrade, N.J.; Silva, L.H.M.; Carvalho, A.F.; Silva, C.A.S.; Ramos, A.M. Control of microbial adhesion as a strategy for food and bioprocess technology. *Food Bioprocess Technol.* **2010**, *3*, 321–332. [CrossRef]
11. Zheng, S.; Bawazir, M.; Dhall, A.; Kim, H.; He, L.; Heo, J.; Hwang, G. Implication of Surface Properties, Bacterial Motility, and Hydrodynamic Conditions of Bacterial Surface Sensing and Their Initial Adhesion. *Front. Bioeng. Biotechnol.* **2021**, *9*, 643722. [CrossRef] [PubMed]

12. Xavier, E.A.; Almeida, A.C.; Nogueira, M.M.; Vieira, L.M. Effects of substratum type and orientation on the recruitment of bryozoans in an artificial area of the Western Atlantic. *Biofouling* **2023**, *39*, 748–762. [CrossRef] [PubMed]
13. Raw, J.L.; Miranda, N.A.; Perissinotto, R. Chemical cues released by heterospecific competitors: Behavioural responses of native and alien invasive aquatic gastropods. *Aquat. Sci.* **2015**, *77*, 655–666. [CrossRef]
14. Vieira, E.A.; Flores, A.A.V.; Dias, G.M. Colonization history meets further niche processes: How the identity of founders modulates the way predation structure fouling communities. *Oecologia* **2021**, *196*, 1167–1178. [CrossRef]
15. Somma, E.; Terlizzi, A.; Costantini, M.S.; Madeira, M.; Zupo, V. Global Changes Alter the Successions of Early Colonizers of Benthic Surfaces. *J. Mar. Sci. Eng.* **2023**, *11*, 1232. [CrossRef]
16. Soroldoni, S.; Castro, Í.B.; Abreu, F.; Duarte, F.A.; Choueri, R.B.; Möller, O.O., Jr.; Fillmann, G.; Pinho, G.L.L. Antifouling paint particles: Sources, occurrence, composition and dynamics. *Water Res.* **2018**, *137*, 47–56. [CrossRef]
17. Yu, X.; Wang, J.; Kou, M.; Shi, Z.; Young-Dong, Y. Research Progress and Prospect of Marine Antifouling Coatings. *Stud. Soc. Sci. Res.* **2023**, *4*, 152–157. [CrossRef]
18. Liu, W.; Li, T.; Si, S.; Wang, C.; Zang, Y.; Wang, C.; Chaoyi, W.; Tao, A. 960 MPa Grade Ultrahigh-Strength Steel Plate with Marine Fouling Resistance and Manufacturing Method Therefor. WO Patent 2023240850, 21 December 2023. Available online: https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2023240850&_cid=P20-MFWIQ7-32382-1 (accessed on 3 June 2025).
19. Thouvenin, M.; Peron, J.J.; Langlois, V.; Guerin, P.; Langlois, J.Y.; Valee-Rehel, K. Formulation and antifouling activity of marine paints: A study by a statistically based experiments plan. *Prog. Org. Coat.* **2002**, *44*, 85–92. [CrossRef]
20. Yebra, D.M.; Kiil, S.; Dam-Johasen, K. Antifouling technology—Past, present and future steps towards efficient and environmentally friendly antifouling coatings. *Prog. Org. Coat.* **2004**, *50*, 75–104. [CrossRef]
21. Bers, V.; Wahl, M. The influence of natural surface microtopographies on fouling. *Biofouling* **2004**, *20*, 43–51. [CrossRef] [PubMed]
22. Barrios, C.A.; Xu, Q.; Cutright, T.; Newby, B.M.Z. Incorporating zosteric acid into silicone coatings to achieve its slow release while reducing fresh water bacterial attachment. *Colloids Surf. B Biointerfaces* **2005**, *41*, 83–93. [CrossRef]
23. Hellio, C.; Maréchal, J.; Da Gama, B.; Pereira, R.; Clare, A. Natural marine products with antifouling activities. In *Advances in Marine Antifouling Coatings and Technologies*; Hellio, C., Yebra, D., Eds.; Woodhead Publishing: Cambridge, UK, 2009; pp. 572–622. [CrossRef]
24. Trepos, R.; Cervin, G.; Hellio, C.; Pavia, H.; Stensen, W.; Stensvåg, K.; Svendsen, J.; Haug, T.; Svenson, J. Antifouling Compounds from the Sub-Arctic Ascidian *Synoicum pulmonaria*: Synoxazolidinones A and C, Pulmonarins A and B, and Synthetic Analogues. *J. Nat. Prod.* **2014**, *77*, 2105–2113. [CrossRef]
25. Gittens, J.E.; Smith, T.J.; Suleiman, R.; Akid, R. Current and emerging environmentally-friendly systems for fouling control in the marine environment. *Biotechnol. Adv.* **2013**, *31*, 1738–1753. [CrossRef]
26. Silva, E.R.; Ferreira, O.; Ramalho, P.A.; Azevedo, N.F.; Bayón, R.; Igartua, A.; Bordado, J.C.; Calhorda, M.J. Eco-friendly non-biocide-release coatings for marine biofouling prevention. *Sci. Total Environ.* **2019**, *650*, 2499–2511. [CrossRef]
27. Gu, Y.; Yu, L.; Mou, J.; Wu, D.; Xu, M.; Zhou, P.; Ren, Y. Research strategies to develop environmentally friendly marine antifouling coatings. *Mar. Drugs* **2020**, *18*, 371. [CrossRef]
28. Donthu, N.; Kumar, S.; Mukherjee, D.; Pandey, N.; Lim, W.M. How to conduct a bibliometric analysis: An overview and guidelines. *J. Bus. Res.* **2021**, *133*, 285–296. [CrossRef]
29. Amini, S.; Kolle, S.; Petrone, L.; Ahanotu, O.; Sunny, S.; Sutanto, C.N.; Hoon, S.C.L.; Weaver, J.C.; Aizenberg, J.; Vogel, N.; et al. Preventing mussel adhesion using lubricant-infused materials. *Science* **2017**, *357*, 668–673. [CrossRef] [PubMed]
30. Xiao, L.; Li, J.; Mieszkin, S.; Di Fino, A.; Clare, A.S.; Callow, M.E.; Callow, J.A.; Grunze, M.; Rosenhahn, A.; Levkin, P.A. Slippery liquid-infused porous surfaces showing marine antibiofouling properties. *ACS Appl. Mater. Interfaces* **2013**, *5*, 10074–10080. [CrossRef] [PubMed]
31. Bannister, J.; Sievers, M.; Bush, F.; Bloecher, N. Biofouling in marine aquaculture: A review of recent research and developments. *Biofouling* **2019**, *35*, 631–648. [CrossRef]
32. Srinivasan, R.; Santhakumari, S.; Poonguzhali, P.; Geetha, M.; Dyavaiah, M.; Xiangmin, L. Bacterial biofilm inhibition: A focused review on recent therapeutic strategies for combating the biofilm mediated infections. *Front. Microbiol.* **2021**, *12*, 676458. [CrossRef]
33. Braithwaite, R.A.; McEvoy, L.A. Marine biofouling on fish farms and its remediation. *Adv. Mar. Biol.* **2005**, *47*, 215–252. [CrossRef]
34. Wang, P.; Zhang, D.; Sun, S.; Li, T.; Sun, Y. Fabrication of slippery lubricant-infused porous surface with high underwater transparency for the control of marine biofouling. *ACS Appl. Mater. Interfaces* **2017**, *9*, 972–982. [CrossRef]
35. Chen, L.; Duan, Y.; Cui, M.; Huang, R.; Su, R.; Qi, W.; He, Z. Biomimetic surface coatings for marine antifouling: Natural antifoulants, synthetic polymers and surface microtopography. *Sci. Total Environ.* **2021**, *766*, 144469. [CrossRef]
36. Leonardi, A.K.; Ober, C.K. Polymer-based marine antifouling and fouling release surfaces: Strategies for synthesis and modification. *Ann. Rev. Chem. Biomol. Eng.* **2019**, *10*, 241–264. [CrossRef]
37. Ferrari, M.; Benedetti, A. Superhydrophobic surfaces for applications in seawater. *Adv. Colloid Interface Sci.* **2015**, *222*, 291–304. [CrossRef]

38. Nicklisch, S.C.; Waite, J.H. Mini-review: The role of redox in Dopa-mediated marine adhesion. *Biofouling* **2012**, *28*, 865–877. [CrossRef] [PubMed]
39. Whelan, A.; Regan, F. Antifouling strategies for marine and riverine sensors. *J. Environ. Monit.* **2006**, *8*, 880–886. [CrossRef] [PubMed]
40. Li, D.; Wei, Q.; Wu, C.; Zhang, X.; Xue, Q.; Zheng, T.; Cao, M. Superhydrophilicity and strong salt-affinity: Zwitterionic polymer grafted surfaces with significant potentials particularly in biological systems. *Adv. Colloid Interface Sci.* **2020**, *278*, 102141. [CrossRef] [PubMed]
41. Rosenhahn, A.; Ederth, T.; Pettitt, M.E. Advanced Nanostructures for the Control of Biofouling: The FP6 EU Integrated Project AMBIO. *Biointerphases* **2008**, *3*, IR1–IR5. [CrossRef]
42. Pinteus, S.; Lemos, M.F.L.; Alves, C.; Neugebauer, A.; Silva, J.; Thomas, O.P.; Botana, L.M.; Gaspar, H.; Pedrosa, R. Marine invasive macroalgae: Turning a real threat into a major opportunity-the biotechnological potential of *Sargassum muticum* and *Asparagopsis armata*. *Algal Res.* **2018**, *34*, 217–234. [CrossRef]
43. Sun, W.; Feng, L.; Zhang, J.; Lin, K.; Wang, H.; Yan, B.; Feng, T.; Cao, M.; Liu, T.; Yuan, Y.; et al. Amidoxime group-anchored single cobalt atoms for anti-biofouling during uranium extraction from seawater. *Adv. Sci.* **2022**, *9*, 2105008. [CrossRef]
44. Wu, S.; Wu, S.; Xing, S.; Wang, T.; Hou, J.; Zhao, Y.; Li, W. Research Progress of Marine Anti-Fouling Coatings. *Coatings* **2024**, *14*, 1227. [CrossRef]
45. He, S.; Xue, Q.; Fu, Z.; Bao, L.; Li, K.; Zhang, G.; Zhang, H.; Qiu, T. Biofouling Community Dynamics on Nylon and Polyethylene Aquaculture Nets in the North Yellow Sea: Colonization Patterns and *Mytilus edulis* Mechanical Properties. *Water* **2025**, *17*, 1250. [CrossRef]
46. Wang, T.; Hou, J.; Wang, Y.; Feng, X.; Liu, X. Urushiol-Based Antimicrobial Coatings: Molecular Mechanisms, Structural Innovations, and Multifunctional Applications. *Polymers* **2025**, *17*, 1500. [CrossRef]
47. Zhang, H.; Ding, Q.; Zhang, Y.; Lu, G.; Liu, Y.; Tong, Y. Prevention and Control of Biofouling Coatings in *Limnoperna fortunei*: A Review of Research Progress and Strategies. *Polymers* **2024**, *16*, 3070. [CrossRef] [PubMed]
48. Tian, W.; Jin, H.; Tian, L. Ideas Inspired by Nature to Combat Marine Biofouling and Corrosion. *Coatings* **2022**, *12*, 1434. [CrossRef]
49. Gosens, J.; Hellsmark, H.; Kåberger, T.; Liu, L.; Sandén, B.A.; Wang, S.; Zhao, L. The limits of academic entrepreneurship: Conflicting expectations about commercialization and innovation in China's nascent sector for advanced bio-energy technologies. *Energy Res. Soc. Sci.* **2018**, *37*, 1–11. [CrossRef]
50. Shi, X.; Liang, H.; Li, Y. Review of Progress in Marine Anti-Fouling Coatings: Manufacturing Techniques and Copper- and Silver-Doped Antifouling Coatings. *Coatings* **2024**, *14*, 1454. [CrossRef]
51. Li, L.; Hong, H.; Cao, J.; Yang, Y. Progress in Marine Antifouling Coatings: Current Status and Prospects. *Coatings* **2023**, *13*, 1893. [CrossRef]
52. Ning, J.; Pang, S.; Arifin, Z.; Zhang, Y.; Epa, U.P.K.; Qu, M.; Zhao, J.; Zhen, F.; Chowdhury, A.; Guo, R.; et al. The Diversity of Artificial Intelligence Applications in Marine Pollution: A Systematic Literature Review. *J. Mar. Sci. Eng.* **2024**, *12*, 1181. [CrossRef]
53. Tai, P.F. Why the Asian craze for publication? An examination from academic regime. In *Research, Development, and Innovation in Asia Pacific Higher Education*; Neubauer, D.E., Ed.; Palgrave Macmillan: New York, NY, USA, 2015; pp. 61–79. ISBN 978-1-137-51384-0.
