Review of the Main Parameters for the Development of Antifouling Supports

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Marine biofouling is the process by which organisms such as barnacles, mollusks, algae, and corals attach themselves to submerged surfaces, compromising the performance of structures such as ship hulls, sensors, and pipes. This accumulation increases hydrodynamic resistance, raises fuel consumption, and favors the spread of invasive species. To mitigate these effects, anti-fouling coatings began to be used, initially formulated with highly toxic biocides such as tributyltin (TBT) and triphenyltin (TPT). However, due to the prolonged environmental impacts of these compounds, their use was banned. Given this scenario, alternatives based on natural compounds, polymers, bio-inspired surfaces, and nanoparticles have emerged. This study aimed to conduct a systematic review of the literature to identify the main parameters involved in the development of anti-fouling coatings applied in marine environments. The search was conducted in the ScienceDirect, Scopus, Web of Science, PubMed, and SciELO databases, using the keyword "antifouling," with no time restriction. Approaches regarding material types, physicochemical properties, evaluation methods, and technical gaps were analyzed. VOSviewer software was used to map trends through keyword analysis. The results indicated a significant growth in publications from 2020 onwards, with contributions from China, the United States, and Brazil standing out. The review identified technological approaches, as well as testing standards that seek to ensure effectiveness, durability, and environmental safety. Despite advances, challenges such as field validation and the long-term durability of coatings remain significant obstacles.
Keywords: Marine Biofouling. Antifouling. Coating, Biocides.

Marine biofouling is a natural process in which organisms such as barnacles, mollusks, corals, mussels, and algae attach themselves to submerged surfaces, such as ship hulls, industrial structures, filtration membranes, and sensors, compromising their performance and integrity [1].

The accumulation of these organisms increases hydrodynamic resistance, raises fuel consumption, and intensifies carbon emissions, in addition to favoring the spread of invasive species [2]. In structures such as pipes and sensors, biofouling reduces efficiency, increases maintenance frequency, and shortens the useful life of surfaces [3]. Conventional anti-fouling coatings have made extensive use of highly toxic biocides, such as tributyltin (TBT), widely recognized as the most effective compound ever developed for this purpose. However, its serious environmental impacts, including toxicity to marine organisms, led to its total ban in 2008 by the International Maritime Organization (IMO] [4]. Considering the environmental damage associated with the use of toxic compounds in anti-fouling coatings, it is essential to develop solutions that are truly non-toxic and environmentally safe. To achieve this goal, it is essential to adopt multidisciplinary approaches that integrate knowledge of chemistry and physics, whose interactions contribute to the development of more effective anti-fouling strategies. The objective of this study was to conduct a systematic review of the literature focusing on the main parameters involved in the development of anti-fouling supports with low environmental impact applied to marine environments. The study sought to identify technological trends, characteristics of the materials used, and challenges faced, based on the analysis of scientific publications and keyword mapping performed with VOSviewer software.

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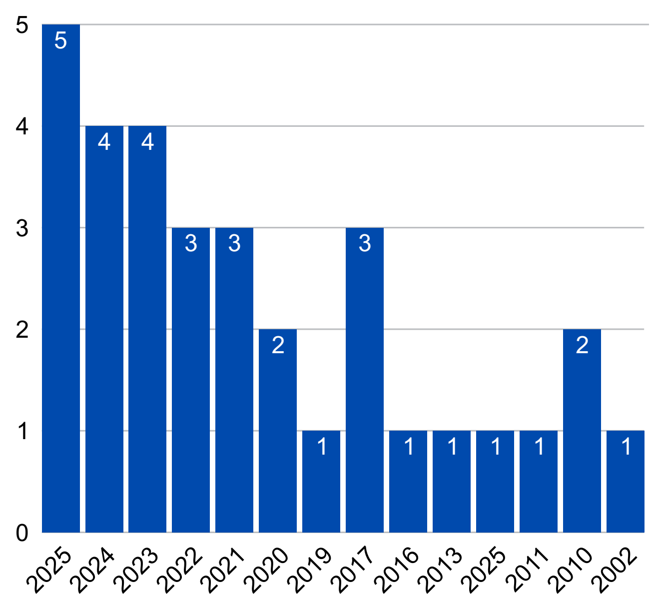
Materials and Methods

