The Effect of Biofouling on Cement based Concrete Substrate: Insights from Microfouling and Macrofouling Growth

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Abstract. Biofouling poses a significant impact to the durability of offshore structures and vessels, yet its impact on cement-based concrete structures in marine environments remains underexplored. This study investigated biofouling growth on concrete substrates both microbial biofilms (microfouling) up to macrofouling and their effect on cement based concrete surface. The discussion is supported by a literature review to contextualize the findings. The type and growth of microorganisms forming biofilms and macrofouling are influenced by the specific marine environment, substrate characteristics, and immersion duration. These factors collectively impact concrete substrates by altering microbial community composition, biochemical activity, and mechanisms of attachment. The microfouling and macrofouling growth contribute to chemical degradation, surface roughness alteration, and the addition of weight. Such combined effects accelerate the biodeterioration and highlighting the critical need for effective mitigation strategies to enhance the durability. Protective approaches, including antifouling coatings, surface treatments, and advanced materials resistant to bioadhesion, are essential to prolong the lifespan and ensure the durability of marine concrete structures exposed to both biofilm formation and macrofouling.

1 Introduction

Biofouling is the accumulation or colonization of microorganisms, plants, algae, and animals on hard man-made surface structure that submerged in marine environments [1]. The stages of biocolonization started from the substrate is submerged. In a second after the structure submerged, the organic and mineral content from seawater is adsorbed onto the surface, a process known as surface conditioning. This process changes the surface's physicochemical properties, stabilizing bacterial adhesion mechanisms. Continued by attaching one or more bacterial species forming bacterial biofilms (microfouling). These biofilms consist of one or

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more bacterial species adhered to the surface and encapsulated within an extracellular polymeric substance (EPS) matrix. This matrix is composed of proteins, glycoproteins, glycolipids, extracellular DNA, and polysaccharides [2]. Several days to months, other microorganisms and macroorganisms, such as diatoms, algae, and larvae, attach to the surface, leading to the formation of macrofouling [3]. Microorganisms are mainly represented by sessile bacteria, diatoms, microscopic fungi, heterotrophic flagellates, sarcodines, and sessile ciliates. Macroorganisms such as sponges, hydroids, corals, sessile polychaetes, barnacles, mussels, bryozoans, sea cucumbers, ascidians [4]. While biofouling is an inevitable phenomenon in aquatic environments, its implications vary significantly depending on the substrate and context [5].

The durability and stability of offshore platforms, oil rigs, ships, and aquaculture equipment are particularly vulnerable to the long-term effects of biofouling. However, the role of biofouling on concrete substrates remains less understood. This paper reviews the effects of biofouling on concrete substrates, focusing on whether the growth of microbial biofilms and macrofouling organisms results in biodegradation or bioprotection. By examining both the literature and recent findings, this study seeks to clarify the role of biofouling and its implications for the durability of cement-based structures in marine environments.

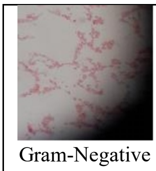
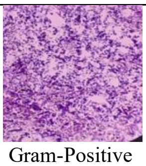
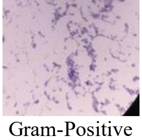
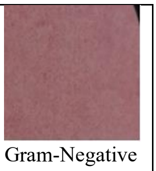
2 Biofouling Growth on Concrete Structure

2.1 Microfouling Growth

The biochemical mechanism of microbial colonization on cement surfaces in marine environments begins with the formation of biofilms [5]. It is complex structure created by bacterial metabolic activity. Bacteria initially adhere to the concrete substrate, facilitated by the production of extracellular polymeric substances (EPS), which form the primary matrix of biofilms. EPS, composed of polysaccharides, proteins, lipids, and nucleic acids, serve as a scaffold that stabilizes bacterial communities and enhances their adhesion to the surface [11], [12]. The EPS matrix also traps nutrients and metabolites, creating a localized environment conducive to microbial growth and survival.

Table 1 shows the result of microscopic identification by swapping the biofilm sample from the concrete surface immersed under Suramadu Bridge, Indonesia at the tidal zone. By the microscopic identification revealed that the biofilms composed both gram-negative and gram-positive bacteria in cocci and bacilli forms. More comprehensive research related to biofilm growth was continued by identifying the types of bacteria in other places from previous studies as shown in Table 2.