54. Patelli, A.; Cimini, G.; Pugliese, E.; Gabrielli, A. The scientific influence of nations on global scientific and technological development. *J. Informetr.* **2017**, *11*, 1229–1237. [CrossRef]
55. Huang, J.; Li, W.; Huang, X.; Wang, Y.; Guo, L. Technology and innovation in China: A patent citation-based analysis. *Sci. Techol. Soc.* **2021**, *26*, 344–365. [CrossRef]
56. Wahl, M.; Goecke, F.; Labes, A.; Dobretsov, S.; Weinberger, F. The second skin: Ecological role of epibiotic biofilms on marine organisms. *Front. Microbiol.* **2012**, *3*, 292. [CrossRef] [PubMed]
57. Salta, M.; Chambers, L.; Wharton, J.; Wood, R.; Briand, J.F.; Blache, Y.; Stokes, K. Marine fouling organisms and their use in antifouling bioassays. In Proceedings of the EUROCORR; European Federation of Corrosion: Nice, France, 2009; pp. 6–9.
58. Siboni, N.; Lidor, M.; Kramarsky-Winter, E.; Kushmaro, A. Conditioning film and initial biofilm formation on ceramics tiles in the marine environment. *FEMS Microbiol. Lett.* **2007**, *274*, 24–29. [CrossRef] [PubMed]
59. Dobretsov, S. Inhibition and induction of marine biofouling by biofilms. In *Marine and Industrial Biofouling*; Flemming, H.C., Murthy, P.S., Venkatesan, R., Cooksey, K., Eds.; Springer: Berlin/Heidelberg, Germany, 2009; p. 20.
60. Satheesh, S.; Wesley, S. Biofilm development on acrylic coupons during the initial 24 hour period of submersion in a tropical coastal environment. *Oceanol. Hydrobiol. Stud.* **2010**, *39*, 27–38. [CrossRef]
61. Wang, C.; Bao, W.Y.; Gu, Z.Q.; Li, Y.F.; Liang, X.; Ling, Y.; Cai, S.L.; Shen, H.D.; Yang, J.L. Larval settlement and metamorphosis of the mussel *Mytilus coruscus* in response to natural biofilms. *Biofouling* **2012**, *28*, 249–256. [CrossRef]
62. Archana, S.; Sundaramoorthy, B.F.M. Review on impact of biofouling in aquafarm infrastructures. *Int. J. Curr. Microbiol. Appl. Sci.* **2019**, *8*, 2942–2953. [CrossRef]
63. Wahl, M. Marine epibiosis I. Fouling and antifouling: Some basic aspects. *Mar. Ecol. Prog. Ser.* **1989**, *58*, 175–189. [CrossRef]

64. Kavouras, J.H.; Maki, J.S. Effects of biofilms on zebra mussel postveliger attachment to artificial surfaces. *Invertebr. Biol.* **2003**, *122*, 138–151. [CrossRef]
65. Rittschof, D.; Chai, C.; Teo, S.L.M.; Maki, J.S. Fouling and Its Next Generation Management: A Perspective. *J. Agric. Mar. Sci.* **2015**, *20*, 16–23. [CrossRef]
66. Bhosle, N.B.; Garg, A.; Fernandes, L.; Citon, P. Dynamics of amino acids in the conditioning film developed on glass panels immersed in the surface seawaters of Dona Paula Bay. *Biofouling* **2005**, *21*, 99–107. [CrossRef]
67. Stavridou, I.; Forzi, L. Biofilms: Friend or foe? Meeting report; June 2011. *Virulence* **2011**, *2*, 475–489. [CrossRef] [PubMed]
68. Stoodley, P.; Sauer, K.; Davies, D.G.; Costerton, J.W. Biofilms as complex differentiated communities. *Annu. Rev. Microbiol.* **2002**, *1*, 187–209. [CrossRef]
69. Anil, A.C.; Patil, J.S.; Mitbavkar, S.; DeCosta, P.M.; DeSilva, S.; Hegde, S.; Naik, R. Role of diatoms in marine biofouling. *CSMCRI* **2006**, *1*, 351–365. Available online: http://drs.nio.org/drs/handle/2264/810 (accessed on 8 June 2025).
70. Mitbavkar, S.; Anil, A.C. Species interactions within a fouling diatom community: Roles of nutrients, initial inoculum and competitive strategies. *Biofouling* **2007**, *23*, 99–112. [CrossRef]
71. Nagarkar, S.; Williams, G.A.; Subramanian, G.; Saha, S.K. Cyanobacteria-dominated biofilms: A high quality food resource for intertidal grazers. In Proceedings of the 2nd Asian Pacific Phycological Forum, Hong Kong, China, 21–25 June 1999; pp. 89–95.
72. Roeselers, G.; Loosdrecht, M.V.; Muyzer, G. Phototrophic biofilms and their potential applications. *J. Appl. Phycol.* **2008**, *20*, 227–235. [CrossRef]
73. Rossi, F.; De Philippis, R. Role of Cyanobacterial Exopolysaccharides in Phototrophic Biofilms and in Complex Microbial Mats. *Life* **2015**, *5*, 1218–1238. [CrossRef] [PubMed]
74. Sawall, Y.; Richter, C.; Ramette, A. Effects of eutrophication, seasonality and macrofouling on the diversity of bacterial biofilms in equatorial coral reefs. *PLoS ONE* **2012**, *7*, e39951. [CrossRef]
75. Patil, J.S.; Anil, A.C. Biofilm diatom community structure: Influence of temporal and substratum variability. *Biofouling* **2005**, *21*, 189–206. [CrossRef]
76. Whalan, S.; Webster, N.S. Sponge larval settlement cues: The role of microbial biofilms in a warming ocean. *Sci. Rep.* **2014**, *4*, 4072. [CrossRef] [PubMed]
77. Thompson, R.C.; Norton, T.A.; Hawkins, S.J. Physical stress and biological control regulate the producer—Consumer balance in intertidal biofilms. *Ecology* **2004**, *85*, 1372–1382. [CrossRef]
78. Passarelli, C.; Meziane, T.; Thiney, N.; Boeuf, D.; Jesus, B.; Ruivo, M.; Jeanthon, C.; Hubas, C. Seasonal variations of the composition of microbial biofilms in sandy tidal flats: Focus of fatty acids, pigments and exopolymers. *Estuar. Coast. Shelf Sci.* **2007**, *153*, 29–37. [CrossRef]
79. Costerton, J.W.; Lewandowski, Z.; Caldwell, D.E.; Korber, D.R.; LappinScott, H.M. Microbial biofilms. *Annu. Rev. Microbiol.* **1995**, *49*, 711–745. [CrossRef] [PubMed]
80. McElroy, D.J.; Doblin, M.A.; Murphy, R.J.; Hochuli, D.F.; Coleman, R.A. A limited legacy effect of copper in marine biofilms. *Mar. Pollut. Bull.* **2016**, *109*, 117–127. [CrossRef]
81. Guo, X.; Niu, Z.; Lu, D.; Feng, J.; Chen, Y.; Tou, F.; Liu, M.; Yang, Y. Bacterial community structure in the intertidal biofilm along the Yangtze Estuary, China. *Mar. Pollut. Bull.* **2017**, *124*, 314–320. [CrossRef] [PubMed]
82. Maki, J.S.; Mitchell, R. Biofouling in the marine environment. In *Encyclopedia of Environmental Microbiology*; Bitton, G., Ed.; Wiley: New York, NY, USA, 2002; p. 3730. [CrossRef]
83. Dobretsov, S. Marine biofilms. In *Biofouling*; Simone Dürr, S., Thomason, J.C., Eds.; Blackwell Publishing Ltd.: Hoboken, NJ, USA, 2009; p. 13. [CrossRef]
84. Crisp, D.J. Overview of research on marine invertebrate larvae, 1940–1980. In Proceedings of the Symposium on Marine Biodeterioration, Uniformed Services University of Health Sciences, Bethesda, MD, USA, 20–23 April 1981; pp. 103–126.
85. Haderlie, E.C. A brief overview of the effects of macrofouling. In *Marine Biodeterioration: An Interdisciplinary Study*; Costlow, J.D., Tipper, R.C., Eds.; Naval Institute Press: Annapolis, MD, USA, 1984; p. 163. ISBN 978-1-4615-9722-3.