A systematic review of the literature was conducted to identify and analyze the main scientific advances in the development of antifouling coatings applicable to marine environments. Searches were performed on ScienceDirect, Scopus, Web of Science, PubMed, and SciELO platforms using the descriptor “antifouling” without time restrictions, with the aim of providing a comprehensive and up-to-date overview of the topic. Specific criteria were applied to refine the results: there was no language restriction, and only complete scientific articles with an experimental approach were considered. In addition, priority was given to studies available in open access and presenting technical data, such as type of material, physical-chemical and mechanical properties, exposure time, evaluation methods, and performance results under laboratory and/or field conditions. After the initial screening, 32 articles met the selection criteria and were included in the detailed analysis. The final choice was based on a qualitative analysis, considering the main technical highlights, such as the parameters evaluated and the experimental methods used. The evaluation of the data extracted from the articles was conducted with the support of Microsoft Excel, used for data organization and analysis, and VOSviewer, used for keyword mapping from the Web of Science database, which allowed conceptual connections between studies and the detection of recent advances related to the development of approaches that minimize environmental damage in the control of biofouling.

Results and Discussion

The analysis was qualitative in nature and resulted in the selection of 32 articles. Figure 1 shows the temporal evolution of publications on anti-fouling coatings, based on the analysis of the selected scientific articles. There was limited production between 2010 and 2020, with few papers published during this period, marked by initial approaches focused on natural extracts [5–7]. From 2021 onwards, there has been a steady stream of academic production, driven by the search for alternatives to conventional biocides and the advancement of analytical tools, such as X-ray fluorescence spectroscopy (XRF) [8] and computational modeling applied to coating performance [1]. Research has focused on superhydrophobic surfaces [9,10], bio-inspired coatings [11,12], with emphasis on the use of functional nanoparticles and the development of biocides with low environmental impact [13–16], in addition to previous studies focused on conventional systems with controlled release of metal ions, especially copper-based ones [8].

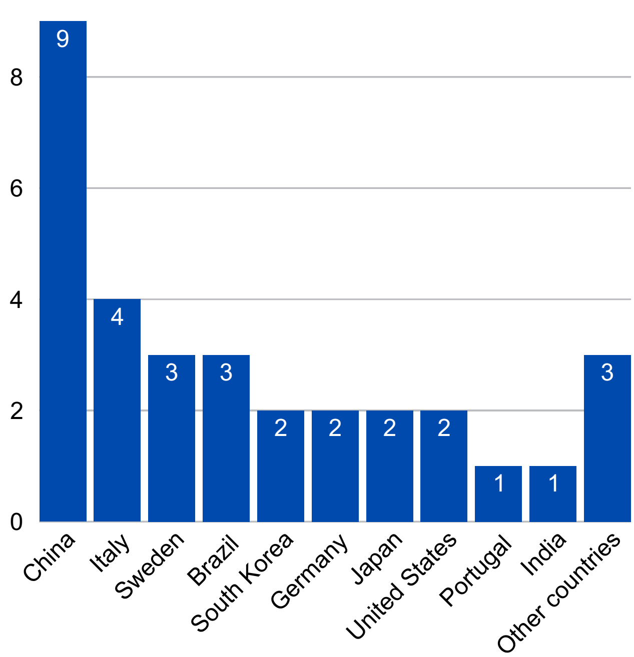
Figure 1. Annual distribution of scientific publications on antifouling coatings.



Currently, there is a continuous growth in the number of publications, reflecting the increase in interest and scientific production, with an emphasis on innovative biomaterials and nanotechnological approaches [17,18]. Recent trends point to the consolidation of technologies such as zwitterionic polymers [19,20] and multifunctional nanostructures [21], in addition to the growing demand for long-term studies and comprehensive ecological assessments of new anti-fouling materials.