Table 1. Microscopic identification of Micro-organisms from the Concrete Surface Immersed Under Suramadu Bridge, Surabaya, Indonesia

 Gram-Negative Coccus form	 Gram-Positive Bacilus form	 Gram-Positive Bacilus form	 Gram-Positive Bacilus form	 Gram-Positive Bacilus form	 Gram-Negative Coccus form

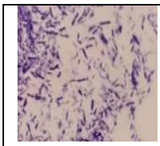
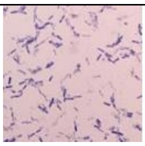
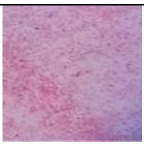
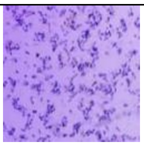
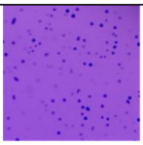
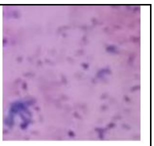
 Gram-Positive Bacilus form	 Gram-Positive Bacilus form	 Gram-Positive Coccus form	 Gram-Positive Coccus form	 Gram-Positive Coccus form	 Gram-Positive Coccus form

Table 2. Bacteria Forming Biofilm on the Concrete Surface in Various Location

Ref	Location	Type of substrate	Exposure and Observation Time	Type of the micro-fouling	Representation About the Growth
[3]	Seawater Basin	Concrete	28 days after immersion	Undescribe	Colony-forming units up to 140 CFU.cm-3
[13]	Seawater from Fiskeb¨ackskil, Sweden	Concrete blocks	455 days	*Caulobacterales, Rhodobacterales, Planctomycetales, Magnetospiraceae, Portibacter, Rubripirellula,* and *Rhodopirellula*	Identified the presence of biofilm formers by DNA
[14]	Weizhou Island, China	Artificial reef	12 weeks after immersion	*Cyanobacteria, Proteobacteria,* and *Planctomycetota*	Identified the presence of biofilm formers by DNA
[15]	Oslofjord tunnel, Norway	Tunnel	-	*Nitrosopumilus* sp, *Desulfobacteria, Nitrospira, Nitrosomonas, Scalindua, Mariprofundus*	Identified the presence of biofilm formers by DNA
[16]	Chiba, Japan	Concrete blocks	1, 2, 3, 7, 14, 21, 30 days after immersion	Diatoms, Red Algae, Green Algae, *Cyanobacteria, Thecate hydrozoa*	Biomass after 30 days exposure up to 70 mg.m-2
[17]	The Fylde coast, UK	The concrete stepped	7 years after immersion	Algae (ulva)	Algal filament penetrated the cement matrix
[18]	Mornington, County Meath, on Ireland's Eastern coast	Concrete tile	a month after immersion	Diatoms, Cyanobacteria, Green Algae	Biomass of diatom and cyanobacteria ranged from 0.1 to 0.5 µg.cm-2 and up to 2.5 µg.cm-2 for green algae.
[19]	Kalpakkam, India	Concrete cylinder	1, 15, 30, 180 days after immersion	Aerobic bacteria, slime formers like Pseudomonas sp., anaerobic sulfate reducing bacteria	Total Viability Count (TVC) of aerobes, slime formers and anaerobes up to 6.48 E9 cfu.cm-2, 2.38 E8 cfu.cm-2, 1157 cfu.cm-2
[20]	Rance river, France	Concrete cylinder	90, 180, and 360 days after immersion	spiral tubes of Spirogyra	Photosynthetic capacity up to 126 µmol.electrons.m-2.s-1

Table 2 shows that the type and growth of microorganisms forming biofilms on concrete surfaces in marine environments are highly influenced by the environmental conditions, substrate type, and the duration of immersion. The water parameter such as salinity, pH, nutrient availability, and temperature, strongly influence the types of microorganisms that colonize concrete surfaces. For example, previous research conducted by Qian et al (2022) revealed that biofilms formed dominated by Cyanobacteria in the western Pacific (Hong Kong and Zhuhai) but are the minority in biofilms from the western Atlantic, where *Verrucomicrobia* dominate [21]. The chemical compositions of the substrate affected the microbial colonization. Previous study by Natanzi et al (2021) found that adding GGBS (Ground Granulated Blast Slag) increasing the biomass of diatoms, *Cyanobacteria*, green algae and barnacle after one month immersion [18].