86. Clare, A.S.; Rittschof, D.J.; Gerhart, J.S.M. Molecular approaches to nontoxic antifouling. *Invertebr. Reprod. Dev.* **1992**, *22*, 67–76. [CrossRef]
87. Christensen, A.M.; McDermott, J.J. Life-history and biology of the oyster crab, *Pinnotheres ostreum* Say. *Biol. Bull.* **1958**, *114*, 146–179. [CrossRef]
88. Raman, S.; Kumar, R. Interfacial morphology and nanomechanics of cement of the barnacle, *Amphibalanus reticulatus* on metallic and non-metallic substrata. *Biofouling* **2011**, *27*, 569–577. [CrossRef] [PubMed]
89. Li, A.; Jia, Y.; Sun, S.; Xu, Y.; Minsky, B.B.; Stuart, M.C.; Colfen, H.; Von Klitzing, R.; Guo, X. Mineral-enhanced polyacrylic acid hydrogel as an oyster-inspired organic–inorganic hybrid adhesive. *ACS Appl. Mater. Interfaces* **2018**, *10*, 10471–10479. [CrossRef]
90. Rajagopal, S.; Nair, K.V.K.; Azariah, J.; Van der Velde, G.; Jenner, H.A. Chlorination and mussel control in the cooling conduits of a tropical coastal power station. *Mar. Environ. Res.* **1996**, *41*, 201–221. [CrossRef]
91. Edyvean, R.G.; Videla, H.A. Biological corrosion. *Interdiscip. Sci. Rev.* **1991**, *16*, 267–282. [CrossRef]

92. Neville, A.; Hodgkiess, T. Localised effects of macrofouling species on electrochemical corrosion of corrosion resistant alloys. *Br. Corros. J.* **2000**, *35*, 54–59. [CrossRef]
93. Blackwood, D.J.; Lim, C.S.; Teo, S.L.; Hu, X.; Pang, J. Macrofouling induced localized corrosion of stainless steel in Singapore seawater. *Corros. Sci.* **2017**, *129*, 152–160. [CrossRef]
94. Li, Y.; Ning, C. Latest research progress of marine microbiological corrosion and bio-fouling, and new approaches of marine anti-corrosion and anti-fouling. *Bioact. Mater.* **2019**, *4*, 189–195. [CrossRef] [PubMed]
95. Wang, Z.; Huang, Y.; Wang, X.; Xu, Y.; Cai, F. Effects of oyster as macrofouling organism on corrosion mechanisms of a high-strength low-alloy steel. *Corros. Sci.* **2022**, *207*, 110580. [CrossRef]
96. Ezgi, C.; Ozbalta, N. Optimization of heat exchanger cleaning cycle on a ship. *J. Nav. Sci. Eng.* **2012**, *8*, 33–46.
97. Woods, C.M.; Floerl, O.; Jones, L. Biosecurity risks associated with in-water and shore-based marine vessel hull cleaning operations. *Mar. Pollut. Bull.* **2012**, *64*, 1392–1401. [CrossRef]
98. Klijnstra, J.; Zhang, X.; van der Putten, S.; Röckmann, C. Technical Risks of Offshore Structures. In *Aquaculture Perspective of Multi-Use Sites in the Open Ocean*; Buck, B.H., Langan, R., Eds.; Springer: Cham, Switzerland, 2017; p. 404. [CrossRef]
99. Azevedo, J.; Antunes, J.T.; Machado, A.M.; Vasconcelos, V.; Leao, P.N.; Froufe, E. Monitoring of biofouling communities in a Portuguese port using a combined morphological and metabarcoding approach. *Sci. Rep.* **2020**, *10*, 13461. [CrossRef] [PubMed]
100. Mathew, N.T.; Kronholm, J.; Bertilsson, K.; Despeisse, M.; Johansson, B. Environmental and economic impacts of biofouling on marine and coastal heat exchangers. In *EcoDesign and Sustainability II: Social Perspectives and Sustainability Assessment*; Springer: Singapore, 2020; p. 661.
101. Rao, T.S. Biofouling (Macro-Fouling) in Seawater Intake Systems. In *Water-Formed Deposits*; Elsevier: Amsterdam, The Netherlands, 2022; pp. 565–587. [CrossRef]
102. Sell, D. Marine fouling. *Proc. R. Soc. Edinb. Sect. B Biol. Sci.* **1992**, *100*, 169–184. [CrossRef]
103. Naser, H.A. Variability of marine macrofouling assemblages in a marina and a mariculture centre in Bahrain, Arabian Gulf. *Reg. Stud. Mar. Sci.* **2017**, *16*, 162–170. [CrossRef]
104. Lezzi, M.; Del Pasqua, M.; Pierri, C.; Giangrande, A. Seasonal non-indigenous species succession in a marine macrofouling invertebrate community. *Biol. Invasions* **2018**, *20*, 937–961. [CrossRef]
105. Mineur, F.; Johnson, M.P.; Maggs, C.A. Macroalgal introductions by hull fouling on recreational vessels: Seaweeds and sailors. *Environ. Manag.* **2008**, *42*, 667–676. [CrossRef]
106. Perkol-Finkel, S.; Shashar, N.; Barneah, O.; Ben-David-Zaslow, R.; Oren, U.; Reichart, T.; Yacobovich, T.; Yahel, G.; Yahel, R.; Benayahu, Y. Fouling reefal communities on artificial reefs: Does age matter? *Biofouling* **2005**, *21*, 127–140. [CrossRef]
107. Nelson, M.L.; Craig, S.F. Role of the sea anemone Metridium senile in structuring a developing subtidal fouling community. *Mar. Ecol. Prog. Ser.* **2011**, *421*, 139–149. [CrossRef]
108. Lim, S.C.; de Voogd, N.J.; Tan, K.S. Fouling sponges (Porifera) on navigation buoys from Singapore waters. *Raffles Bull. Zool.* **2009**, *22*, 41–58.
109. Khalaman, V.V.; Komendantov, A.Y. Structure of fouling communities formed by *Halichondria panicea* (Porifera: Demospongiae) in the White Sea. *Russ. J. Ecol.* **2011**, *42*, 493–501. [CrossRef]
110. Kremer, L.P.; Rocha, R.M. The role of *Didemnum perlucidum* F. Monniot, 1983 (Tunicata, Ascidiacea) in a marine fouling community. *Aquat. Invasions* **2011**, *6*, 441–449. [CrossRef]
111. Lins, D.M.; Rocha, R.M. Cultivated brown mussel (*Perna perna*) size is reduced through the impact of three invasive fouling species in southern Brazil. *Aquat. Invasions* **2020**, *15*, 114–126. [CrossRef]
112. Calder, D.; Carlton, J.T.; Larson, K.; Mallinson, J.J.; Choong, H.H.; Keith, I.; Ruiz, G. Hydroids (Cnidaria, Hydrozoa) from marine fouling assemblages in the Galápagos Islands, Ecuador. *Aquat. Invasions* **2019**, *14*, 21–58. [CrossRef]
113. Ajala-Batista, L.; de Miranda, L.D.; Haddad, M.A. Diversity of estuarine and marine hydroids (Cnidaria, Hydrozoa) from subtropical ecosystems of Brazil. *Mar. Biodivers.* **2020**, *50*, 97. [CrossRef]
114. Agostini, V.O.; Ozorio, C.P. Biofouling initial succession on offshore artificial substrate under subtropical conditions. *An. Acad. Bras. Ciênc.* **2022**, *94*, e20201357. [CrossRef] [PubMed]
115. Silva, L.C.C.; Xavier, E.A.; Gouveia, R.L.; Silva, A.K.P.; Fernandes, M.L.B. Balanomorpha Community of Confined Artificial Substrate in a Thermal Power Plant of Pernambuco, Brazil. *Indian J. Appl. Res.* **2018**, *8*, 76–78. Available online: https://www.worldwidejournals.com/indian-journal-of-applied-research-(IJAR)/file.php?val=October_2018_1538401838__154.pdf (accessed on 26 September 2025).
