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Review

Biofouling on Offshore Wind Energy Structures: Characterization, Impacts, Mitigation Strategies, and Future Trends

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Abstract

Biofouling, the accumulation of marine organisms on submerged surfaces, presents a significant challenge to the design, performance, and maintenance of offshore wind turbines (OWTs). This work synthesizes current knowledge on the physical and operational impacts of biofouling on OWT marine substructures, with a particular focus on how it alters hydrodynamic loading, increases drag and mass, and affects fatigue and structural response. Drawing from experimental studies, computational modeling, and real-world observations, this paper highlights the critical need to integrate biofouling effects into design practices. Additionally, emerging mitigation strategies are explored, including advanced antifouling materials and AI-driven monitoring systems, which offer promising solutions for long-term biofouling management. By addressing both engineering and ecological perspectives, this paper underscores the importance of developing robust, adaptive approaches to biofouling that can support the durability, reliability, and environmental sustainability of the offshore wind industry.

Keywords: biofouling; offshore; marine; wind energy; coating

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1. Introduction

The rapid growth of the global population and economic activity, combined with the pressing challenges of climate change and energy security, has intensified the global drive toward alternative energy sources, particularly moving away from non-renewable fossil fuels [1]. Wind energy has emerged as a key player in this transition, with recent years showing a notable shift from onshore to offshore installations [2]. This offshore expansion has led to a significant increase in the number, scale, and diversity of submerged static artificial structures (SSASs) in marine environments, reflecting the broader human footprint in coastal and offshore zones [3]. However, these structures are highly susceptible to biofouling, which can have both immediate and long-term negative effects. As a result, effective biofouling management is critical, offering multiple benefits such as improved structural performance, enhanced cost-efficiency, greater sustainability, increased productivity, and reinforced biosecurity [4].

While the negative effects of biofouling on ships have been understood and managed since ancient times, the recognition of its impact on SSASs is a more recent development [4]. Understanding the typical biofouling effects associated with marine structures is crucial for engineers to establish suitable loading criteria, while also providing valuable insights for other stakeholders regarding the ecological consequences of introducing new artificial habitats. However, there are limited data on the composition of biofouling communities, including their weight and density, on floating structures linked to emerging marine renewable energy technologies [5].

The introduction and spread of non-indigenous species (NIS) in marine environments can have severe and often irreversible consequences, affecting ecosystems, industries, and even cultural practices [6]. Similar to non-indigenous macroorganisms, marine pathogens pose a significant threat due to the difficulty of controlling or eradicating them once they become established, with eradication efforts frequently proving ineffective [7]. As a result, prevention remains the most reliable and effective strategy for minimizing their impacts [8]. Despite the implementation of various vector control measures, biofouling on static marine infrastructure continues to serve as a critical reservoir for species dispersal, highlighting the urgent need for further research to better understand and manage these risks [4].

This work aims to provide a comprehensive understanding of biofouling and its multifaceted impacts on offshore floating wind turbines (OFWTs), spanning hydrodynamic performance, structural integrity, operational costs, and ecological consequences. In doing so, it seeks to bridge the gap between engineering and environmental considerations by synthesizing current research findings, real-world observations, and innovative mitigation strategies. This paper is structured to first examine the environmental, physical, and material causes influencing biofouling. It then delves into the specific impacts on OFWTs, including economic, operational, and ecological dimensions. The subsequent sections explore both conventional and emerging technologies for biofouling management, categorized into mechanical, biological, chemical, and physical approaches. Lastly, future trends and innovations such as eco-inspired coatings, AI-driven monitoring systems, and advanced materials are highlighted, emphasizing the interdisciplinary efforts needed to develop sustainable and adaptive solutions for long-term biofouling control in offshore wind energy applications.

2. Factors Impacting the Biofouling Process

2.1. Environmental Conditions

2.1.1. Water Temperature, Season, and Salinity

Seawater temperature, influenced by latitude and seasonal changes, plays a key role in shaping marine communities, including biofouling composition. It impacts the timing of the spawning, settlement, growth, and reproduction of organisms. Generally, biofouling growth rates increase with temperature. As a result, biofouling is less prevalent in polar regions, where low sea temperatures (<5 °C) limit growth, typically confining biofouling to mid-summer, when temperatures rise. In contrast, tropical and subtropical areas experience more intense biofouling due to consistently warmer temperatures (>20 °C), which support continuous reproduction of fouling organisms and accelerated growth rates. In regions with moderate sea temperatures (5–20 °C), biofouling occurs year-round but exhibits strong seasonality, with the majority of spawning and growth happening between spring (April) and early autumn (October) according to Vinagre et al. [9]. The temperature of the substrate to which organisms adhere has a much smaller effect on their growth [10].

Temperature profoundly influences both the survival and physiological functions of marine organisms. Numerous biological processes, including oxygen consumption, heart rate, feeding, locomotion, and enzyme activity, are temperature-dependent [11]. Researchers have identified three main phases in the physiological response to temperature change: (1) an immediate, short-term (acute) response; (2) a longer-term adjustment over days or weeks, known as thermal acclimation or, in more complex seasonal contexts, seasonal acclimatization; and (3) genetic adaptation across generations [11]. Classification systems reported by [12] describe how organisms compensate for new temperature conditions, ranging from no adjustment (Type 4) to overcompensation (Type 1) or even paradoxical responses (Type 5).

These physiological responses vary across different functions and species and are often best understood using multidimensional models. Importantly, even though various physiological processes are interrelated, scientists find it useful to categorize them into two broad energy-related groups: those responsible for energy intake (e.g., feeding and irrigation), and those related to energy use (e.g., metabolism). Effective thermal compensation involves coordinated adjustments across these processes to optimize energy gain and minimize energy loss when environmental temperatures shift [11].

Marine bivalves such as *Arctica islandica* and *Modiolus modiolus* exhibit physiological adaptations that help them to maintain energy balance as environmental temperatures increase. As shown in Table 1, filtration rates rise between 4 °C and 12 °C, leading to greater food intake, while absorption efficiency remains relatively constant. However, at 20 °C, there is a marked increase in absorption efficiency, which significantly boosts the amount of assimilated energy despite only a modest further increase in filtration. This combination of enhanced food capture and improved assimilation allows these species to offset rising metabolic costs and sustain the energy needed for growth and reproduction during warmer conditions [13].

Table 1. The connection between the amount of food consumed, how efficiently it is absorbed, and the portion of it that is assimilated, in relation to temperature, in two bivalve species [11].

Species	Temperature (°C)	Ingested Ration (mg 24 h^{-1})	Absorption Efficiency (%)	Absorbed Ration (mg 24 h^{-1})
Modiolus modiolus (2.31 g dry tissue weight)	4	33.5	77.5	26
	12	70.4	82.5	58
	20	101.5	92.9	94.3
Arctica islandica (4.4 g dry tissue weight)	4	80.4	67.3	54
	12	161.3	67.2	108
	20	172.7	83.6	144

Research comparing the effects of temperature on oxygen consumption in two sea anemone species, *Actinia equina* (a high-shore species) and *Anemonia natalensis* (a subtidal species), reveals distinct physiological adaptations (Table 2). *Actinia* exhibits a significantly lower respiration rate, about half that of *Anemonia*, and maintains a relatively stable respiratory rate across a wide temperature range, particularly in warmer conditions. This temperature independence is reflected in low Q_{10} values (Q_{10} is the biological process sensitivity when temperature increases by 10 °C), and it extends further in summer due to thermal acclimation. Additionally, *Actinia* is capable of acclimating to different temperatures, while *Anemonia* shows no such ability. These traits allow *Actinia* to conserve energy in its food-limited, high-shore environment, unlike the subtidal *Anemonia*, which lacks these compensatory mechanisms [14].