The surface roughness and micropatterns affect cell recruitment and short-term biofilm biomass accumulation rates, but not long-term growth trends [22]. In the other hand, the timeline of immersion significantly impacts microbial succession. Gaylarde et al (2023) stated that of the microorganisms detected in biofilms on immersed concrete permanently such as Cyanobacteria, Planctomycetales and intermittently i.e. desulfobacteria and nitrosomonas sp. [23]. Biofilm found in Kalpakkam, India in 15, 30, 180 days, both aerobic bacteria and anaerobic sulfate-reducing bacteria [19]. This was indicated the dynamic changes in community composition as the biofilm matured.

For the longer immersion duration i.e. on the Fylde Coast after 7 years, algae (Ulva) filamentous structures penetrating the concrete matrix, demonstrating long-term biodeterioration [17]. Certain conditions need to increase the colonization and the growth of microorganism forming biofilm are the relative humidity in the range of 60 to 98%, High CO_2 concentrations, High chloride ion concentrations or other salts (marine-like environments) [24], [25]. Anothers parameter effected the growth of microorgansm is the abundance of nutrient. Microorganisms such as *Cyanobacteria* and algae absorb CO_2 from atmosphere or water and use sunlight as the source of energy [26]. Karaˇci´ et al (2022) stated that microbial community composition influenced by concrete surface type. For exampel Magnetospiraceae, Portibacter, Rubripirellula, and Rhodopirellula more abundant in biofilms on steel-fiber containing concrete caused by their ability in the oxidation and reduction of iron [13].

In summary, the type and growth of microorganisms forming biofilms on concrete substrates are influenced by the marine environment, substrate characteristics, and immersion duration. These factors determine the microbial community composition, as well as their biochemical activity, which significantly impacts the surface properties of the concrete.

2.2 Macrofouling Growth

The growth and type of marine fouling organisms on concrete substrates are heavily influenced by environmental factors such as salinity, nutrient availability, and hydrodynamic forces, as well as the properties of the concrete and the duration of immersion. Observations conducted at the Suramadu Bridge in Surabaya, Indonesia, highlight this influence. Macrofouling organisms, particularly barnacles, were found colonizing the pile surfaces of the bridge as seen in Fig. 1.

In a controlled experiment beneath the bridge, cubical concrete blocks were deployed in the tidal zone to monitor macrofouling growth. Over time, barnacle coverage on the concrete blocks increased significantly. As illustrated in Fig. 2, the coverage area reached 81.82% after 75 days of immersion, demonstrating the rapid colonization and growth of barnacles in this environment. These findings emphasize the importance of environmental and substrate factors in determining the rate and extent of macrofouling on marine concrete structures, as well as the implications for structural maintenance and durability. In order to providing a comprehensive understanding of macrofouling growth, the types of macrofouling observed in various locations listed at Table 3.

Chtamalus antennatus *Amphibalanus amphitrite* *Amphibalanus improvisus* *Amphibalanus reticulatus*

Fig. 1. The Species Found at Suramadu Bridge Pile, Indonesia.

Duration (day)	Coverage area (%)
15	54,06
30	62,13
45	71,37
60	74,20
75	81,82

Fig. 2. Concrete Cube Covered with Barnacles at Tidal Zone Under Suramadu Bridge, Indonesia

Table 3. Macrofouling on the Concrete Surface in Various Location

Ref	Location	Type of substrate	Exposure and Observation Time	Type of the micro-fouling	Representation About the Growth
[3]	Seawater Basin	Concrete tile	113 days after immersion	undescribe	Dry biomass up to 0.4 mg.cm^{-2}
[18]	Mornington, Ireland's Eastern coast	Concrete tile	a month after immersion	Barnacle	Ranged from 200 to 3000 individu
[19]	Kalpakkam, India	Concrete cylinder	1, 15, 30, 180 days after immersion	Barnacles, Mussels, Bivalve	Coverage area up to 100% over the surface
[20]	Rance river, France	Concrete sylinder	90, 180, 360 days after immersion	Oyster, Rhodophyta, Chlorophyta, Calcareus Tubeworm	The chlorophyll biomass up to 276 a.u after 360 days
[27]	Madeira Island, (NE Atlantic, Portugal)	Rocky form	12 months after immersion	Bryozoans, ascidians, annelids, macrophytes	Coverage area of Bryozoans 29.2%, ascidians 24.9%, annelids 18.7%, macrophytes 10.4%
[28]	Suramadu, Indonesia	Pile of Bridge	4 weeks observation	Bernacles, Mussels	Adding 3875 – 16544 ind.m^{-2} in every week
[29]	Karimunjawa Islands, Indonesia	Artificial reef	-	*Septifer* sp and *Neodexiospira* sp.	96 ind.m^{-2}