The mapping of scientific production by country, shown in Figure 2, highlights China's leadership, especially in studies involving nanomaterials (such as cuprous oxide and silica) and surface modification techniques, such as controlled roughness [10,15,17]. Europe is represented by Italy, which stands out in the development of advanced polymers [22], while Sweden focuses its efforts on analytical methods and reducing environmental impacts [14]. Despite its vast marine biodiversity, Brazil still invests little in research aimed at developing non-toxic anti-fouling agents. This is still an innovative area in the country, with few research groups dedicated to the topic [5–7]. In terms of technological trends, Asian countries such as China, Korea, and Japan lead in the synthesis of new materials, while Europe and the United States prioritize practical applications, such as the use of sensors and field tests [12]. It is worth noting that in three articles, it was not possible to identify the country of origin of the research.

Figure 2. Countries with the highest scientific output on antifouling coatings.

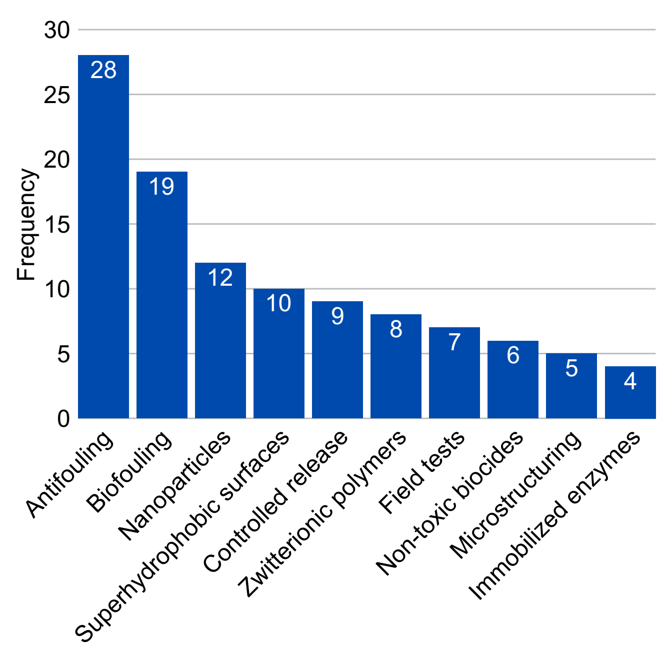


The analysis of the most frequent keywords in the articles, presented in Figure 3, reinforces the predominant focus on the terms “antifouling” and “biofouling,” which are the most frequent in research on antifouling coatings, reflecting the central focus of the area. Technological approaches such as nanoparticles [15,16], superhydrophobic surfaces [9,10], and controlled release [18] also stand out, indicating a trend toward effective solutions with low environmental impact. Terms such as “field tests” and “non-toxic biocides” [5,23,24,33], although less frequently cited, point to important gaps in practical validation and environmental safety. Figure 3 shows a transition from traditional methods to innovative and bio-inspired strategies.

The systematic review was expanded with the use of keyword mapping through VOSviewer, using 5,647 records from Web of Science with the word “antifouling” in the title.

In Figure 4, the graph shows four main clusters. The first, represented by the color green, focuses on studies related to coating technologies and the performance of materials applied to

Figure 3. Most frequent keywords in studies on antifouling coatings.



marine environments, highlighting terms such as "antifouling coating," "fouling release coatings," and "performance." The red cluster brings together research on colonization mechanisms and the challenges caused by biofouling, with an emphasis on keywords such as "biofouling," "adhesion," "settlement," and "toxicity." The blue cluster addresses investigations into interactions at the molecular level, including terms such as "surfaces," "protein adsorption," and "poly (ethylene glycol)." The yellow cluster integrates works that explore chemical composition, protein behavior, and material behavior in improving antifouling performance. The term "adhesion" stood out as the link between the biological and innovation areas in coatings, while "nanoparticles" presented more limited connections, indicating potential gaps to be explored. Overall, the results show that, although there have been significant advances in the practical effectiveness of antifouling agents, there is still a need for innovation to address biofouling.

Table 1 highlights the advancement and complexity of anti-fouling technologies, showing a critical balance between effectiveness and environmental responsibility. Biocidal coatings [8,14–16] remain effective but raise concerns about ecotoxicity. Alternatively, solutions based on natural bioactives [7,9,24,25] offer lower environmental impact but have reduced durability. Physical technologies, such as superhydrophobic [9,10,12] and micro/nanotextured [17,26,27] surfaces, stand out for their durability and absence of toxic compounds, making them particularly suitable for offshore structures that are difficult to maintain.