116. Freitas, L.E.L.D.; Feitosa, C.V.; Araújo, M.E.D. Mangrove oyster (*Crassostrea rhizophorae*) (Guilding, 1928) farming areas as artificial reefs for fish: A case study in the state of Ceará, Brazil. *Braz. J. Oceanogr.* **2006**, *54*, 31–39. [CrossRef]
117. Mansur, M.C.D.; Pereira, D.; dos Santos, C.P.; Bergonci, P.E.A.; Thormann, B.M.; Takeda, A.M. Colonização de substrato artificial pelo mexilhão dourado, *Limnoperna fortunei* (Dunker, 1857) (Bivalvia, Mytiloida, Mytilidae), no delta do rio Jacuí (RS, Brasil). *Biotemas* **2009**, *22*, 75–80. [CrossRef]

118. Nedved, B.T.; Hadfield, M.G. Hydroides elegans (Annelida: Polychaeta): A model for biofouling research. In *Marine and Industrial Biofouling*; Flemming, H.C., Murthy, P.S., Venkatesan, R., Cooksey, K., Eds.; Springer Series on Biofilms; Springer: Berlin/Heidelberg, Germany, 2009; Volume 4, pp. 203–219. [CrossRef]
119. Schwan, I.D.S.; Brasil, A.C.D.S.; Neves, D.; Dias, G.M. The invasive worm *Hydroides elegans* (Polychaeta–Serpulidae) in southeastern Brazil and its potential to dominate hard substrata. *Mar. Biol. Res.* **2016**, *12*, 96–103. [CrossRef]
120. Subías-Baratau, A.; Sanchez-Vidal, A.; Di Martino, E.; Figuerola, B. Marine biofouling organisms on beached, buoyant and benthic plastic debris in the Catalan Sea. *Mar. Pollut. Bull.* **2022**, *175*, 113405. [CrossRef] [PubMed]
121. Thiel, M.; Gutow, L. The ecology of rafting in the marine environment. I. The floating substrata. *Oceanogr. Mar. Biol.* **2004**, *42*, 181–264. [CrossRef]
122. da Gama, B.A.; Santos, R.P.; Pereira, R.C. The effect of epibionts on the susceptibility of the red seaweed *Cryptonemia seminervis* to herbivory and fouling. *Biofouling* **2008**, *24*, 209–218. [CrossRef]
123. Roberts, D.; Rittschof, D.; Holm, E.; Schmidt, A.R. Factors influencing initial larval settlement: Temporal, spatial and surface molecular components. *J. Exp. Mar. Biol. Ecol.* **1991**, *150*, 203–221. [CrossRef]
124. Skinner, L.F.; Coutinho, R. Effect of microhabitat distribution and substrate roughness on barnacle *Tetraclita stalactifera* (Lamarck, 1818) settlement. *Braz. Arch. Biol. Technol.* **2005**, *48*, 109–113. [CrossRef]
125. Bravo, M.; Astudillo, J.C.; Lancellotti, D.; Luna-Jorquera, G.; Valdivia, N.; Thiel, M. Rafting on abiotic substrata: Properties of floating items and their influence on community succession. *Mar. Ecol. Prog. Ser.* **2011**, *439*, 1–17. [CrossRef]
126. Whalan, S.; Abdul Wahab, M.A.; Sprungala, S.; Poole, A.J.; De Nys, R. Larval settlement: The role of surface topography for sessile coral reef invertebrates. *PLoS ONE* **2015**, *10*, e0117675. [CrossRef]
127. Delgado, A.; Richards, C.; Daly, P.; Power, S.; Briciu-Burghina, C.; Delauré, Y.; Regan, F. Assessment of Biofouling on Typical Marine Sensors Materials. In Proceedings of the OCEANS 2023-Limerick, Limerick, Ireland, 12 September 2023; pp. 1–8. [CrossRef]
128. Gizer, S.G.; Sahiner, N. The effect of sulphur on the antibacterial properties of succinic acid-Cu (II) and mercaptosuccinic acid-Cu (II) MOFs. *Inorg. Chim. Acta* **2021**, *528*, 120611. [CrossRef]
129. Connell, S.D.; Glasby, T.M. Do urban structures influence local abundance and diversity of subtidal epibiota? A case study from Sydney Harbour, Australia. *Mar. Environ. Res.* **1999**, *47*, 373–387. [CrossRef]
130. Shevalkar, M.; Mishra, A.; Meenambiga, S.S. A review on invasive species in marine biofouling. *Res. J. Pharm. Technol.* **2020**, *13*, 4517–4521. [CrossRef]
131. Tian, M.; Xu, H.; Yao, L.; Wang, R. A biomimetic antimicrobial surface for membrane fouling control in reverse osmosis for seawater desalination. *Desalination* **2021**, *503*, 114954. [CrossRef]
132. Venettacci, S.; Ponticelli, G.S.; Tagliaferri, F.; Guarino, S. Environmental and economic impact of an innovative biocide-free antifouling coating for naval applications. *Materials* **2023**, *16*, 748. [CrossRef] [PubMed]
133. Vuong, P.; McKinley, A.; Kaur, P. Understanding biofouling and contaminant accretion on submerged marine structures. *Npj Mater. Degrad.* **2023**, *7*, 50. [CrossRef]
134. Reise, K.; Buschbaum, C.; Büttger, H.; Wegner, K.M. Invading oysters and native mussels: From hostile takeover to compatible bedfellows. *Ecosphere* **2017**, *8*, e01949. [CrossRef]
135. Montalto, V.; Mangano, M.C.; Sarà, G.; Mangano, C.; Rinaldi, A.; Ape, F.; Mirto, S. Functional role of biofouling linked to aquaculture facilities in Mediterranean enclosed locations. *Aquac. Environ. Interact.* **2020**, *12*, 11–22. [CrossRef]
136. Marques, A.C.; Klôh, A.S.; Migotto, A.E.; Cabral, A.C.; Rigo, A.P.R.; Bettim, A.L.; Razzolini, M.L.; Matthews-Cascon, H.; Bardi, J.; Kremer, L.P.; et al. Rapid assessment survey for exotic benthic species in the São Sebastião Channel, Brazil. *Lat. Am. J. Aquat. Res.* **2013**, *41*, 265–285. [CrossRef]
137. Xavier, E.A.; Almeida, A.C.; Vieira, L.M. The role of artificial habitats on fouling bryozoan fauna in the southwestern Atlantic. *Mar. Pollut. Bull.* **2021**, *167*, 112310. [CrossRef]
138. Serrano, E.; Ribes, M.; Bolivar, M.; Coma, R. Fouling of a boat hull by the invasive zooxanthellate coral *Oculina patagonica*-could shipping be enhancing its unique large-scale spread? *Mediter. Mar. Sci.* **2023**, *24*, 76–86. [CrossRef]
139. Faccioli, Y.E.D.S.; de Oliveira, K.W.; Campos-Guerra, J.M.; Converti, A.; Soares da Silva, R.D.C.F.; Sarubbo, L.A. Biosurfactants: Chemical properties, ecofriendly environmental applications, and uses in the industrial energy sector. *Energies* **2024**, *17*, 5042. [CrossRef]
140. Karataş, A.R.; Kazak, H.; Akcan, A.T.; Akkaş, E.; Arık, M. A bibliometric mapping analysis of the literature on patent analysis. *World Pat. Inf.* **2024**, *77*, 102266. [CrossRef]
141. Yang, W.; Wang, X. The impact of patent protection on technological innovation: A global value chain division of labor perspective. *Technol. Forecast. Soc. Change* **2024**, *203*, 123370. [CrossRef]
142. Eilertsen, A.; Karlsen, K.; Haugereid, J. System and Method for Cleaning of Biofouling and Pathogens and Use of the System. WO Patent 2024151170, 18 July 2024.

143. Shimpo, C.; Takahashi, J. Membrane Treatment Method and Biofouling Suppression Method. WO Patent 2024128050, 20 June 2024.
144. Kim, Y.W. Biofouling Prevention System for Vessel. WO Patent 2024117880, 6 June 2024. Available online: https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2024117880&_cid=P20-MFWJNA-62883-1 (accessed on 12 June 2025).
145. Andersson, T. Reduction of Biofouling on Watercraft. WO Patent 2024094622, 10 May 2024.
146. Samaniego, A.M. Mixed Metal Oxide Coatings for Protecting Titanium Alloys from Biofouling. ES WO Patent 2024079222, 18 April 2024.
147. Feng, L.; Machado, C.J.; Park, K.C.K. Photocatalytic Surfaces for Anti-Biofouling. WO Patent 2024044665, 29 February 2024.
148. Abramo, G.P.; Jayaraman, A.; Demarest, V.A.; Fabiny, W.J.; Repollet, P.H. Roof Coating Resistant to Biofouling. EP Patent 4519372, 12 March 2025.
149. Samad, N.A. Controlling Biofouling in Water Purification. WO Patent 2023028503, 2 March 2023.
150. Kim, J.W. Biofouling Preventing Device for Ships and Method for Manufacturing Same. WO Patent 2022255578, 8 December 2022.
151. Barbosa, M.L.; Correia, E.S.; Rocha, L.S.N.; Almeida, E.S.; Meneses, M.S.; Jorge, C.E.S.; Oliveira, F.G.; Ledezma, L.C.M.; Silva, A.Q.; Oliveira, J.S.S.; et al. Underwater Robot for Removing Marine Biofouling from Hulls of Floating Units, with System for Containing and Capturing Waste. WO Patent 2022140831, 7 July 2022.
152. Salters, B.A.; Hietbrink, R.B.; Niessen, E.M.J.; Marsman, A.W. A Marine System Comprising an Anti-Biofouling Light Arrangement That Includes a Polarizing Device. EP Patent 4103468, 21 December 2022.
153. Hatch, M.; Fisher, J. Anti-Biofouling in Marine Applications Using UV Light Source. WO Patent 2021055500, 25 March 2021.
154. Baek, S.J.; Seo, J.M. Marine Biofouling Prevention Apparatus for Seawater Battery. WO Patent 2020013378, 16 January 2020.
155. Takashi, N.; Kappock, P.; Iwase, Y.; Schroeer, J.; Riegler, J.; Van Aken, P. Compositions for antifouling protection. JP Patent 2023126913A, 12 September 2023.
156. Zhao, J.; Chunguang, Y.; Ke, Y.; Jiqiang, W.; Xinyu, C.; Tianying, X. Stainless steel coating with marine organism fouling resistance function and preparation method thereof. CN Patent 114150306, 08 March 2022.
157. Tian, L.; Jin, H.; Wang, J.; Yin, Y.; Shang, Y.; Zhao, J.; Sun, J. Environment-friendly marine antifouling coating and preparation method thereof. CN Patent 112876984, 01 June 2021.
158. Ligeiro Barbosa, M.L.; Correia, E.S.; Rocha, L.S.N.; Almeida, E.S.; Meneses, M.S.; Jorge, C.E.S.; Oliveira, F.G.; Ledezma, L.C.M.; Silva, A.Q.S.; Oliveira, J.R.S. Integrated System for Removing and Treating Marine Biofouling on Submerged Metal Surfaces. NZ Patent 802311, 28 July 2023.
159. Liu, C.; Sun, J.; Duan, J. High-Transmittance Ultraviolet Antifouling Coating System with Embedded Ultraviolet LED Lamp Beads and Preparation Method Thereof. CN Patent 111117477, 8 May 2020.
160. Barbosa, M.L.; Correia, E.S.; Rocha, L.S.N.; Almeida, E.S.; Menezes, M.S.; Jorge, C.E.S.; Oliveira, F.G.; Ledezma, L.C.M.; Da Silva, A.Q.; Oliveira, J.R.S. Modular System for Treating Effluent from Cleaning Hulls of Floating Units. CA Patent 3203772, 7 July 2022.
161. Dasgupta, N.P.; Wang, J.; Tuteja, A. Transparent Nanowire Architectures for Marine Anti-Fouling. U.S. Patent 20210262089, 26 August 2021.
162. Yachen, C.; Wenjuan, J.; Hongzhi, L.; Yaqi, D.; Jihui, W. Environment-Friendly Antifouling Slow-Release Material as well as Preparation Method and Application Thereof. CN Patent 118085433, 7 August 2024.
163. Ri, Q.; Qiu, Z.; Jin, Z. Dispositivo e Método para Prevenção de Bioincrustação de Hélices Marinhas. CN Patent 111498071, 7 August 2020.
164. Pawar, S.S.; Naik, R.B.; Balasubramanian, K.; Malvankar, N.G.; Naik, R.S.; Rath, S.K.; Mahato, T.K. Stratified Poly Dimethyl Siloxane-Epoxy Coating Possessing Anticorrosive & Foul Release Properties in a Single Coat and Their Method of Preparation Thereof. IN Patent 202111011420, 18 November 2022.
165. Tang, H.; Wang, Y.; Ye, Q.; Yu, Z.; Chen, Y.; Zhu, J.; Zhang, Y.; Li, G. Antibacterial Polytitanilazane Coating Composition and Preparation Method Thereof. CN Patent 115558323, 3 January 2023.
166. Leijssen, J.J. Light Emitting Unit Configured to Be Applied to Surface Area of Marine Object. CN Patent 112771309, 7 May 2021.
167. Woelk, E. Apparatus and Methods to Prevent Biofouling. U.S. Patent 20210138519, 13 May 2021.
168. Kessel, R.; Carloni, C.; Coutinho, R.; Messano, L. Process for Biofouling Cohibition in Marine Environments. U.S. Patent 20210395900, 23 December 2021.