Ref	Location	Type of substrate	Exposure and Observation Time	Type of the micro-fouling	Representation About the Growth
		(concrete blocks)			
[30]	Trenggalek, Indonesia	Artificial reef	2 years after immersion	tubeworm, barnacle, hermit crab, bryozoan, green algae, tunicate, hydroid, brown algae, sponge, and red algae	The growth of barnacle up to 6114 individu and the tubeworm 10 individu
[31]	West Nusa Tenggara, Indonesia	Artificial reef	10 months after immersion	Alga, barnacle, Gastropod, Bivalve, Echinoida, Tunicata, Soft Coral,	The growth of biofouling up to 1137 individu
[32]	Yellow Sea, China	Breakwater/ seawall	15 years after immersion	Barnacle	Coverage area ranged from 10.4% to 75.2%
[33], [34]	Puducherry, India	Concrete cube	9 months after immersion	Alga: *Chaetomorpha antennina, Ulva fasciata*	By SEM show that *Chaetomorpha antennina* attached concrete surface
[35]	Suruga Bay, Japan	Reinforced concrete	9 years after immersion	barnacles, oysters and mussels	Coverage area up to 96% over the surface
[36]	Arabian Gulf, mediterranean sea	Concrete cylinder	6, 12, and 18 months	shells, algae, and other marine organisms	Coverage area up to 100% over the surface
[37]	Yokosuka, Honshu, Japan	Concrete cylinder	Observed monthly up to 12 months	*Mytilus edulis galloprovincialis*, *Chthamalus challeneri*, *Crassostrea gigas* red algae (*Porphyra* sp. and *Gracilaria verrucosa*)	Identified the presence of macrofouling
[38]	Cornwall, UK	Concrete cube	32 months after immersion	barnacles *(Chthamalus spp.)*	Coverage area up to 95% over the surface

The environmental factors significantly influence on macrofouling development. Table 3 illustrated the type of macrofouling in various location to fit up the comprehensive knowledge about macrofouling growth in others places. Research by Natanzi et al. (2021) revealed that the density of barnacles colonizing concrete tiles in Mornington, Ireland, ranged from 200 to 3,000 individuals per tile after one month of immersion. In contrast, long-term studies conducted by Isdianto et al. (2020) at Trenggalek, Indonesia, showed significantly higher barnacle densities, reaching up to 6,114 individuals per square meter on artificial reefs after two years of immersion. This comparison highlights the influence of environmental factors and immersion duration on barnacle colonization.

The macrofouling communities vary based on environmental conditions. The growth of macrofouling, as represented by biomass measurements in various studies, highlights distinct differences across locations. Research conducted at the Rance River in France demonstrated significant macrofouling biomass, particularly from oysters and chlorophyta algae, with chlorophyll biomass reaching 276 a.u. after one year of immersion [20]. Meanwhile, studies in the Karimunjawa Islands in Indonesia identified a dominance of serpulid worms, specifically Neodexiospira and Septifer species [29]. The differences in water salinity, nutrient availability, and exposure determine the colonization rate and type of organisms [39], [40]. Bryozoans, ascidians, and macrophytes dominate Madeira Island, Portugal [27] meanwhile in Suramadu, Indonesia, encourage barnacle and mussel colonization due to their texture and nutrient adsorption capabilities [28].

The growth and type of marine fouling organisms on concrete substrates are directly influenced by environmental conditions, substrate properties, and time [4], [8], [41]–[43]. Regions with higher nutrient availability and optimal marine conditions encourage rapid colonization, while the substrate type determines species diversity. These findings are essential for understanding biodeterioration in marine environments and managing biofouling on concrete structures.

3 Impact of Biofouling on Concrete Substrate

3.1 The Effect of Micro-organisms to Concrete Substrate

3.1.1 Biochemical Mechanism

Bacterial metabolism within biofilms plays a critical role in altering the chemical properties of the cement matrix [44]. The microorganism and bacterial metabolism on concrete produce many biogenic corrosive substances as seen in Table 4 that causing the damage of the cement matrix [45]. The damage of the cement matrix resulting the deterioration of the concrete surface. As the surface concrete deteriorates the depth of cover over the reinforcement is reduced which potentially make the structure more susceptible to corrosion of the reinforcement [46].