However, Table 1 also highlights the lack of standardization in validation criteria. The variation in testing methods, ranging from field tests [5,28] to projections based on laboratory data [26], makes it difficult to compare the results obtained between different technologies. In this context, hybrid systems [13,18,20] stand out for integrating different mechanisms (physical, chemical, biological), achieving synergy in

Figure 4. Keyword mapping in VOSviewer, highlighting four main clusters.

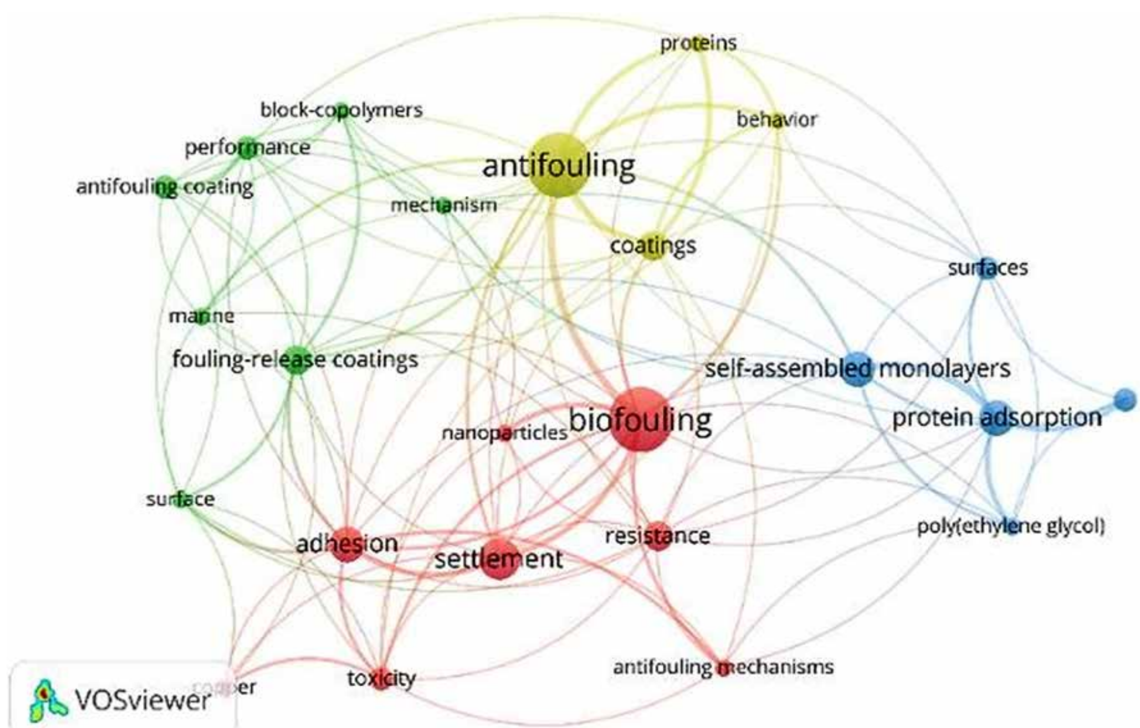


Table 1. Comparison of the main antifouling coatings in terms of mechanism of action, durability, removal, and applications.