169. Xiangfeng, K.; Zhongliang, S.; Qian, W.; Guangli, H.; Dongzhi, C.; Conggang, W.; Yan, L.; Xuan, C.; Qingpeng, L. Biofouling Prevention Device for Marine Instrument. CN Patent 210146517, 13 March 2020.
170. Salters, B.A.; Hietbrink, R.B.; Niessen, E.M.J.; Marsman, A.W. Ocean System Comprising Device for Preventing Biofouling Light Comprising Polarizing Device. CN Patent 115087592, 20 September 2022.
171. Shixiong, C.; Guoqiang, L.; Xianwei, H. Marine Plastic Pipeline with High Impact Resistance, High Biofouling Resistance and High Wear Resistance and Preparation Method Thereof. CN Patent 112480520, 12 March 2021.
172. Yusuke, K. Biofouling Prevention Device. JP Patent 2024121088, 6 September 2024.
173. Dürr, S.; Shaw, A.; Moejes, K.B. Sensor Device. WO Patent 2024094996, 10 May 2024.

174. Baldaev, L.K.; Baldaev, S.L.; Mankovskij, S.A.; Kozlov, N.S.; Pavlov, A.Y.; Ishchenko, Y.N. Method for Producing a Coating with Low Surface Energy against Biofouling. RU Patent 0002760600, 29 November 2021.
175. Jung, K.K.; Han, W.B.; Son, J.H. Biofouling Prevention Film Structure Formed on Surface of Ship Structure. KR Patent 1020230066865, 16 May 2023.
176. Räftegård, V. A System for Mitigating Biofouling. SE Patent 2350663, 31 May 2023.
177. Hongying, Y.; Dizhu, Y.; Xuzhou, J.; Donbai, S. Biological Fouling Prevention Coating as Well as Preparation Method and Application Thereof. CN Patent 115521709, 27 December 2022.
178. Towson, J.D. Anti-Fouling Robot. WO Patent 2022268300, 29 December 2022.
179. MacDonald, J. An Apparatus for Vessel Drag Reduction and Planetary Cooling. AU Patent 2023204574, 27 July 2023.
180. Yi, P.; Hongyu, J.; Xiaoshuang, Y.; Jian, M.; Yong, F.; Jiawei, S.; Shengbo, Y. Preparation Method of Photocatalytic Material Composite Micro-Texture Anti-Microbial Attachment Surface. CN Patent 114985937, 2 September 2022.
181. Isaksson, D.; Hoffmann, M. Polímero e Composição Anti-Incrustante, Monômero Polimerizável, Artigo, Método para Produzir um Monômero de Medetomidina e um Polímero Anti-Incrustante. BR Patent 1120230074541 A2, 23 May 2023. Available online: https://busca.inpi.gov.br/pePI/servlet/PatenteServletController?Action=detail&CodPedido=1699432&SearchParameter=BR%201120230074541%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20&Resumo=&Titulo= (accessed on 16 June 2025).
182. Lopes, C.C.; Braga, E.F.; Lopes, R.S.C. Processo de Síntese por Via Úmida e Seca de Compostos Lisoglicerofosfocolinas e Seus Derivados O-Alquilados como Aditivos Biocidas em Revestimentos de Ação Anti-Incrustante. BR Patent 1020200200453 A2, 12 April 2022. Available online: https://busca.inpi.gov.br/pePI/servlet/PatenteServletController?Action=detail&CodPedido=1590395&SearchParameter=BR%201020200200453%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20&Resumo=&Titulo= (accessed on 21 June 2025).
183. Nakae, T.; Kappock, P.; Iwase, Y.; Schröer, J.; Riegler, J.; Aken, P. Composição Anti-Incrustação e Seu Uso, Tinta para Pintura Anti-Incrustação e Método para Inibir Bioincrustação Marinha. BR Patent 1120210097287 A2, 17 August 2021. Available online: https://busca.inpi.gov.br/pePI/servlet/PatenteServletController?Action=detail&CodPedido=1612269&SearchParameter=BR%201120210097287%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20&Resumo=&Titulo= (accessed on 14 June 2025).
184. Wang, Y. Has China Established a Green Patent System? Implementation of Green Principles in Patent Law. *Sustainability* **2022**, *14*, 11152. [CrossRef]
185. Lakshmi, V.V.; Akondi, K.B. Control of biofouling in marine environment—Past, present and future. *Int. J. Sci. Eng. Res.* **2015**, *6*, 283–286.
186. Zan, H. Research on the Impact of High-Tech Enterprise Certification Policy on Corporate Technological Innovation: An Empirical Study Based on Listed Company Data. *Adv. Econ. Manag. Polit. Sci.* **2024**, *87*, 9–23. [CrossRef]
187. Sánchez, D.; García, S.; Ruiz, A.; Boullosa-Falces, D.; Esteban, G. Antifouling and Anticorrosive Prevention with Ceramic Coatings on Offshore Structures for Renewable Energy. In Proceedings of the 15th European Wave and Tidal Energy Conference (EWTEC 2023), Bilbao, Spain, 3–7 September 2023. [CrossRef]
188. Satasiya, G.; Kumar, M.A.; Ray, S. Biofouling dynamics and antifouling innovations: Transitioning from traditional biocides to nanotechnological interventions. *Environ. Res.* **2025**, *269*, 120943. [CrossRef]
189. Borges, M.N. Ciência, Tecnologia e Inovação para o Desenvolvimento do Brasil. *Sci. Plena* **2016**, *12*, 1–11. [CrossRef]
190. Vasconcelos, C.R.D.; Silva, D.P.D. Intellectual property challenges for the roads of innovation in Brazil. *Innov. Manag. Rev.* **2019**, *16*, 185–192. [CrossRef]
191. Silva, L.C.S.; Oliveira Lima, V. Innovation and Technology Transfer Policies in the Brazilian Public Sector. In *Perspectives on Innovation and Technology Transfer in Managing Public Organizations*; Silva, L., Ed.; IGI Global: Hershey, PA, USA, 2024. [CrossRef]
192. Cavalcanti, M.; Neto, A.P. Inovação tecnológica no Brasil: Há uma pedra no meio do caminho. *Liinc Rev.* **2014**, *10*, 726–741. [CrossRef]
193. Tulyakova, I.R.; Gregova, E.; Dengov, V.V. Assessment of Competitiveness of Shipbuilding Industry in Russia. *NAŠE MORE Znan. Časopis Za More I Pomor.* **2017**, *64*, 112–119. [CrossRef]
194. Gizer, G.; Önal, U.; Manoj, K.R.; Sahiner, N. Biofouling and Mitigation Methods: A Review. *Biointerface Res. Appl. Chem.* **2022**, *13*, 185. [CrossRef]
195. Miromanova, A.; Hovhannisyan, N. To Innovate or Not to Innovate: International Sanctions and Their Impact on Patenting of Target Countries. *SSRN Prepr.* **2025**. [CrossRef]
196. Hellio, C. The potential of marine biotechnology for the development of new antifouling solutions. *Res. Paper* **2010**, *2*, 35–41.
197. Sommerscales, E.F.C.; Bergles, A.E. Enhancement of Heat Transfer and Fouling Mitigation. *Adv. Heat Transf.* **1997**, *30*, 197–253. [CrossRef]
198. Zhao, Y.J.; Wu, K.F.; Wang, Z.J.; Zhao, L.; Li, S.S. Fouling and cleaning of membrane-a literature review. *J. Environ. Sci.* **2000**, *12*, 241–251.

199. Bott, T.R. *Industrial Biofouling*; Elsevier: Oxford, UK, 2011.
200. Cabot, C.G. Compositions and Method for Inhibiting Biofouling and Barnacle Growth on Substrates under Water. U.S. Patent 20170275473, 28 September 2017.
201. Trueba, A.; Garcia, S.; Otero, F.M. Mitigation of biofouling using electromagnetic fields in tubular heat exchangers–condensers cooled by seawater. *Biofouling* **2014**, *30*, 95–103. [CrossRef] [PubMed]
202. Müller-Steinhagen, H.; Malayeri, M.R.; Watkinson, A.P. Heat exchanger fouling: Mitigation and cleaning strategies. *Heat Transf. Eng.* **2011**, *32*, 189–196. [CrossRef]
203. Peng, J.; Qiu, Y.; Gehr, R. Characterization of permanent fouling on the surfaces of UV lamps used for wastewater disinfection. *Water Environ. Res.* **2005**, *77*, 309–322. [CrossRef] [PubMed]
204. Chatzikonstantinou, K.; Tzamtzis, N.; Pappa, A.; Liodakis, S. Membrane fouling control using high-frequency power vibration, in an SMBR pilot system—Preliminary studies. *Desalin. Water Treat.* **2016**, *57*, 11550–11560. [CrossRef]
205. Benito, A.; Garcia, G.; Gonzalez-Olmos, R. Fouling reduction by UV-based pretreatment in hollow fiber ultrafiltration membranes for urban wastewater reuse. *J. Membr. Sci.* **2017**, *536*, 141–147. [CrossRef]
206. Zhao, F.; Chu, H.; Zhang, Y.; Jiang, S.; Yu, Z.; Zhou, X.; Zhao, J. Increasing the vibration frequency to mitigate reversible and irreversible membrane fouling using an axial vibration membrane in microalgae harvesting. *J. Membr. Sci.* **2017**, *529*, 215–223. [CrossRef]
207. Xing, J.; Liang, H.; Xu, S.; Chuah, C.J.; Luo, X.; Wang, T.; Wang, J.; Li, G.; Snyder, S.A. Organic matter removal and membrane fouling mitigation during algae-rich surface water treatment by powdered activated carbon adsorption pretreatment: Enhanced by UV and UV/chlorine oxidation. *Water Res.* **2019**, *159*, 283–293. [CrossRef]
208. Baudequin, C.; Mai, Z.; Rakib, M.; Deguerry, I.; Severac, R.; Pabon, M.; Couallier, E. Removal of fluorinated surfactants by reverse osmosis–role of surfactants in membrane fouling. *J. Membr. Sci.* **2014**, *458*, 111–119. [CrossRef]
209. Amjad, Z.; Koutsoukos, P.G.A. Current Review of Polymeric Dispersants and Their Practical Significance in Industrial Water Treatment. In Proceedings of the CORROSION 2019, Nashville, TN, USA, 24–28 March 2019. NACE-2019-12988.
210. Silva, M.G.C.; Medeiros, A.O.; Almeida, D.G.; Silva, M.E.P.; Meira, H.M.; Sarubbo, L.A. Application of green surfactants to control barnacle recruitment. *Reg. Stud. Mar. Sci.* **2021**, *45*, 101–854. [CrossRef]
211. Martensson, L.; Gunnarsson, F. Preventing Marine Biofouling by Inhibiting Adhesive Release from Barnacles. U.S. Patent 20060045864, 2 March 2006.