In a research work by Martin et al. [15], environmental conditions such as temperature, salinity, and dissolved oxygen in water were shown to significantly shape macrofouling assemblages on moored buoys in the eastern Arabian Sea. In this study, the pelagic gooseneck barnacle (*Lepas anatifera*) dominated the biofouling communities across depths up to 130 m, with regional variation (assemblages in the southeastern (SEAS), east–central (ECAS), and northeast (NEAS) regions of the Arabian Sea were distinct) in its density attributed to the stability of near-surface temperature and salinity. Diurnal and seasonal variability in these parameters, particularly low salinity and rapid fluctuations, negatively affected the fouling intensity. Subsurface biomass maxima happened at depths of 10–20 m, corresponding to thermally stable zones, highlighting the importance of microclimate within the water column. While biological productivity and zooplankton presence had limited influence, the authors suggested that long-term anomalies like El Niño–Southern Oscillation (ENSO) events and broader climate trends (e.g., ocean warming and acidification) may substantially impact future biofouling patterns. Notably, many macrofoulants on moorings could serve as bioindicators of environmental change, emphasizing the importance of sustained, large-scale monitoring to track climate-driven shifts in pelagic ecosystems.

Table 2. Comparison of oxygen consumption in the subtidal *Anemonia natalensis* with that of the high-shore *Actinia equina* [11].

Species	Season	Temperature (°C)	Oxygen Consumption ($\frac{\mu l}{mgh}$)
Anemonia natalensis	Summer	19	0.5
		25	0.6
		31	1.15
		37	1.2
	Winter	19	0.5
		25	0.6
		31	1.2
		37	1.35
Actinia equina	Summer	19	0.25
		25	0.27
		31	0.27
		37	0.28
	Winter	19	0.25
		25	0.27
		31	0.39
		37	0.42

2.1.2. Depth, Light Penetration, and Distance from Shore

Depth and light availability significantly influence the composition and growth of biofouling organisms. Photosynthetic macrofoulers, such as macroalgae, are typically more abundant within the euphotic zone (0–40 m), where conditions are warmer, light levels are higher, and plankton is abundant [16]. Within this zone, biofouling growth and biomass generally decline with increasing depth due to reduced light intensity. However, even as the biofouling pressure diminishes with depth, sessile filter-feeding invertebrates like acorn barnacles and mussels, which often dominate macrofouling communities, can settle at considerable depths [10]. Furthermore, the biofouling organisms impact the environmental conditions for their own proliferation. For example, organisms such as the blue mussel (*Mytilus edulis*) filter the water, capturing particles that would normally remain suspended, leading to reduced turbidity and greater light penetration. This "biofilter" effect has been observed on a local scale and under laboratory conditions, and it could potentially have broader impacts when multiple offshore structures are involved [17].

In addition to depth, the distance from shore also influences the composition and biodiversity of marine fouling communities on offshore substructures, as demonstrated in a study of five gas platforms in the southern North Sea [18]. Species richness increased with depth up to approximately 15–20 m, likely due to more stable conditions and optimal light levels, but declined beyond that depth, possibly due to reduced light penetration and changes in environmental parameters. The distance from shore also affected fouling, with species richness generally decreasing further offshore. However, this pattern may be influenced by community age, as platforms nearer to shore were subject to more frequent cleaning, leading to younger communities. The study emphasizes that depth, light availability, and distance from shore, along with platform maintenance schedules, are key factors shaping biofouling assemblages.

The observed decrease in biofouling diversity with increasing distance from shore can be attributed to several interrelated environmental and operational factors. For example, there is a well-documented gradient in food availability in the southern North Sea, with coastal areas typically exhibiting higher concentrations of suspended organic matter. This enhanced food supply nearshore supports a greater abundance and diversity of filter-feeding organisms such as *Mytilus edulis*, which were notably less abundant or absent on platforms situated further offshore [18].

Another aspect to consider is that cleaning practices vary with proximity to shore. Platforms located closer to the coast are cleaned more frequently—particularly in the upper 10 m of the structure—due to operational accessibility and higher levels of marine growth. This regular cleaning disrupts community development, effectively resetting the ecological succession and potentially masking the full effect of distance from shore by maintaining younger, less-developed fouling assemblages.

Lastly, species-specific habitat preferences also play a role. For example, the soft coral *Alcyonium digitatum* was found only on platforms located further offshore, indicating that some taxa may prefer or require the more stable environmental conditions found at greater distances from land, such as lower temperatures or reduced sedimentation [18].

2.1.3. Immersion Time

A 10-year study by Degraer et al. [19] on two types of OWTs (i.e., gravity-based and monopile foundation) off the Belgian coast, in the first decade after the installation, revealed three distinct stages of ecological succession (Figure 1): an initial short pioneer stage (0–2 years), followed by a more diverse intermediate stage (3–5 years) dominated by numerous suspension-feeding invertebrates, and a final "climax" stage (6+ years) co-dominated by plumose anemones (*Metridium senile*) and blue mussels (*Mytilus edulis*).

2.2. Hydrodynamic Factors

The composition and extent of biofouling on a colonizable substratum are influenced by currents and proximity to shore [10]. Organisms such as mussels, barnacles, and tubeworms benefit from currents by feeding on particles suspended in the water or nutrients dissolved in it [20]. Currents also transport the motile larvae of many invertebrates and algae spores, making colonization success more likely for substrata located closer to the shore, especially for fixed structures like platforms [10]. The impact of currents and water flow on biofouling communities depends on the velocities and shear forces generated near the substratum [21]. For example, sessile filter-feeding organisms may benefit from high water flow, as it provides food particles, but strong currents can also dislodge them. To counter this risk, many sessile species, such as barnacles, have developed advanced adhesion mechanisms for secure attachment [22]. On the other hand, lower water flows may enhance the settlement of larvae and spores of some organisms.

2.3. Material Composition

2.3.1. Certain Materials Are More Prone to Colonization

The materials used for offshore substructures influence their reactivity and toxicity, thereby affecting their susceptibility to biofouling. The physicochemical properties of these materials can alter the water chemistry and the seawater–substratum interface, impacting the formation and nutrient content of the macromolecular conditioning layer. These properties also affect the bacterial communities on the substratum, with biologically and chemically inert materials, which are more stable, typically supporting greater bacterial diversity. This stability facilitates quicker macromolecular conditioning and subsequent biofilm formation [23], potentially influencing the settlement and growth of macrofouling organisms. Research has shown that materials like aluminum, carbon steel, and bronze are generally more prone to biofouling than non-metallic materials such as glass fiber, polyethylene, polyamide, and rubber [24]. Among metallic materials, aluminum substrata tend to experience less biofouling compared to bronze- or Monel-based materials [9]. However, the response of biofoulers to materials is not consistent across all species. Different biofouling groups, or even species within the same group, may respond differently to the same material, depending on factors like temperature and depth.