Type	Mechanism of Action	Shelf Life	Removal	Applications	References
Biocides	Controlled release of toxic ions (Cu, Zn) or organic compounds (capsaicin).	1–5 years (depending on release rate) .	Natural degradation or mechanical cleaning.	Ship hulls, port structures	[8,13–16]
Physical (Micro/ Nanotextured)	Creation of rough/irregular surfaces to reduce larval adhesion.	2–10 years (high durability).	Abrasion resistant.	Marine sensors, pipes.	[17,26, 27,29]
Hydrophobic	Reduced wettability to hinder organism attachment.	1–3 years (limited by chemical degradation).	Cleaning with water jets or solvents.	Submerged equipment, aquaculture.	[9,10,21
Superhydrophobic	Combines extreme hydrophobicity and microstructures (contact angle >150°). and microstructures (contact angle >150°).	3–8 years (high resistance).	Self-cleaning (lotus effect).	Offshore wind energy, aquatic drones.	[9,10,12]
Polymers (Zwitterionic/ Hydrogels)	Neutral surface charge and hydration to repel biofilms.	6 months–2 years (renewable).	Degradation or recoating.	Membranes, medical implants.	[19–22,30]
Natural Bioactive Compounds	Release of extracts/ enzymes that inhibit larval settlement.	6 months–3 years (depending on stability).	Biodegradation.	Marine protected areas, sustainable aquaculture.	[5,7,22, 24,31]
Hybrids	Combines multiple mechanisms (e.g., biocide + texture).	2–7 years (synergy).	Varies depending on components.	Critical applications (petroleum, defense).	[13,18,20]

performance, durability, and functionality. The analysis reinforces that future developments should prioritize technologies with lower environmental impact, greater durability, and standardized validation, with hybrid systems emerging as a promising solution for critical environments, such as offshore platforms and oil industry structures.

Table 2 presents the main technical parameters of antifouling coatings, highlighting criteria such as thickness, adhesion, durability, environmental resistance, and effectiveness.Thin coatings, such as PDMS [27], are ideal for sensors, while thick coatings, such as thermoplastics [26], are suitable for robust structures. Hydrogels and zwitterionic polymers [19–21, 30] showed good adhesion, and durability ranged from 6 months to 10 years, with textured surfaces standing out [27]. In terms of environmental resistance, coatings with amorphous Fe [11] and PDMS [10] stood out, while materials such as capsaicin [18] showed lower stability. Antifouling efficacy was high on superhydrophobic surfaces [9], PDMS [10], chitosan [17], and enzymes [22]. Challenges remain, such as the lack of standardization of tests and the scarcity of long-term validations. Recommended solutions include combined methodologies, such as XRF with bioassays [14], as well as hybrid criteria.

Conclusion

Marine biofouling represents a significant technical and environmental challenge, especially

Table 2. Technical parameters and validation methods for anti-fouling coatings.

Parameter	Range/Description	Validation Methods	Representative Articles (No.)
Thickness	20–500 μm	Profilometry	[10,17,19,21, 26,27,30]
		Electron microscopy	
Adhesion	Zwitterionic polymers/ hydrog els: Excellent	Lab: ASTM D3359 (cross-cut), pull-off	[9,10,19–21, 26,30]
	Hydrophobic surfaces: Average	Field: Exposure to waves/currents	
Durability	6 months–10 years	Lab: Accelerated aging (UV saline)	[10,12,14, 26–28]
		Field: Monitoring (6–24 months)	
UV/Saltwater Resistance	High: PDMS, Amorphous Fe	Lab: UV/Saline Chambers (ASTM G154)	[10,11,13,19, 22,30]
	Medium/Low: Hydrogels, enzymes	Field: Exposure in coastal areas	
Antifouling efficacy	70–99% inhibition	Lab: Bioassays (larvae/biofilms)	[1,13,14,17, 22,24,28,32]
		Field: Natural colonization (6–12 months)	
Combined Methods	XRF + ecotoxicology	Example: XRF laboratory + field	[1,8,14,27]
	Microstructuring + bioassays		

in submerged structures, where it compromises functional performance, increases operating costs, and exacerbates ecological impacts. The systematic review carried out allowed us to map the main advances in the development of anti-fouling coatings with less environmental impact.

There has been a significant shift from the use of toxic biocides to bio-inspired solutions, driven by the negative impacts of conventional substances, such as toxicity to non-target organisms, bioaccumulation, and ecological imbalance in the marine environment. The analysis of the tables showed technological diversity, with emphasis on superhydrophobic surfaces, zwitterionic polymers, hydrogels, and hybrid systems, which have shown promise due to their high anti-fouling effectiveness. However, important challenges remain, such as the absence of standardized evaluation protocols, the scarcity of long-term studies, and the production limitations of some emerging technologies.

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