212. Isaksson, D.; Mårtensson Lindblad, L. Use of the Enantiomer Dexmedetomidine as Inhibitor for Marine Biofouling of Surfaces. WO Patent 2015011178, 20 January 2015.
213. Pereira, M.O.; Vieira, M.J.; Beleza, V.M.; Melo, L.F. Comparison of two biocides-carbamate and glutaraldehyde-in the control of fouling in pulp and paper industry. *Environ. Technol.* **2001**, *22*, 781–790. [CrossRef]
214. Liu, M.; Chen, Q.; Wang, L.; Yu, S.; Gao, C. Improving fouling resistance and chlorine stability of aromatic polyamide thin-film composite RO membrane by surface grafting of polyvinyl alcohol (PVA). *Desalination* **2015**, *367*, 11–20. [CrossRef]
215. Kasongo, G.; Steenberg, C.; Morris, B.; Kapenda, G.; Jacobs, N.; Aziz, M. Surface grafting of polyvinyl alcohol (PVA) cross-linked with glutaraldehyde (GA) to improve resistance to fouling of aromatic polyamide thin film composite reverse osmosis membranes using municipal membrane bioreactor effluent. *Water Pract. Technol.* **2019**, *14*, 614–624. [CrossRef]
216. Paradas, W.C.; Filho, G.M.A. Are metals of antifouling paints transferred to marine biota. *Braz. J. Oceanogr.* **2007**, *55*, 51–56. [CrossRef]
217. Joshi, M.; Mukherjee, A.; Misra, S.C.; Ramesh, U.S. Natural biocides in antifouling paints. *Technol. Innovat. Shipbuild.* **2013**, *12*, 1–11.
218. Campos, B.G.; Figueiredo, J.; Perina, F.; Abessa, D.M.D.S.; Loureiro, S.; Martins, R. Occurrence, effects and environmental risk of antifouling biocides (EU PT21): Are marine ecosystems threatened? *Crit. Rev. Environ. Sci. Technol.* **2022**, *52*, 3179–3210. [CrossRef]
219. Zheng, J.; Lin, C.; Duan, D. Method for Preparing Ulva pertusa Kjellm Extract for Marine Antifoulant. CN Patent 101564050, 28 October 2009.
220. Characklis, W.G. Bioengineering report: Fouling biofilm development: A process analysis. *Biotechnol. Bioeng.* **1981**, *23*, 1923–1960. [CrossRef]
221. Dobretsov, S.; Dahms, H.U.; Qian, P.Y. Inhibition of biofouling by marine microorganisms and their metabolites. *Biofouling* **2006**, *22*, 43–54. [CrossRef]
222. Ma, Y.; Liu, P.; Yu, S.; Li, D.; Cao, S. Inhibition of common fouling organisms in mariculture by epiphytic bacteria from the surfaces of seaweeds and invertebrates. *Acta Ecol. Sin.* **2009**, *29*, 222–226. [CrossRef]
223. Zuo, Y.; Shao, Y.; Wang, L.; Sun, Y.; An, Y.; Jiang, L.M.; Yu, N.; Hao, R.; Zhou, C.; Tá, J.; et al. Simultaneous sludge minimization and membrane fouling mitigation in membrane bioreactors by using a microaerobic-Settling pretreatment module. *J. Environ. Manag.* **2023**, *328*, 116977. [CrossRef]

224. Al-Amoudi, A.; Lovitt, R.W. Fouling strategies and the cleaning system of NF membranes and factors affecting cleaning efficiency. *J. Membr. Sci.* **2007**, *303*, 4–28. [CrossRef]
225. Krause, S.; Zimmermann, B.; Meyer-Blumenroth, U.; Lamparter, W.; Siembida, B.; Cornel, P. Enhanced membrane bioreactor process without chemical cleaning. *Water Sci. Technol.* **2010**, *61*, 2575–2580. [CrossRef] [PubMed]
226. Erol, E.; Cansoy, C.E.; Aybar, O.Ö. Assessment of the impact of fouling on vessel energy efficiency by analyzing ship automation data. *Appl. Ocean Res.* **2020**, *105*, 102418. [CrossRef]
227. Hellio, C.; Yebra, D. (Eds.) *Advances in Marine Antifouling Coatings and Technologies*; Elsevier: Cambridge, UK, 2009.
228. Sullivan, T.; O'Callaghan, I. Recent developments in biomimetic antifouling materials: A review. *Biomimetics* **2020**, *5*, 58. [CrossRef]
229. Banerjee, S.; Das, A.; Das, R.; Bhattacharjee, C. Mesoporous Mg–Al–Ti Composite oxide incorporated mixed matrix ultrafiltration membrane with superior multi-heavy metal removal capacity, anti-fouling & anti-microbial property. *J. Membr. Sci.* **2024**, *703*, 122836. [CrossRef]
230. Ramotowski, T.S. Method and Apparatus for Preventing Biofouling of Surfaces. U.S. Patent 8309625, 13 November 2012.
231. Epstein, N. Thinking about Heat Transfer Fouling: A 5 × 5 Matrix. *Heat Transf. Eng.* **1983**, *4*, 43–56. [CrossRef]
232. Panchal, C.B.; Knudsen, J.G. Mitigation of water fouling: Technology status and challenges. *Adv. Heat Transf.* **1998**, *31*, 431–474. [CrossRef]
233. Kazi, S.N. Fouling and fouling mitigation on heat exchanger surfaces. Fouling and fouling mitigation on heat exchanger surfaces. In *Heat Exchangers-Basics Design Applications*; Mitrović, J., Ed.; Intechopen: Berlin, Germany, 2012; p. 600. [CrossRef]
234. Albuquerque Filho, L.H.; Casagrande, M.D.T.; Almeida, M.S.d.S.; Costa, W.G.S.; Santana, P.R.L.d. Mechanical Performance and Life Cycle Assessment of Soil Stabilization Solutions for Unpaved Roads from Northeast Brazil. *Sustainability* **2024**, *16*, 9850. [CrossRef]
235. Poohphajai, F.; Gubenšek, A.; Černoša, A.; Butina Ogorelec, K.; Rautkari, L.; Sandak, J.; Sandak, A. Bioinspired Living Coating System for Wood Protection: Exploring Fungal Species on Wood Surfaces Coated with Biofinish during Its Service Life. *Coatings* **2024**, *14*, 430. [CrossRef]
236. Lee, S.; Shon, H.K.; Hong, S. Dewatering of activated sludge by forward osmosis (FO) with ultrasound for fouling control. *Desalination* **2017**, *421*, 79–88. [CrossRef]
237. Fortunato, H.F.; Figueira, R.M.; de Souza, R.F.; Theodoro Junior, N.; Mello, V.B. Artificial intelligence as an ally to assess and manage the golden mussel (*Limnoperna fortunei* (Dunker, 1857)) bioinvasion. *Aquat. Sci.* **2025**, *87*, 53. [CrossRef]
238. Zeidan, G.C.; Boehs, G. Assessment of tributyltin contamination based on imposex in *Stramonita rustica* (Mollusca: Gastropoda) along southern Bahia coast, northeastern Brazil. *Braz. J. Biol.* **2017**, *77*, 185–190. [CrossRef]
239. Goldeberg, E.D. TBT: An environmental dilemma. *Environ. Sci. Policy Sustain. Dev.* **1986**, *28*, 17–44. [CrossRef]
240. Kotrikla, A. Environmental management aspects for TBT antifouling wastes from the shipyards. *J. Environ. Manag.* **2009**, *90*, S77–S85. [CrossRef] [PubMed]
241. Selim, M.S.; El-Safty, S.A.; Shenashen, M.A.; Higazy, S.A.; Elmarakbi, A. Progress in biomimetic leverages for marine antifouling using nanocomposite coatings. *J. Mater. Chem. B* **2020**, *8*, 3701–3732. [CrossRef]
242. Alonso Felipe, J.V. Evaluation of the Effects of Biocides in Antifouling Coatings (AF Coatings) on Marine Ecosystems. Master's Thesis, E.T.S.I. Minas, Universidad Politécnica de Madrid, Madrid, Spain, 2011.
243. Elia, A.C.; Magara, G.; Pastorino, P.; Zaccaroni, A.; Caldaroni, B.; Andreini, R.; Righetti, M.; Silvi, M.; Dörr, A.J.M.; Prearo, M. Ecotoxicity in *Hyriopsis bialatus* of copper and zinc biocides used in metal-based antifouling paints. *Environ. Sci. Pollut. Res.* **2022**, *29*, 18245–18258. [CrossRef]
244. Ferreira, A.M.P.; Matos, J.M.; Silva, L.K.; Viana, J.L.M.; Freitas, M.S.D.; Amarante Júnior, O.P.; Franco, T.C.R.S.; Brito, N.M. Assessing the spatiotemporal occurrence and ecological risk of antifouling biocides in a Brazilian estuary. *Environ. Sci. Pollut. Res.* **2024**, *31*, 3572–3581. [CrossRef]
245. Paz-Villarraga, C.A.; Castro, Í.B.; Fillmann, G. Biocides in antifouling paint formulations currently registered for use. *Environ. Sci. Pollut. Res.* **2022**, *29*, 30090–30101. [CrossRef]
246. International Maritime Organization. *Resolution A.774(18), Guidelines for Preventing the Introduction of Unwanted Aquatic Organisms and Pathogens from Ships' Ballast Water and Sediment Discharges*; Adopted by the 18th Assembly; IMO: London, UK, 4 November 1993.
247. International Maritime Organization. *Resolution A.868(20): Guidelines for the Control and Management of Ships' Ballast Water to Minimize the Transfer of Harmful Aquatic Organisms and Pathogens*; Adopted by the 20th Assembly; IMO: London, UK, 27 November 1997.