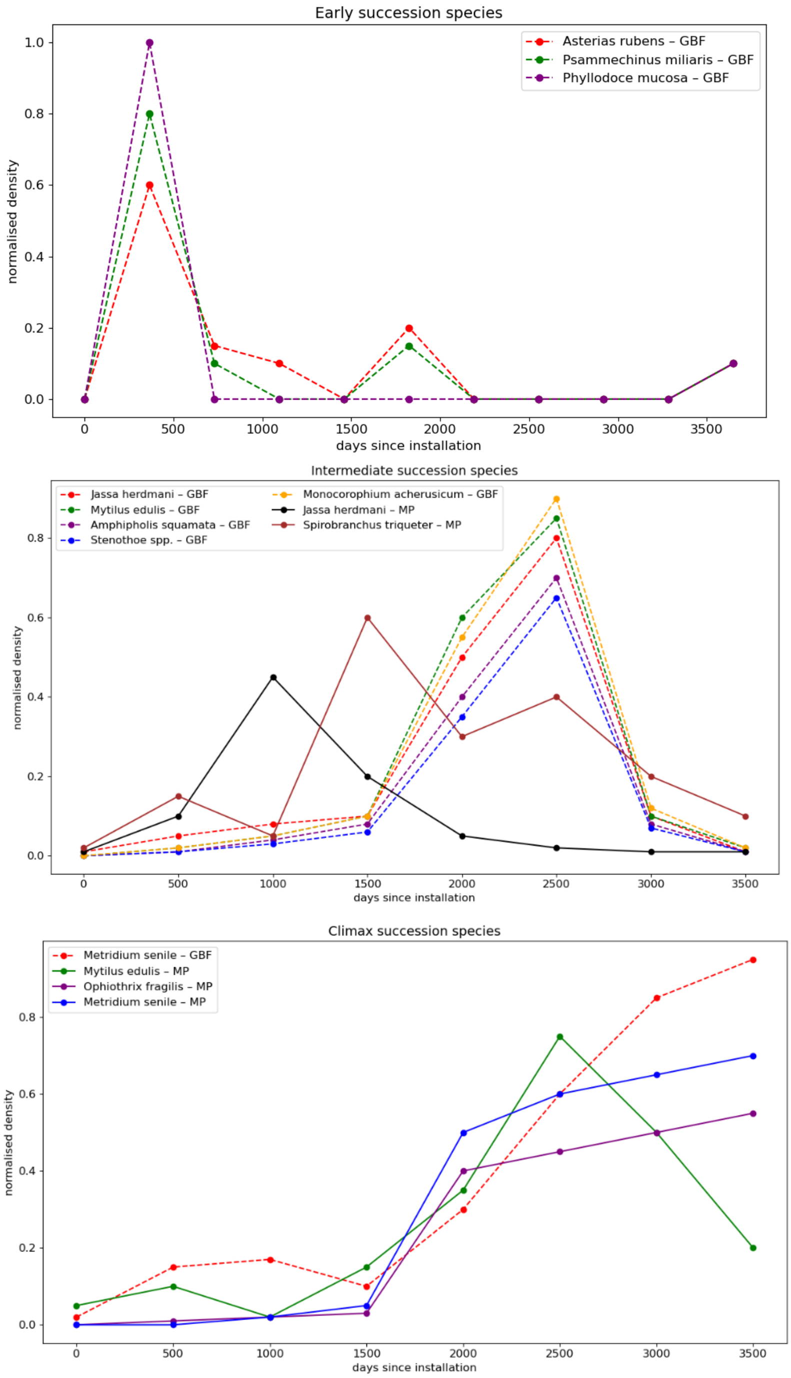

Figure 1. Succession stages and species turnover were observed on gravity-based foundations (GBF; dashed lines, approximately 10 years) and monopile foundations (MP; solid lines, approximately 9 years). Normalized density: for each species and foundation type, the absolute densities were adjusted relative to the highest density recorded for that species in the time series (based on [19]).

Metallic surfaces are particularly prone to biofouling due to the strong interactions between microbial extracellular polymeric substances (EPSs) and the metal substrate. EPSs—composed primarily of polysaccharides, proteins, lipids, and nucleic acids—contain functional groups such as hydroxyl, carboxyl, carbonyl, and phosphate, which have a high affinity for metal ions. These groups facilitate the chelation of metal cations (e.g., Fe^{2+}, Cu^{+}), enhancing microbial adhesion and initiating stable biofilm formation on the metal surface [25].

In addition to their adhesive properties, many EPS components are electrochemically active and capable of participating in redox reactions. This redox activity promotes extracellular electron transfer between microorganisms and metal surfaces, often resulting in anodic metal dissolution and localized corrosion. Such corrosion processes further roughen the surface, providing additional anchoring points for microbial cells and strengthening the overall biofouling structure [25].

Furthermore, EPSs contribute to the formation of cohesive and stress-resistant biofilms that modify the physicochemical properties of the metal–solution interface. This stable microenvironment not only supports sustained microbial colonization but also accelerates microbially influenced corrosion (MIC), making metallic surfaces more vulnerable to biofouling than non-metallic materials [25].

2.3.2. Topography and Wettability of Substrata

The topography of substrata plays a crucial role in shaping the physical and environmental conditions available to organisms. Greater substratum heterogeneity creates more diverse microhabitats by increasing the surface area, promoting higher species diversity and reducing interspecies competition. Features like microtopography (which constitutes the small-scale surface features or patterns on a material, often measured at the microscopic level), roughness, and texture can influence an organism's ability to attach to the surface, thereby affecting biofilm formation and the extent of biofouling [21]. Non-motile algal spores, which have little or no substratum selectivity, benefit from microtopography, as it physically traps the spores and aids their adhesion. Similarly, the settlement of many invertebrate larvae is influenced by microtopographical features, which act as cues for site selection [24]. As a result, microtopography—small-scale surface structures typically ranging from 1 to 300 μm—can influence an organism's ability to attach to a surface, thereby affecting biofilm formation and the extent of biofouling [26].

The microtopography of a substratum also affects its wettability, which influences how biofouling organisms adhere. Wettability determines the contact area and interaction forces between the adhesive material and the surface. However, no universal relationship exists between surface hydrodynamics and adhesion strength. For instance, acorn barnacles exhibit stronger adhesion on surfaces with higher wettability [27], while settlement rates differ among species based on surface properties—some preferring hydrophobic surfaces that have low wettability (e.g., *Balanus improvisus*), and others hydrophilic ones with high wettability (e.g., *B. amphitrite*) [28].

2.3.3. Color of the Surface

The color of a substratum influences the amount of energy it reflects and absorbs, as well as its temperature, which can impact biofouling settlement [29]. Studies have shown that substratum color has a greater effect during the early stages of biofouling, making it a significant factor for equipment submerged for short durations. Many larvae and spores exhibit negative phototaxis, preferring darker, less reflective surfaces for settlement [30]. Additionally, bacterial biofilms, which play a key role in biofouling, are affected by substratum color and may indirectly influence the subsequent settlement of organisms that are not directly responsive to color [30]. Over longer periods (months to years), as biofouling communities develop and become more complex, the differences between darker and lighter substrata tend to diminish [31].

Satheesh and Wesley [32] investigated the influence of substratum color on the recruitment of macrofouling communities by deploying red, green, blue, white, and yellow acrylic panels in coastal waters. Their results showed that surface color significantly affects larval settlement, particularly for barnacles and tubeworms, which recruited more on darker colors like red and blue. This preference was attributed to larvae avoiding highly reflective surfaces and seeking out darker, less illuminated areas. The study emphasized that larval responses to color can vary by species and are influenced by factors such as light absorption and biofilm presence. It concluded that substratum color is a critical variable in both ecological biofouling studies and antifouling technology development, with light-colored surfaces potentially offering reduced recruitment in marine applications. Figure 2 shows the recruitment of tubeworms (*sabellariids*) during five months on different colored panels (12 panels used for each month) at Kudankulam, on the east coast of India.