Microbial biofilms in marine environment significantly affected concrete substrate by initiating and accelerating biodeterioration through various biochemical mechanisms. Nitrifying bacteria, such as Nitrosomonas, Nitrosococcus, Nitrosospira, and Nitrosolobus, oxidize ammonium (NH_4^+) to nitrite (NO_2^-) and nitrate (NO_3^-), producing nitric acid as a byproduct. This acid reacts with cement matrix, forming calcium nitrate which is water-soluble product that easily leaches from the concrete. This mechanis can reduce the strength and durability [47], [48]. Crenothrix, Gallionella, Leptothrix, and Acidithiobacillus ferrooxidans, concluded as iron-oxidizing bacteria can oxidize the ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}). This process promotes the corrosion of steel reinforcement within concrete, particularly in environments where steel-reinforced concrete is exposed to seawater [49]. The corrosion products weaken the bond between steel and the surrounding concrete, leading to structural failure over time [50], [51].

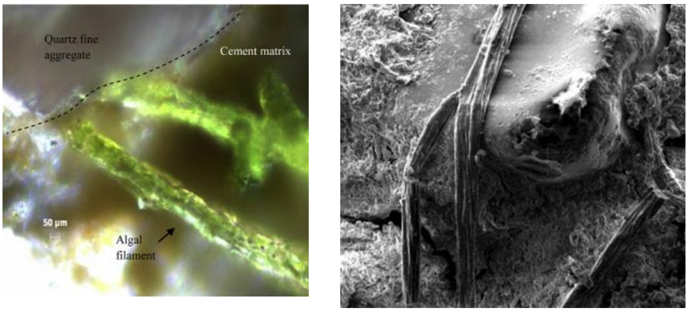
Sulfate-reducing bacteria, such as Desulfobacteria, contribute to biodeterioration by reducing sulfate (SO_4^{2-}) to hydrogen sulfide (H_2S). This byproduct reacts with calcium compounds in cement to form gypsum ($CaSO_4 \cdot 2H_2O$) and other expansive materials. The material induces cracking and spalling of the concrete surface, known as sulfate attack, is a major concern in marine environments [52]. Cyanobacteria, a group of photosynthetic microorganisms, play a dual role in biodeterioration. They produce extracellular polymeric substances (EPS), organic acids, and other metabolites that dissolve minerals and alter the pH of the concrete surface. These activities result in calcium ion leaching and the precipitation of calcium carbonate, creating rough surfaces that enhance microbial colonization [13]. The development of biofilm contributes to the surface roughness of concrete, facilitating the adhesion of other organisms and accelerating biodeterioration. EPS-producing bacteria, such as Pseudomonas sp., form a protective biofilm matrix consisting of polysaccharides, proteins, lipids, and nucleic acids. This matrix traps moisture and acidic metabolites, creating a microenvironment that promotes the dissolution of calcium hydroxide and carbonate. The resulting decrease in pH (as low as 5) further accelerates concrete degradation [11]. Algae can affect concrete by absorbing minerals from concrete such as calcium, magnesium, and silica [24].

Table 4. The microorganism metabolism and its Biodeterioration Activity on Concrete Surface

Microorganism	Biochemical process	Biodeterioration activity	Ref
Nitrifying Bacteria: Nitrosomonas, Nitrosococcus, Nitrosospira, Nitrosolobus	oxidation $NH_4^+ \rightarrow NO_2^-$	Producing the water-soluble calcium nitrate which is easily washed away from the concrete.	[45], [53], [54]
Portibacter, Rubripirellula, and Rhodopirellula, Crenothrix, Gallionella, Leptothrix, Sphaerotilus, Sulfobacillus, Acidithiobacillus ferrooxidans	oxidation $Fe_2^+ \rightarrow Fe_3^+$	involved in the oxidation and reduction of iron	[13], [45]
Desulfobacteria	reduce $SO_4^{2-} \rightarrow H_2S$	produce gypsum and other corrosion products.	[55], [56]
Cyanobacteria,		dissolution of minerals and the precipitation of calcium carbonate	[56]
Slime (EPS) forming bacteria like Pseudomonas sp.	polysaccharides, proteins, lipids, and nucleic acid	Produce calcium hydroxide, carbonate, higher humidity and acidity (pH decrease up to <5)	[55], [57]

The type and growth of microorganisms forming biofilms depend on the specific marine environment, substrate characteristics, and immersion duration. These factors collectively influence microbial community composition, biochemical activity, and their effects on surface concrete substrates. Such findings are essential for developing strategies to mitigate biodeterioration in marine structures.