248. Riadh, M. Preventing Marine Pollution through MARPOL: Enhancing Protection for Coastal Ecosystems and Mangroves. *Collab. Eng. Dly. Book Ser.* **2024**, *2*, 125–130. [CrossRef]
249. Horiguchi, T. Ecotoxicological Impacts of Organotins: An Overview. In *Biochemical and Biological Effects of Organotins*, 1st ed.; Pagliarani, A., Trombetti, F., Ventrella, V., Eds.; Bentham Science Publishers: Sharjah, United Arab Emirates, 2012; pp. 3–24. [CrossRef]
250. Muadtrap, M.; Thiramanas, R.; Crespy, D. Amphiphilic materials for advanced antifouling and anticorrosion coatings. *Prog. Org. Coat.* **2025**, *207*, 109391. [CrossRef]

251. Wei, C.; Zhang, Y.; Tang, Z.; Zhang, C.; Wu, J.; Wu, B. Surface Reconstruction of Silicone-Based Amphiphilic Polymers for Mitigating Marine Biofouling. *Polymers* **2024**, *16*, 1570. [CrossRef] [PubMed]
252. Jeong, J.; Do, J.; Kang, S.M. Polydopamine-Mediated, Amphiphilic Poly (Carboxybetaine Methacrylamide-r-Trifluoroethyl Methacrylate) Coating with Resistance to Marine Diatom Adhesion and Silt Adsorption. *Adv. Mater. Interfaces* **2024**, *11*, 2300871. [CrossRef]
253. Callow, J.A.; Callow, M.E. Trends in the development of environmentally friendly fouling-resistant marine coatings. *Nat. Commun.* **2011**, *2*, 244. [CrossRef] [PubMed]
254. Gu, Y.; Zhou, S.; Luo, H.; Wu, L.; Gao, W.; Yang, J. Temperature-dependent phase-segregation behavior and antifouling performance of UV-curable methacrylated PDMS/PEG coatings. *J. Polym. Sci. Part B Polym. Phys.* **2016**, *54*, 1612–1623. [CrossRef]
255. Chen, Y.; Song, Q.; Zhao, J.; Gong, X.; Schlaad, H.; Zhang, G. Betulin-constituted multiblock amphiphiles for broad-spectrum protein resistance. *ACS Appl. Mater. Interfaces* **2018**, *10*, 6593–6600. [CrossRef] [PubMed]
256. Tian, S.; Zhang, J.; Liu, S.; Li, J.; Pu, J.; Hao, Y.; Ying, G.; Xue, Q.; Lu, G. An Integrated Anti-Fouling and Anti-Corrosion Coating Enabled by RGO/AgNPs and Amphiphilic Networks. *Engineering* **2024**, *42*, 223–234. [CrossRef]
257. Li, Y.; Liao, J.; Zhang, H.; Tang, X.; Zhong, S.; Yu, Y.; Li, Q. Super-structural 2D ultrathin carbon nitride/acrylate boron silane polymer with multi-function for enhancing antifouling performance. *J. Coat. Technol. Res.* **2021**, *18*, 1051–1064. [CrossRef]
258. Benda, J.; Stafslien, S.; Vanderwal, L.; Finlay, J.A.; Clare, A.S.; Webster, D.C. Surface modifying amphiphilic additives and their effect on the fouling-release performance of siloxane-polyurethane coatings. *Biofouling* **2021**, *37*, 309–326. [CrossRef]
259. Yan, D.; Lin, J.; Zhang, B.; Zhang, S.; Ling, S.; Song, J. Drag reduction and antifouling of a spontaneous fast moving air film. *J. Mater. Chem. A* **2024**, *30*, 19268–19276. [CrossRef]
260. Lin, J.; Wang, X.; Wang, H.; Sun, Z.; Yan, D.; Song, J. High drag reduction by spontaneous capture and transportation of bubbles. *Nanoscale* **2025**, *17*, 10892–10900. [CrossRef]
261. Yan, D.; Lu, Y.; Lin, J.; Li, W.; Song, J. Enhancing water transportation capacity by asymmetrical patterned surface with super-wettability. *Appl. Phys. Lett.* **2024**, *125*, 071601. [CrossRef]
262. Pu, X.; Li, G.; Huang, H. Preparation, anti-biofouling and drag-reduction properties of a biomimetic shark skin surface. *Biol. Open* **2016**, *5*, 389–396. [CrossRef] [PubMed]
263. Rostami, S.; Garipcan, B. Evolution of antibacterial and antibiofouling properties of sharkskin-patterned surfaces. *Surf. Innov.* **2022**, *10*, 165–190. [CrossRef]
264. Zhang, P.; Lin, L.; Zang, D.; Guo, X.; Liu, M. Designing bioinspired anti-biofouling surfaces based on a superwettability strategy. *Small* **2017**, *13*, 1503334. [CrossRef] [PubMed]
265. Zhu, G.H.; Cho, S.H.; Zhang, H.; Zhao, M.; Zacharia, N.S. Slippery liquid-infused porous surfaces (SLIPS) using layer-by-layer polyelectrolyte assembly in organic solvent. *Langmuir* **2018**, *34*, 4722–4731. [CrossRef]
266. Richards, C.; Slaimi, A.; O'Connor, N.E.; Barrett, A.; Kwiatkowska, S.; Regan, F. Bio-inspired Surface Texture Modification as a Viable Feature of Future Aquatic Antifouling Strategies: A Review. *Int. J. Mol. Sci.* **2020**, *21*, 5063. [CrossRef]
267. Subbaiyan, R.; Ganesan, A.; Varadharajan, V. Bioprospecting and exploration of the natural antifouling approaches against marine foulers. *J. Pure Appl. Microbiol.* **2023**, *17*, 1374–1390. [CrossRef]
268. Acervado, M.S.; Puentes, C.; Carreño, K.; León, J.G.; Stupak, M.; García, M.; Pérez, M.; Blustein, G. Antifouling paints based on marine natural products from Colombian Caribbean. *Int. Biodeterior. Biodegrad.* **2013**, *83*, 97–104. [CrossRef]
269. Aldred, N.; Phang, I.Y.; Conlan, S.L.; Clare, A.S.; Vancso, G.J. The effects of a serine protease, Alcalase®, on the adhesives of barnacle cyprids (*Balanus amphitrite*). *Biofouling* **2008**, *24*, 97–107. [CrossRef] [PubMed]
270. Pettitt, M.E.; Henry, S.L.; Callow, M.E.; Callow, J.A.; Clare, A.S. Activity of commercial enzymes on settlement and adhesion of cypris larvae of the barnacle *Balanus amphitrite*, spores of the green alga *Ulva linza*, and the diatom *Navicula perminuta*. *Biofouling* **2004**, *20*, 299–311. [CrossRef] [PubMed]
271. Ashbridge, Z.; Fielden, S.D.; Leigh, D.A.; Pirvu, L.; Schaufelberger, F.; Zhang, L. Knotting matters: Orderly molecular entanglements. *Chem. Soc. Rev.* **2022**, *51*, 7779–7809. [CrossRef]
272. Cappitelli, F.; Salvadori, O.; Albanese, D.; Villa, F.; Sorlini, C. Cyanobacteria cause black staining of the National Museum of the American Indian Building, Washington, DC, USA. *Biofouling* **2012**, *28*, 257–266. [CrossRef]
273. Rolin, C.; Inkster, R.; Laing, J.; McEvoy, L. Regrowth and biofouling in two species of cultivated kelp in the Shetland Islands, UK. *J. Appl. Phycol.* **2017**, *29*, 2351–2361. [CrossRef]
274. Szewczyk, P. The role of nanotechnology in improving marine antifouling coatings. *Zesz. Nauk. Akad. Morskiej Szczecinie* **2010**, *24*, 118–123.
275. Liu, X.; Zhou, J.; Bai, X.; Cao, P. Research Progress on New Environmentally Friendly Antifouling Coatings in Marine Settings: A Review. *Biomimetics* **2023**, *8*, 200. [CrossRef]
276. Zhang, L.; Wang, L.; Zhang, Y.; Wang, D.; Guo, J.; Zhang, M.; Li, Y. The performance of electrode ultrafiltration membrane bioreactor in treating cosmetics wastewater and its anti-fouling properties. *Environ. Res.* **2022**, *206*, 112629. [CrossRef]

277. El-Wahab, H.A.; Al-Shareef, H.F. Novel antifouling paint formulation based on $Ca_2Cr_2O_5$ and $CaMnO_3$ NPs as a protective pigment. *Sci. Rep.* **2024**, *14*, 24474. [CrossRef]
278. Holmström, C.; Kjelleberg, S. Marine *Pseudoalteromonas* species are associated with higher organisms and produce biologically active extracellular agents. *FEMS Microbiol. Ecol.* **1999**, *30*, 285–293. [CrossRef] [PubMed]
279. Holmström, C.; Egan, S.; Franks, A.; McCloy, S.; Kjelleberg, S. Antifouling activities expressed by marine surface associated *Pseudoalteromonas* species. *FEMS Microbiol. Ecol.* **2002**, *41*, 47–58. [CrossRef] [PubMed]
280. Maréchal, J.P.; Hellio, C. Challenges for the development of new non-toxic antifouling solutions. *Int. J. Mol. Sci.* **2009**, *10*, 4623–4637. [CrossRef] [PubMed]
281. Kalinovskaya, N.I.; Ivanova, E.P.; Alexeeva, Y.V.; Gorshkova, N.M.; Kuznetsova, T.A.; Dmitrenok, A.S.; Nicolau, D.V. Low-molecular-weight, biologically active compounds from marine *Pseudoalteromonas* species. *Curr. Microbiol.* **2004**, *48*, 441–446. [CrossRef]
282. Muhammad, A.; Kashere, M.A. Neem, *Azadirachta indica L.*(A. Juss): An eco-friendly botanical insecticide for managing farmersâ€™ insects pest problems-a review. *FUDMA J. Sci.* **2020**, *4*, 484–491. [CrossRef]
283. Mancillas-Salas, S.; Ledón-Smith, J.Á.; Pérez-Álvarez, M.; Cadenas-Pliego, G.; Mata-Padilla, J.M.; Andrade-Guel, M.; Esparza-González, S.C.; Vargas-Gutiérrez, G.; Sierra-Gómez, U.A.; Saucedo-Salazar, E.M. Nanostructured Copper Selenide Coatings for Antifouling Applications. *Polymers* **2024**, *16*, 489. [CrossRef]
284. Maria, V.L.; Barreto, A. Ecotoxicity Assessment of Nanomaterials: Latest Advances and Prospects. *Nanomaterials* **2024**, *14*, 326. [CrossRef]
285. Boros, B.-V.; Ostafe, V. Evaluation of Ecotoxicology Assessment Methods of Nanomaterials and Their Effects. *Nanomaterials* **2020**, *10*, 610. [CrossRef] [PubMed]
286. Perina, F.; Ottoni, C.; Santos, J.; Santos, V.; Silva, M.; Campos, B.; Fontes, M.; Santana, D.; Maia, F.; Abessa, D.; et al. Marine Hazard Assessment of Soluble and Nanostructured Forms of the Booster Biocide DCOIT in Tropical Waters. *Water* **2023**, *15*, 1185. [CrossRef]
287. Yang, H.; Xu, Z.; Xu, Z.; Li, Y. Mini-Review of Biofilm Interactions with Surface Materials in Industrial Piping System. *Membranes* **2023**, *13*, 125. [CrossRef]
288. Sánchez, M.C.; Alonso-Español, A.; Ribeiro-Vidal, H.; Alonso, B.; Herrera, D.; Sanz, M. Relevance of Biofilm Models in Periodontal Research: From Static to Dynamic Systems. *Microorganisms* **2021**, *9*, 428. [CrossRef]
289. AlSawaftah, N.; Abuwatfa, W.; Darwish, N.; Husseini, G.A. A Review on Membrane Biofouling: Prediction, Characterization, and Mitigation. *Membranes* **2022**, *12*, 1271. [CrossRef]
290. Wang, J.; Li, L.; Wu, Y.; Liu, Y. Design and Application of Antifouling Bio-Coatings. *Polymers* **2025**, *17*, 793. [CrossRef]
291. Faria, S.I.; Teixeira-Santos, R.; Romeu, M.J.; Morais, J.; Jong, E.d.; Sjollema, J.; Vasconcelos, V.; Mergulhão, F.J. Unveiling the Antifouling Performance of Different Marine Surfaces and Their Effect on the Development and Structure of Cyanobacterial Biofilms. *Microorganisms* **2021**, *9*, 1102. [CrossRef]
292. Lee, M.-S.; Hussein, H.R.; Chang, S.-W.; Chang, C.-Y.; Lin, Y.-Y.; Chien, Y.; Yang, Y.-P.; Kiew, L.-V.; Chen, C.-Y.; Chiou, S.-H.; et al. Nature-Inspired Surface Structures Design for Antimicrobial Applications. *Int. J. Mol. Sci.* **2023**, *24*, 1348. [CrossRef] [PubMed]
293. Suprobo, Y.; Riyanto, R.; Herawati, S. Sustainable biofouling mitigation: Advancing maritime efficiency and environmental protection. *J. Pendidik. Biol. Indones.* **2025**, *11*, 208–217. [CrossRef]
294. Zhou, J. Composite Coating for Preventing Marine Biofouling and Spraying Method Thereof. WO Patent 2012136127, 11 October 2012.