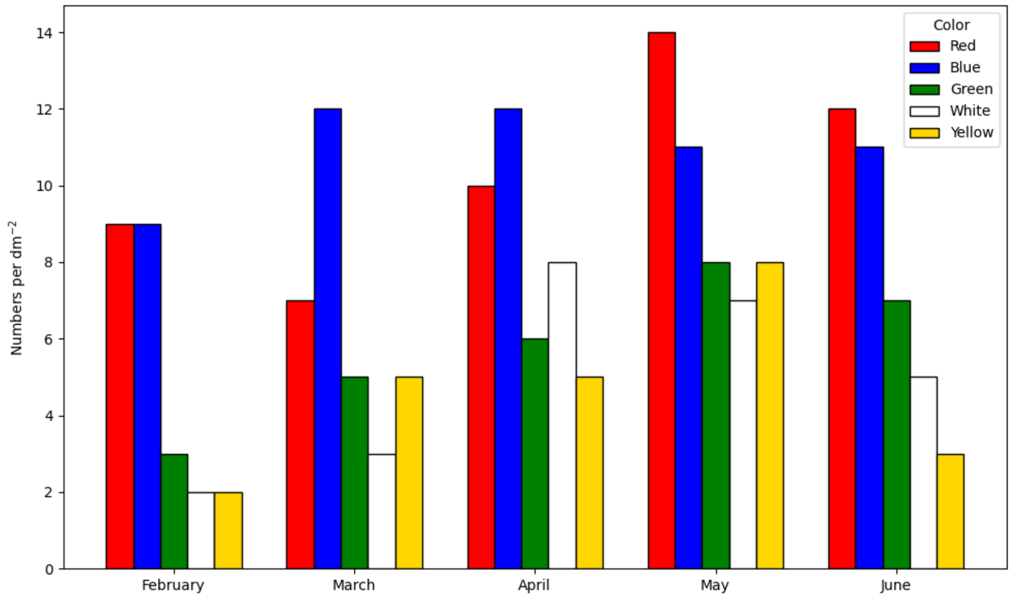

Figure 2. Recruitment trends of tubeworms (*sabellariids*) on acrylic panels of various colors (based on [32]).

3. Impacts of Biofouling on Offshore Structures

3.1. Economic Costs

Material corrosion remains the most critical challenge for infrastructure and equipment operating in marine environments, contributing to 20% of total economic losses [33]. The RobFMS project highlights that biofouling on offshore wind turbine foundations can account for up to 10% of the Levelized Cost of Electricity (LCOE). This is primarily due to increased Operation and Maintenance (O&M) expenses, including the use of divers, remotely operated vehicles (ROVs), support vessels, and substantial human resources. The project aims to implement an autonomous fouling monitoring and cleaning system, potentially reducing existing monopile fouling management costs by over GBP 15,000 per megawatt annually, which represents a 50% cost saving [34]. Also, the Atlantic Area Transnational Programme funded the project to assess the economic impact of biofouling on maritime industries, including shipbuilding, aquaculture, and ocean renewable energy. The project aimed to define the value chain in the nautical industry sector, establish indicators for economic impact, and identify business opportunities for new antifouling technologies [35].

The yearly expenses of offshore wind turbines (OWTs), associated with operational delays, repairs, cleaning, and overall maintenance, are estimated to total USD 150 billion [36]. The buildup of biofouling in the splash and intertidal zones of the turbines at Teesside Offshore Wind Farm (owned and operated by EDF Energy) has emerged as a significant challenge for both operations and maintenance, as well as health and safety. Technicians have noted that from summer through autumn and winter, these areas need to be thoroughly jet-washed every two to three weeks to remove marine growth. This frequent maintenance is especially expensive due to the need for vessels, specialized personnel, and equipment [37]. Therefore, it is crucial to consider this issue in structural design to ensure long-term durability and reliability without increasing costs, as well as to assess potential investment delays in maritime industries [38]. Although Floating Offshore Wind Turbines (FOWTs) are more cost-effective than fixed structures in deeper waters, they remain economically challenging due to their high Operation and Maintenance (O&M) expenses [39]. As illustrated in Figure 3, O&M costs make up roughly one-third of the total expenditures for a floating wind project [40].

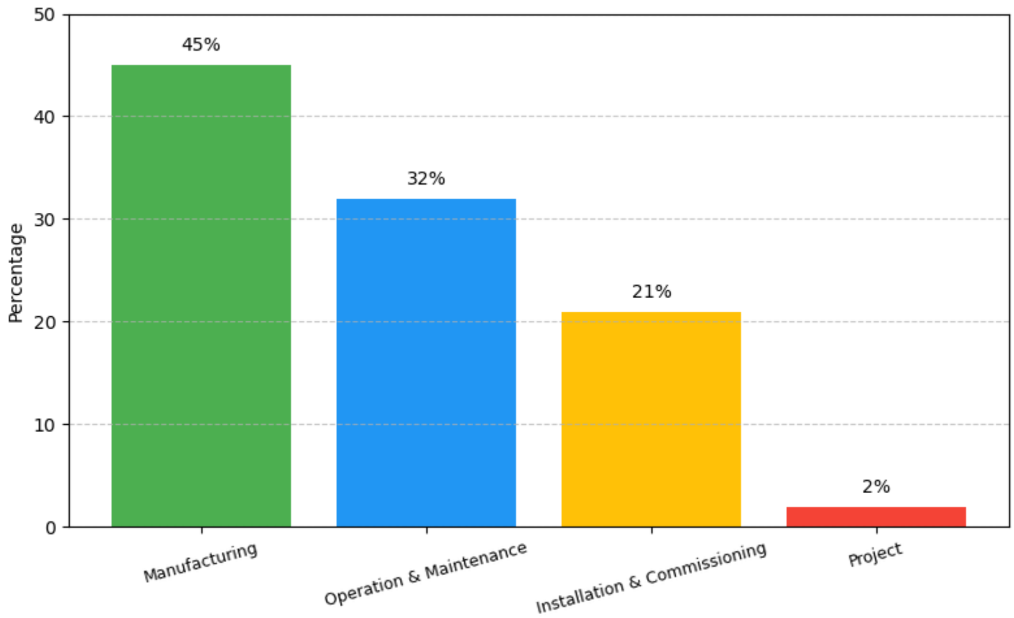

Figure 3. Overview of the cost distribution in a floating offshore wind project (based on [34]).

It is worth noting that applications of Life-Cycle Assessment (LCA) methodologies in offshore wind energy projects are still scarce, and remarkably so in floating offshore wind energy [41]. In previous works, the share of Operation and Maintenance (O&M) activities in the LCOE of floating offshore wind energy projects was estimated between 1% and 6% [42,43]; nevertheless, other authors, like [44], increase the estimated contribution of O&M to 13.9–19.6% of LCOE. However, the specific impact of biofouling in LCA has not been previously addressed in offshore wind energy applications, to the best of the authors' knowledge. In [45] the LCA methodology is introduced in the frame of anti-barnacle biofouling coatings applied to marine vessels.

3.2. Operational Challenges

Although microfoulers can be present in large numbers on a surface, the less diverse macrofouling organisms contribute the most to overall weight, hydrodynamic load, and thickness. Five major groups of macrofoulers have been identified as having the greatest impact on marine renewable energy (MRE) structures through various mechanisms. These include (i) kelp (classified as soft-fouling), (ii) bryozoans (ranging from soft- to hard-fouling depending on the species), (iii) mussels, (iv) acorn barnacles, and (v) calcareous tubeworms (both considered hard-fouling) [9].

The biocolonization of mooring lines in offshore floating wind turbines can create significant operational challenges, particularly by increasing drag forces on the mooring lines. This phenomenon occurs as biofouling organisms such as barnacles, mussels, algae, and other marine life accumulate on the mooring lines, altering their hydrodynamic properties. For instance, biofouling on mooring lines and power cables linked to wave energy converters led to a decrease in energy performance of up to 17% and significantly shortened the mooring fatigue life by as much as 76% [46].

Biofouling on floating wind turbine structures can significantly alter their hydrodynamic loading, affecting the platform stability and mooring system integrity. The study by Wright, Pakrashi, and Murphy [47] investigated the impact of biofouling with varying thickness and surface roughness on a tension-moored floating wind turbine under extreme conditions (wind speeds up to 46 m/s). The results indicate that while increased surface roughness has a minor effect on the platform dynamics, biofouling thickness notably influences the platform dynamics. Increased biofouling reduces platform motions and nacelle accelerations, which can be beneficial. However, it also decreases the minimum tendon tensions, raising the risk of slack mooring events, which could lead to failure in the mooring system. To mitigate this, the study prescribes a maximum allowable biofouling thickness of 80 mm, beyond which cleaning of moored floating wind turbine platforms is necessary. Additionally, motion and tendon force-damping strategies, such as tuned liquid column dampers or tendon spring dampers, are suggested as potential solutions to counteract the adverse effects of biofouling accumulation.

The study by Spraul et al. [48] examined the influence of biofouling thickness and distribution on mooring line dynamics in shallow waters, using data from the 2 MW floating wind turbine (FWT) installed on the SEM-REV test site, along with numerical simulations based on the FLOATGEN project. The floater and mooring configurations used in this study were specifically chosen for research purposes and do not reflect the actual FLOATGEN system. The floating wind turbine modeled has a mass of approximately 5000 tons and a draft of 7 m. Inspired by IDEOL designs, the floater is shaped as a square ring, measuring 36 m wide, 10 m high, and featuring a 21 m moon pool. The turbine's nacelle is positioned 60 m above the water surface. To maintain static balance between the front and rear, the setup includes seven mooring lines. The findings indicate that biofouling distribution is often non-uniform, with variations in thickness depending on depth. Increased biofouling leads to higher line mass and drag diameter, shifting the natural frequency of the mooring lines and amplifying dynamic responses. While the mean tension remains largely unaffected due to pre-tension of 2 MN (20% of the minimum load capacity before failure), biofouling influences in-line excitation forces, reducing the tension amplitudes at the fairlead but increasing them at the anchor. In extreme sea states, biofouling's presence lowers the peak tension and tension range, which benefits the strength and fatigue design, considering uniformly distributed thin biofouling layers (around 2 cm) attached to mooring lines show minimal deviations from baseline conditions, whereas uniform 10 cm thicker layers tend to overestimate biofouling's effects. These results highlight the need to account for biofouling's distribution variability rather than assuming uniform coverage when assessing mooring line performance.

In maritime industries like offshore renewable energy, electric cables generate heat due to the current flowing through them, and this heat is usually convected into the surrounding seawater. However, biofouling on the cables forms a physical layer that obstructs this heat dissipation, which can hinder the cables' cooling process and reduce their efficiency, potentially leading to failure (GESAMP, 2024). The growth of biofouling, especially mussels, can alter the heat transfer around the cable, which, in turn, impacts the maximum conductor temperature and temperature fluctuations, ultimately influencing the fatigue lifespan [49].

3.3. Environmental Concerns

Offshore wind farms (OWFs) locally modify the environment both above and beneath the sea surface. Notably, these impacts may affect parts of the ecosystem and can be viewed as either (potentially) negative, such as bird collisions, or (potentially) positive, like enhanced biodiversity and growth in local fish populations [50].

According to Langhamer [51], offshore renewable energy structures, including floating wind turbines and their scour protections, function as artificial reefs, promoting marine biodiversity by providing new surfaces for colonization. These installations can enhance habitat complexity and act as no-trawl zones, potentially increasing fish biomass and supporting spillover to adjacent areas. However, they may also facilitate the spread of invasive species, altering native ecosystems. The ecological outcome depends on the site conditions, reef design, and native species composition. Langhamer [51] stresses the need for long-term monitoring, strategic siting, and coordinated environmental assessments to maximize ecological benefits while minimizing risks.

Coolen et al. [52] investigated how artificial structures influence benthic biodiversity in the North Sea by comparing old oil and gas platforms, a young offshore wind farm, and natural rocky reefs. Their results show that artificial hard substrates increase habitat availability for epifouling organisms, with species richness influenced by factors such as depth, season, and the abundance of key species like *Mytilus edulis* and *Psammechinus miliaris*. Notably, communities on steel and rock substrates overlapped significantly, especially in deeper waters, where artificial structures resembled natural reefs more closely. The study suggests that to promote natural reef-like communities, artificial reefs should mimic the structure and conditions of natural habitats. Additionally, adding rocky substrates around steel installations can enhance colonization by reef-associated species.

De Mesel et al. [53] examined the development of epifaunal communities on offshore wind turbine foundations in Belgian waters, highlighting their role as artificial reefs and potential stepping stones for non-indigenous species (NIS). Within a year, a clear vertical zonation was established, ranging from *Telmatogeton japonicus* in the splash zone to a subtidal community dominated by *Jassa herdmani*, *Tubularia* spp., and *Actiniaria* spp. Colonization occurred rapidly, with high initial species turnover giving way to seasonal dynamics. While the overall biodiversity remained substantial, competition and predation shaped succession patterns. Notably, ten NIS were recorded, primarily in the intertidal zone, indicating that offshore wind infrastructure facilitates their spread. The study emphasizes the need for ongoing monitoring to assess long-term ecological impacts and the potential for future NIS proliferation.

Adams et al. [54] explored how offshore renewable energy devices can act as ecological stepping stones, enabling the spread of both native and marine NIS across biogeographical boundaries. Using hydrodynamic and biological models in southwest Scotland, they found that these structures create novel habitats in open waters, enhancing larval survival and allowing previously restricted species to disperse across natural barriers. This was particularly relevant for organisms with short pelagic larval durations. The study emphasized that while these devices offer minimal habitat individually, their spatial configuration and positioning near coastal flow paths can significantly influence species connectivity, range expansion, and even climate-driven migrations. However, they also raised concern about facilitating the spread of invasive species through both larval dispersal and shipping activity. The authors stressed the need for pre- and post-installation monitoring, integration of habitat mapping, and targeted models to guide biosecurity planning and understand the long-term ecological implications.

Rumes et al. [55] investigated the ecological consequences of offshore wind turbine installations in the Belgian part of the North Sea and found that the introduction of hard substrates, such as turbine foundations and scour protection, led to a marked increase in local biodiversity and biomass. At the scale of individual turbines, the benthic biomass increased nearly 4000-fold, while at the scale of the entire wind farm, the biomass increased approximately 14-fold. The number of benthic species tripled, with hard-substrate-associated taxa increasing tenfold. These structures acted as artificial reefs, enhancing habitat complexity and attracting a variety of epifaunal organisms and commercial fish species, such as Atlantic cod. While the findings highlight the potential for artificial structures to promote local biodiversity and productivity, the authors also noted possible ecological trade-offs, such as shifts in soft-sediment communities and long-term habitat alterations. They emphasized the importance of strategic wind farm planning that considers both renewable energy production and marine biodiversity conservation. Table 3 illustrates the calculated autumn biomass in ash-free dry weight (AFDW) for the entire Thorntonbank wind farm concession area, before (2005) and after construction (2012).

Table 3. Biomass of the Thorntonbank wind farm concession area in kg AFDW.

	Pre-Construction	Post-Construction
Epibenthos	201	827
Endobenthos	4624	15,280
Hard-substrate epifauna	0	53,511

4. Current Antifouling Mitigation Technologies

4.1. Biocidal Coatings

Biocidal antifouling coatings function through the release of certain toxic chemicals (biocides) to deter the settlement and growth of organisms. Research indicates that while biocidal coatings can provide proactive protection against biofouling, their effectiveness is often reduced in static environments. This is because many biocidal coatings are designed to be most effective on vessels in motion, where water flow facilitates the removal of organisms. In contrast, stationary structures may experience diminished performance of these coatings [4].

It is important to note that both biocidal and non-biocidal coatings must either endure for the entire lifespan of the structure or be reapplied at suitable intervals to maintain their effectiveness. While reapplication might be achievable for systems like aquaculture installations, which operate on shorter cycles of several months to a couple of years, it poses a significant challenge for long-term structures such as wharf piles, marina pontoons, and renewable energy infrastructure, where maintenance or reapplication is often impractical and not economically viable.

Additional obstacles facing new biocidal coatings for submerged offshore substructures include navigating complex regulatory approval processes, complying with food safety standards, and addressing positive public perception. A critical hurdle also lies in ensuring that any new coatings or materials are environmentally safe [4].