295. Tian, L.; Jin, E.; Ke, Q.; Shang, Y.; Li, Y.; Sun, H.; Liu, Y.; Ren, L. Method for Preventing Marine Biofouling by Using Principle of Harmonic Vibration. U.S. Patent 20170158876, 8 June 2017.
296. Chang-Lun, S.; Xiao-Feng, M.; Mei-Yan, W. A kind of nitrogenous compound and preparation method thereof and application as marine antifoulant. CN Patent 108658975A, 16 October 2018.
297. Wang, L.; Lin, C. Preparation Method of Self-Polishing Enzyme-Based Antifouling Paint. CN Patent 104774519, 15 July 2015.
298. Ren, X. Novel Antifouling Agent Composite Paint Applied to a Soluble Antifouling Paint. CN Patent 104710936A, 17 June 2015.
299. Qian, P.; Huang, X.; Xu, Y.; Zhang, Y.; Wong, Y.H.; Yin, Y.; Han, Z. Use of Amide Compounds for Preventing Marine Biofouling. U.S. Patent 20140044810, 13 February 2014.
300. Salamanca, C.E.R. Bacterial Product from Marine Origin, Useful for Preventing the Macro and Micro Biofouling Caused by Macroalgae and Marine Invertebrates. EP Patent 1811848, 1 August 2007.
301. Messersmith, P.B.; Lee, H.; Statz, A.R.; Lee, B.P.; Dalsin, J.L.; Sherman, D. Surface Independent, Surface-Modifying, Multifunctional Coatings and Applications Thereof. U.S. Patent 20100330025, 30 December 2010.
302. Claes, M.; Bonduel, D.; Dubois, P.; Beigbeder, A.; Devalckenaere, M. Anti-Adhesive and Anti-Static Composition. EP Patent 1914277A1, 23 April 2008.
303. Vladkova, T.G.; Dineff, P.D.; Zlatanov, I.Y.; Kathioli, S.; Ramasammy, V.; Vasudeva, P.S.M. Composition Coating for Biofouling Protection. WO Patent 2008074102, 26 June 2008.

304. Hannah, J.; Hartshorne, R.S.; Neser, D.; Tustin, G.J. Systems and Methods for Marine Anti-Fouling. AU Patent 2010329601, 5 July 2019.
305. Hartshorne, R.S.; Tustin, G.J.; Westwood, J.F.; Gahlings, S.A. Systems and Methods for Marine Anti-Fouling. U.S. Patent 20120321809, 20 December 2012.
306. Lee, C.G.; Kim, K.M.; Lim, S.M.; Lee, Y.W.; Park, H.W.; Jeong, I.J.; Park, J.H. Fotobiorreator Marinho Flutuante. KR Patent 1019589380000, 15 March 2019.
307. Becker, A.T.; Stiblo, G.K. Paint Coating. RU Patent 0002648082, 22 March 2018.
308. Grozea, C.M.; Walker, G.C. Nanostructured Block Copolymer Films for Inhibition of Marine Organism Attachment to Surfaces. WO Patent 2010045728, 29 April 2010.
309. Grozea, C.M.; Walker, G.C. Block Copolymer Morphology Trapping in Thin Films Using Low Temperature Treatment and Annealing for Inhibition of Marine Organism Attachment to Surfaces. U.S. Patent 20110104452, 5 May 2011.
310. Lobe, H.; Knapp, J.; Das, A.K.; Moffat, G. Optically Clear Biofouling Resistant Compositions and Methods for Marine Instruments. U.S. Patent 20100278771, 4 November 2010.
311. Lee, H. Multiscale Microdevices with Nanopillars for Chronically Implanted Devices. U.S. Patent 20190313955, 17 September 2019.
312. Tsuruta, N.; Yamashita, M.; Shinohara, H.; Hamada, K.; Fukutomi, T.; Furusawa, H.; Takizawa, M.; Yoshikawa, Y.; Nakamura, M. Anti-Biofouling Agent, Anti-Fouling Coating, Anti-Fouling Treatment Method, and Anti-Foulingly Treated Material. WO Patent 2007116912, 18 October 2007.
313. Suzuki, S.; Tomoya, N.; Takeshi, H.; Kazuko, A.; Naoki, K. Adhesive Tape for Preventing Aquatic Biofouling. JP Patent 2018048331, 29 March 2018.
314. Letchford, G. Improved Process of Preventing Marine Bio-Foul. AU Patent 2012100045, 2 February 2012. Available online: https://patentscope.wipo.int/search/en/detail.jsf?docId=AU181568567&_cid=P20-MFWKDZ-85176-1 (accessed on 26 June 2025).
315. Gopalan, S.; Pitchai, V.; Seeni, P. An Apparatus for the Prevention of Biofouling. IN Patent 2162/DEL/2006—Concession 267686, 25 April 2008.
316. Zheng, J.; Cunguo, L.; Zhenghui, Q.; Ri, Q. Cathode Probe for Electrochemical Monitoring of Microscopic Biofouling, Real-Time and In-Situ Electrochemical Monitoring Device and Method for Microscopic Biofouling. CN Patent 109030603, 18 December 2018.
317. Kuik, S.H.; Chew, T.T.; Chew, H.H.; Chua, C.Y. System and Method of Ballast Water Treatment with Continuous Biofouling Control. EP Patent 2890610, 8 July 2015.
318. Otvalko, Z.A.; Railkin, A.I.; Tverdov, A.I.; Korotkov, S.I.; Fomin, S.E.; Rudakova, E.V. Method for Protection From Biofouling. RU Patent 0002588253, 31 March 2015. Available online: https://patentscope.wipo.int/search/en/detail.jsf?docId=RU174259979&_cid=P21-MG9N42-86954-1 (accessed on 27 June 2025).
319. Kee-Rong, W.; Yu-Tsuen, S.; Chung-Hsuang, H.; Jiing-Kae, W.; Chiung-Wei, Y.; Shun-Hsyung, C. Apparatus Using an Electro-Catalytic Coating to Reduce Ship's Friction and Prevent Biofouling. U.S. Patent 20140331912, 13 November 2014.
320. Nyberg-Swenson, B.A. A Method and a Surface Treatment Agent for Preventing Biofouling on Surfaces Under Water. EP Patent 1578874, 28 September 2005.
321. Shilova, O.A.; Railkin, A.I.; Efimova, L.N.; Shevchenko, V.Y. Coating Composition for Protecting Underwater Surfaces from Biofouling. RU Patent 0002606777, 10 January 2017.
322. Salters, B.A. Dithered Marine UV Reflective Coating with Color. IN Patent 201847002494, 30 March 2018.
323. Matveev, V.A.; Kolesnik, G.V. Coating for Protecting the Submerged Surface of Ships Against Biofouling. WO Patent 2009113893, 17 September 2009.
324. Jinwei, Z.; Cunguo, L.; Deyu, L.; Zhiyong, S.; Li, W. A kind of preparation method of hydrophilic and hydrophobic interactive distribution microstructure surface. CN Patent 109337105, 15 February 2019.
325. Pelzer, R.; Wöhrle, I. Non-Toxic Coating Composition, Methods of Use Thereof and Articles Protected from Attachment of Biofouling Organisms. NZ Patent 542883, 21 December 2007.
326. Guo, X.; Su, X.; Hao, D. Hydrogel Capable of Being used for Marine Antifouling, Preparation Method and Uses Thereof. CN Patent 110358006, 22 October 2019.
327. Koob, T.J. Method of Preventing Biofouling Using an Anti-Fouling bio-Hydrogel Composition. U.S. Patent 8603452, 10 December 2013.
328. Van Delden, M. Device for protecting a protected surface against soiling. CN Patent 110214057, 6 September 2019.
329. Hietbrink, R.B.; Salters, B.A. Marine Cable Device Configured to Prevent Fouling. RU Patent 0002695939, 29 July 2019.
330. Ober, C.K.; Weinman, C.J.; Park, D.; Handlin, D.L. Coatings to Prevent Biofouling of Surfaces. U.S. Patent 20120244369, 27 September 2012.
331. Kem, W.R.; Soti, F.; Rittschof, D. Materials and Methods for Inhibiting Fouling of Surfaces Exposed to Aquatic Environments. U.S. Patent 20050159454, 21 July 2005.
332. Gallardo, M.; Maurel, S.; Pale, M.; Courtois, A.; Thollas, B. Process for Preventing the Formation of Biofouling on Material in Contact with an Aqueous Medium. EP Patent 3411443, 12 December 2018.
333. Hu, W. Antifouling Paint for Fishing Gear. CN Patent 105949398, 21 September 2016.

334. Qiu, J.; De Rijk, R.B.M.; Thies, J.C. Antifouling Coating Composition Comprising Functionalized Nanoparticles. EP Patent 2346952, 27 July 2011.
335. Weed, G. Revestimento Anti-Bio-Incrustação Marinha, Método de Aplicação de Um Revestimento Anti-Bio-Incrustação Marinha. BRPI Patent 0417488-7B1, 22 March 2007.