Biocidal antifouling coatings are formulated using a variety of materials designed to actively combat the settlement and growth of marine organisms on submerged surfaces. Historically, tributyltin-based self-polishing copolymers (TBT-SPC) were widely used, consisting of acrylic polymers with tributyltin (TBT) moieties bonded via ester linkages to the polymer backbone. Upon immersion in seawater, these ester bonds undergo hydrolysis, resulting in the gradual release of TBT, which is a potent biocide capable of inhibiting reproduction and causing morphological disruptions in marine species. Due to severe ecological side effects, TBT has been banned globally, leading to a transition toward tin-free alternatives. Among these, coatings containing copper-based pigments such as cuprous oxide (Cu_2O) are prominent, and their solubility in seawater facilitates the release of copper ions, which interfere with enzymatic systems and metabolic pathways in microorganisms. Modern formulations also incorporate synthetic rosin derivatives to create film-forming binders that regulate biocide diffusion, and some utilize functional acrylic copolymers bearing hydrolysable side chains, such as copper acrylates, zinc acrylates, or silyl acrylates, which mimic the controlled-release behavior of TBT-SPC systems. Certain products further enhance mechanical durability and erosion control by embedding mineral fibers into the coating matrix [56].

The mechanism by which these coatings deactivate microorganisms is centered around controlled release and chemical interference. Once immersed, seawater infiltrates the porous paint matrix, initiating the dissolution of soluble pigments and reactive moieties. In TBT-SPC systems, hydrolysis liberates organotin compounds, while in tin-free variants, ion exchange or hydrolytic cleavage of pendant groups releases copper ions or organosilicon fragments. These bioactive species act by disrupting cellular function, hindering growth, and deterring adhesion. Additionally, the presence of booster biocides such as Sea-Nine, Irgarol, or Diuron enhances efficacy, particularly against algae and bacteria, by targeting specific photosynthetic or metabolic pathways. Many of these coatings exhibit a self-polishing effect, wherein the outermost layer erodes under hydrodynamic forces, continuously exposing fresh biocide-rich surfaces. This erosion not only maintains consistent biocide release rates but also prevents the accumulation of roughness that could facilitate biofilm formation, thus optimizing both antifouling performance and vessel efficiency [56].

4.2. High-Pressure Water Blasting

Ahn et al. [57] investigated the effectiveness of high-pressure water jet cleaning for the removal of biofouling from ship hulls, using the Taguchi method to identify key factors influencing cleaning performance. Their study found that pump pressure is the most critical factor in removing large biofouling organisms. The experiments demonstrated that a minimum pump pressure of 180 bar and a spray distance of 0.05 m were necessary to remove biofouling effectively, while minimizing damage to antifouling coatings. Image analysis revealed significant differences in cleaning efficiency across various materials and biofouling types, with copper and antifouling coatings achieving the highest removal rates. The research provides valuable insights for optimizing high-pressure water jet cleaning systems and minimizing coating damage during biofouling removal.

Ji, Fang, and Kang [58] conducted experimental research to optimize cavitation water jet cleaning for marine biofouling removal, focusing on minimizing hull surface damage while maximizing cleaning efficiency. Their results showed that a water jet pressure of 16 MPa, a standoff distance of 25 mm, and a 90° incidence angle provided optimal cleaning with minimal erosion. They also developed a regression equation to predict surface roughness post-cleaning, aiding future parameter optimization. This study highlights cavitation water jet technology as a promising, effective, and controllable method for biofouling mitigation on marine structures.

4.3. Underwater Robots (ROVs)

Underwater remotely operated vehicles (ROVs) are distance-controlled or autonomous machines equipped with specialized tools, such as brushes or high-pressure water jets, designed for periodic cleaning of mooring lines (Figure 4). Kostenko, Bykanova, and Tolstonogov [59] reported on the use of ROVs to inspect and clean submerged vessel surfaces using laser radiation. Remotely operated brush systems are used to remove fouling from finfish farm production nets [60].

Figure 4. ROV for cleaning with partial inspection function [48].

Research has been conducted on the design of new composite underwater hull-cleaning robots. These studies focus on integrating traditional mechanical cleaning methods with advanced technologies to effectively remove biofouling from submerged surfaces [61]. Furthermore, the offshore renewable energy (ORE) Catapult has analyzed the impacts of robotics in offshore wind operations and maintenance. Their findings suggest that implementing robotic solutions can lead to significant cost reductions and improved safety in offshore wind farm maintenance [62].

Zhao et al. [63] proposed an innovative approach to identifying and classifying biofouling on ship hulls using an underwater cleaning robot equipped with deep learning software. They developed the filter-guided inverse dark-channel inversion exposure compensation (FIDCE) algorithm to enhance underwater images under poor lighting conditions and integrated it with MFONet, a lightweight CNN-based segmentation model optimized for embedded systems. MFONet achieved higher segmentation accuracy and speed than classical methods, improving the mIOU and mPA scores significantly. This system enables fine-grained, pixel-level biofouling detection, supporting adaptive cleaning operations and reducing damage to antifouling coatings. Their work demonstrates the potential of integrating real-time AI and robotics for efficient and intelligent underwater maintenance.

4.4. Ultrasound Waves

Ultrasound waves present a promising non-chemical method for biofouling control on vessel hulls and submerged surfaces. Most effective frequencies range between 17 and 30 kHz, with lower ultrasonic frequencies (~19 kHz) showing higher efficacy against barnacle settlement [64]. Unlike audio frequencies, which may disturb marine life or even attract some fouling species, ultrasound is safer and more targeted. While initial lab and small-scale trials show positive results, large-scale, standardized studies are still needed to optimize its application for offshore structures like floating wind turbines [64].

Underwater vessel noise may promote biofouling by accelerating the settlement of mussel larvae (*Perna canaliculus*). Exposure to the noise produced by a 125 m steel-hulled ferry reduced the settlement time by 22–40% compared to silent controls. The faster settlement of larvae was correlated with the intensity of the vessel sound, suggesting that noise could be a key factor in increasing hull fouling. While further research is needed to explore this effect across different species and surfaces, mitigating underwater noise could reduce fouling problems in marine infrastructure [65].

It must be noted that companies like Sonihull have implemented ultrasonic antifouling systems to control marine growth on offshore wind turbine foundations. Their technology aims to lower capital expenditures by reducing the structural steel requirements needed to account for additional hydrodynamic loadings from biofouling [66].

Salimi et al. [67] proposed a novel ultrasonic system utilizing marinized high-power ultrasound transducers (HPUTs) to remove and prevent biofouling on offshore wind turbine ladders through localized cavitation. The system demonstrated a non-invasive, non-toxic method that remains within safe underwater noise thresholds (below 120 dB SPL at 25 m). While marinization slightly reduced the transducer efficiency due to mechanical and electrical mismatches, the study showcased the system's potential in detaching biofouling. Initial in situ tests confirmed limited yet promising removal effectiveness, suggesting that further optimization could lead to scalable, eco-friendly biofouling mitigation solutions [67]. Figure 5 shows the impact of a single low-amplitude HPUT on biofouling.

Figure 5. Biofouling being removed with an HPUT, with the green arrow indicating the HPUT's position behind the plate [67].

4.5. Biological Control

Augmentative biocontrol using native natural enemies has shown promise as a tool for managing biofouling on artificial submerged structures, such as offshore floating wind turbines. Atalah et al. [68] conducted a field experiment on floating marine structures to assess the effectiveness of three invertebrate biocontrol agents: the 11-arm seastar (*Coscinasterias muricata*), the sea urchin (*Evechinus chloroticus*), and the gastropod (*Cookia sulcata*). Their study found that the identity of the biocontrol agent was more critical to fouling control than the density or diversity of the agents. Specifically, the seastar and the gastropod were the most effective for biofouling reduction and prevention, respectively. Interestingly, higher densities or multi-species treatments did not outperform single-species treatments. Surface orientation also played a significant role in the effectiveness of these agents, with the best results observed on vertical surfaces. The study concluded that biocontrol is more effective for preventing the establishment of fouling organisms on defouled surfaces, but it has limitations in managing established biofouling communities, especially on diagonal or underside surfaces, where the retention of agents is challenging. The authors suggested that biocontrol may not be suitable for movable structures like ship hulls, where alternative methods, such as antifouling coatings, would be more effective [68].

Atalah et al. [69] explored the use of native benthic grazers as biocontrol agents to mitigate biofouling on artificial marine structures. In caging experiments, gastropods such as *Haliotis iris* and *Cookia sulcata* significantly reduced both established biofouling (by over 55%) and new accumulation on pontoons and wharf piles. *C. sulcata* showed particularly promising results due to its high efficacy, survival, and retention. The study highlights augmentative biocontrol as a viable, sustainable strategy for managing marine biofouling and invasive species. It emphasizes the need for further research into scaling, optimal deployment densities, agent combinations, and cost-effectiveness to support broader application.

4.6. Wrapping and Encapsulation

Ref. [70] studied encapsulation as a biofouling management technique, focusing on factors like temperature, biomass, and biocides. Their findings suggest that encapsulation can effectively control biofoulers, with acetic acid accelerating mortality rates, especially for hard biofouling species. In laboratory and field trials, higher temperatures, greater biomass, and longer encapsulation times increased mortality. For offshore floating wind turbines, encapsulation, particularly with biocides, offers a promising non-chemical solution to manage biofouling, with treatment times varying depending on species and environmental conditions. However, further research is needed to optimize protocols for specific offshore applications.

Drawbacks include the potential for plastic waste entering the environment and the accumulation of non-reusable waste over time. Additionally, encapsulation materials can become fouled themselves unless they possess antifouling properties, necessitating timely application to prevent excessive fouling that might worsen the issue. Enhancements in encapsulation fabrics to simplify deployment, improve reusability, and minimize environmental impact would be advantageous [4].

5. Future Trends, Innovations and Active Lines of Research

5.1. Eco-Inspired Coatings

One promising area of research and development focuses on innovative non-biocidal antifouling coatings and materials. Efforts have been directed toward a wide variety of approaches within three primary categories: foul-release, surface topography, and physicochemical properties.

Novel foul-release coatings encompass a broad spectrum of technologies, ranging from advanced amphiphilic polymer composites and fluoropolymers [71,72] to simpler coatings embedded with silicone [73] or food-grade oils [74].

Additionally, an alternative approach consists of antifouling surfaces designed with engineered topographies that replicate natural fouling-resistant surfaces, such as those found on mussel shells and shark skin [75,76]. Munther et al. [77] developed a biomimetic surface inspired by shark skin, using microfabricated placoid scale patterns in polydimethylsiloxane elastomer (PDMSe) Unlike previous designs with uniform heights, this study introduced an engineered height gradient to mimic the natural variability of shark skin, improving its effectiveness against biofouling. The results demonstrated a 75% reduction in *Escherichia coli* settlement on pristine surfaces, and 56% after mechanical wear. These findings show the potential of biomimetic coatings for sustainable biofouling control, particularly with further improvements possible by refining the design to counter bacterial attachment more effectively. Jo et al. [78] introduced an innovative method for creating shark-skin-mimetic surfaces using a photoreconfigurable azopolymer. Inspired by the dermal denticle structures of sharks, which are known for their low drag and antifouling properties, this technique allows for the precise manipulation of denticle features like depth, density, and inclination. The light-designed surfaces exhibited hydrophobicity and antifouling effects similar to those of natural shark skin. This novel fabrication method offers a scalable, cost-effective solution for creating low-drag antifouling surfaces, with potential applications in mitigating biofouling on offshore floating wind turbines and other marine structures.

5.2. AI-Driven Monitoring of Biofouling Accumulation

Signor et al. [79] developed an innovative deep learning methodology for automatic biofouling classification on offshore renewable energy (ORE) structures. Using a convolutional neural network (CNN), the study classified macro-biocolonization into categories like mussels, barnacles, and calcareous worms. Despite a small database of images (1261), the model achieved an overall detection accuracy of 69%, with mussels and "no biofouling" achieving detection rates of 81% and 79%, respectively. This study marks a significant step in applying machine learning to biofouling monitoring, providing ORE operators with a tool for efficient detection and assessment. The authors recommended expanding the image database and refining the algorithms to enhance accuracy and optimize engineering decisions, especially in detecting hydrodynamic impacts and assessing cleaning effectiveness.

Rashid et al. [80] developed an automated system for detecting biofouling on tidal stream turbine blades using camera-based surveillance and You Only Look Once (YOLO) version 8. YOLO is a real-time object detection system based on convolutional neural networks. By training the model with annotated video images, the system effectively distinguishes between biofouled and clean blades. YOLO 8 showed superior performance over previous versions, with improved accuracy through data augmentation. The overall assessment reached an accuracy of 97.3%, as shown in the confusion matrix in Figure 6. This AI-driven approach offers a cost-effective and efficient alternative to traditional biofouling detection, making it a promising solution for offshore substructures.

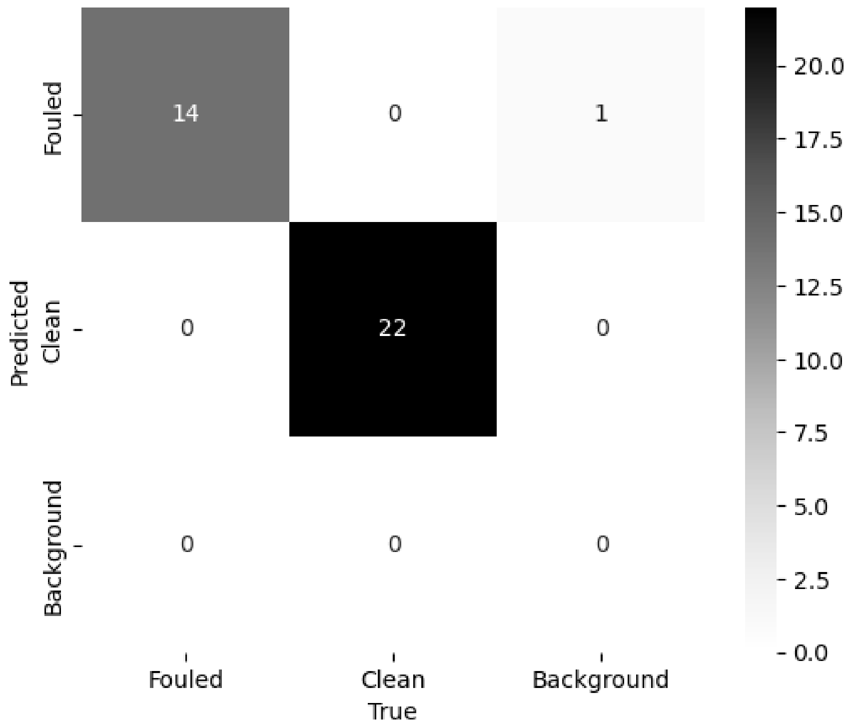

Figure 6. Confusion matrix for the biofouling detection performance [72].

5.3. Advanced Coating Materials

Repairing coatings on offshore wind structures is often challenging and highly costly, potentially reaching up to 50 times the cost of the original application. These challenges could be mitigated by using more durable or self-healing coatings [4].

Extensive global research efforts aim to develop alternative coating technologies [81,82] that provide environmentally friendly solutions to minimize biofouling on submerged substructures. Significant progress has been made in exploring eco-friendly antifouling biocides derived from bioactive natural products. These antifouling compounds have been identified across a broad spectrum of marine and terrestrial invertebrates, plants, and microorganisms [83,84], demonstrating diverse mechanisms of action [85].

Some natural products exhibit antifouling effectiveness comparable to that of current biocides and booster biocides (organic compounds that, in combination with copper, are used in antifouling paints to prevent the colonization on submerged surfaces), and in certain cases, their potency has been enhanced through synthetic or semi-synthetic modifications (e.g., [86–88]). Despite their promise, these natural products have yet to be successfully developed into practical antifouling products. Several obstacles hinder the transition from research and development to a marketable product [4]. These include limited availability, as many natural products exist only in small quantities in nature and are challenging to synthesize. Additionally, some natural products possess unsuitable physicochemical properties, making them incompatible with coating matrix systems, or leading to suboptimal stability. Regulatory hurdles also pose significant challenges, including stringent data gathering requirements and the approvals needed to introduce a new biocide to the market [4].

A strategy that has shown some success involves the development or repurposing of synthetic bioactive compounds. For instance, medetomidine, initially created as a surgical anesthetic and analgesic, has been adapted for use as a deterrent against barnacle settlement [89]. This compound has been successfully registered and commercialized by i-techAB (Sweden) under the name Selektope™, making it the first innovative antifouling biocide to enter the global market in recent years [90].

Zhang et al. [91] developed a novel marine coating that integrates copper-based metal–organic frameworks (Cu-MOF-74), carboxyl-functionalized multi-walled carbon nanotubes (MWCNT-COOH), and self-healing polymers. This multifunctional coating exhibits both stable, controlled release of Cu^{2+} ions for antibacterial activity and excellent self-healing properties due to non-covalent hydrogen bonding within the polymer matrix. The inclusion of MWCNT-COOH enhances antimicrobial effectiveness while reducing the need for a high copper content, improving environmental safety. Laboratory results demonstrated up to 93% antibacterial efficiency and strong resistance to macrofouling adhesion, suggesting the coating's potential for long-term, eco-friendly application in offshore structures exposed to biofouling.

Spera et al. [92] introduced a scalable, self-healing protective coating using core–shell nanofibers created through coaxial electrospinning. The core contains a single-component, water-activated healing agent that autonomously restores coating integrity upon mechanical damage—eliminating the need for complex, multi-component systems. The nanofibers were successfully integrated into a spray-applied solvent-based coating system, compatible with large-scale offshore structures. Electrochemical and salt spray tests demonstrated a rapid healing efficiency of 97.5% and strong corrosion protection, confirming the coating's potential to enhance the durability and resilience of offshore components, particularly against damage-prone environments where biofouling and corrosion risks intersect.

Liu et al. [93] developed a self-healing, antifouling nanocomposite coating based on a novel PDMS-poly(urea-thiourea-imine) (PDMS-PUTI) matrix enhanced with silver nanoparticles (AgNPs). The dynamic bonding network within the polymer enabled complete scratch recovery within 10 min at room temperature. The addition of AgNPs not only enhanced the antibacterial performance, achieving over 96% effectiveness against common marine bacteria, but also improved the fouling resistance by reducing the surface energy, which is the amount of energy present at the surface of a material due to molecular forces. The AgNPs-9/PDMS-PUTI formulation showed a good balance among self-healing, antibacterial efficiency, and surface properties, although higher nanoparticle contents could negatively affect adhesion and coating smoothness. This approach presents a cost-efficient route to high-performance, environmentally friendly silicone-based coatings for marine applications, with the potential to significantly reduce biofouling, energy losses, and environmental impact.

5.4. Physical Methods: Thermal and Electrical

Heat treatment has been successfully used to eradicate the invasive seaweed *Undaria pinnatifida* from a sunken vessel. The method involved applying high temperatures to kill various life stages of the species, including gametophytes. The treatment proved highly effective, achieving eradication with 100% mortality for most taxa after treatment, although monitoring was essential to ensure that no individuals remained. The success of this eradication program highlighted the importance of early detection, rapid response, and targeted treatment of multiple life stages. Additionally, the study demonstrated the potential of heat treatment as an environmentally friendly alternative to toxic chemicals for managing invasive species and preventing further biofouling. Further development of thermal methods could expand their use on natural substrates [94].

Heated seawater is an effective and environmentally friendly method for controlling biofouling in vessel sea chests. Laboratory trials with three temperature regimes (37.5 °C for 60 min, 40 °C for 30 min, and 42.5 °C for 20 min) achieved 100% mortality for most temperate species, although barnacles and oysters showed some resistance. Field trials replicated these results, but challenges in achieving uniform heat distribution hindered complete mortality. This method offers promising potential for vessels in temperate latitudes, although further studies are needed to address its efficacy on more resilient species and determine optimal treatment regimens [95]. Also, its effective application in the ORE industry still requires substantial research and development efforts.

Piyadasa et al. [96] reviewed the application of electromagnetic fields (EMFs), specifically pulsed electromagnetic fields (PEFs), in mitigating scaling and biofouling in reverse-osmosis (RO) membrane systems, which share similar challenges to those faced by offshore substructures. EMF technologies have been proposed as an alternative to chemical antifouling agents. However, while the use of EMFs is a promising approach, its effectiveness is still a subject of debate. Despite several studies suggesting potential benefits, the scientific basis for EMFs' ability to prevent or reduce biofouling has not been firmly established, and much of the available evidence is inconclusive. The authors highlighted that while some studies show that EMFs can alter nucleation and precipitation processes, potentially reducing scaling, there is less convincing evidence for their antimicrobial effects. Furthermore, the application of EMFs in real-world settings, including desalination facilities, has been limited due to a lack of standard operating procedures, and the findings from the few peer-reviewed studies available remain inconsistent. Despite these challenges, the review suggested that, with a better understanding of the mechanisms behind EMF exposure, and improved experimental conditions, this technology could offer a non-chemical solution to biofouling and scaling in membrane systems, and potentially for offshore floating wind turbines as well.

5.5. Bubble Streams

Air bubble curtains offer a non-toxic method to reduce biofouling on stationary marine structures. By continuously releasing bubbles along submerged surfaces, they deter organisms' settlement. Trials on panels and a vessel patch showed effective fouling prevention, with potential for broader use on offshore structures like floating wind turbines [97].

Studies have also demonstrated that continuous bubble streams can significantly reduce the accumulation of macroscopic biofouling organisms on submerged surfaces over short-to-medium timescales. For instance, laboratory and field trials have shown that this approach is effective on various surface types that are commonly used in marine environments [98,99].

However, implementing bubble stream systems on deeper structures, such as offshore wind turbines and oil rigs, presents additional challenges. Factors like increased air dissolution rates and changes in bubble volume with depth necessitate further studies to assess the feasibility and effectiveness of this approach in such settings [99].

6. Conclusions

This study highlights the complex and multifaceted impact of biofouling on offshore floating wind turbines, particularly in terms of structural performance, maintenance challenges, and ecological considerations. Through the analysis of experimental data, computational modeling, and site-specific observations, it was demonstrated that biofouling significantly alters hydrodynamic loading, increases mass and drag, and influences the dynamic response of floating platforms. While current design practices often underrepresent these effects, this work emphasizes the need for more realistic and comprehensive inclusion of biofouling in design standards and simulation models.

The implications of biofouling extend beyond engineering concerns, with potential impacts on local marine biodiversity and the development of novel bioinspired coatings and antifouling strategies. Moving forward, collaborative efforts between marine biologists, engineers, and industry stakeholders will be essential in developing adaptive solutions that balance structural resilience, cost-effectiveness, and environmental stewardship.

Ultimately, accounting for biofouling is not merely a matter of performance optimization but a critical step in ensuring the long-term sustainability, safety, and viability of floating offshore wind as a major pillar in the global renewable energy transition.

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