3.1.2 Physical Mechanism



(a) (b)

Fig. 3. Alga Filaments penetrating the cement matrix in the concrete [17]


(a) (b)

Fig. 4. Biodeterioration caused by microfouling: (a) visual of concrete block day 1 (left), day 301 (middle), and day 413 (right) [13], (b) Biofilms covering concrete surfaces (Cyanobacteria) at San Francisco de Campeche city, Campeche, Mexico [23]

Fig. 3 illustrates the interaction between algal filaments that penetrated the cement matrix into the concrete structure. Algal filaments can infiltrate micro-cracks and interfacial zones within the cement matrix, as seen in this microscopic image Figure 2 (a). These organisms, primarily cyanobacteria and green algae, play a significant role in the biodeterioration of concrete, particularly in marine or humid environments. The unsputter coated sample in Figure 2 (b) showing the filament in its natural condition. A branched mature filament can be seen growing over the exposed fine aggregate. The physical penetration of algal filaments into the concrete exacerbates the damage by increasing porosity and creating pathways for water and ions. This promotes further chemical attack and leaching of critical compounds like calcium from the cement matrix and increase the vulnerability of the concrete to mechanical and environmental stressors. Fig.4 illustrated the biodeterioration influenced by microfouling attachment. This result emphasizes the necessity of implementing strategies for mitigating the biodeterioration caused by microfouling in marine environments. Potential approaches include applying protective coatings to concrete surfaces and incorporating antibacterial or antifouling materials into the concrete mixture to prevent or reduce microbial colonization and its damaging effects.

3.2 The Effect of Macro-organisms to Concrere Substrate

The mechanisms of biodeterioration caused by macrofouling as shown in the Figure 4. Boring organisms, such as piddocks, create physical damage by drilling into the substrate, forming holes that allow water and salt to penetrate deeper into the material. This infiltration weakens the structure, leading to honeycombing and material loss. Mussels and other shell organism contribute to biodeterioration through their byssal threads, which penetrate the substrate, causing microcracks. These microcracks provide pathways for water and salt ingress, accelerating the deterioration process. Algae, through their holdfast attachment structures, exacerbate substrate degradation by penetrating the surface, forming additional microcracks, and facilitating salt and water ingress. Attachment of macrofouling followed by biochemical process as metabolit activity product from macrofouling as describe in Table 5.

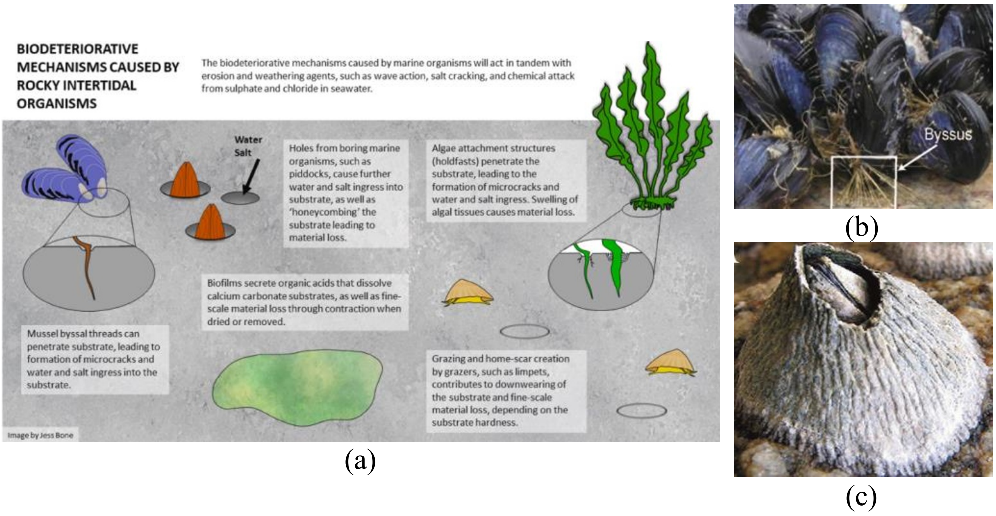


Fig. 5. Biodeterioration caused by Macrofouling Community: (a) Attachment mechanism of macrofouling [58], (b) mussels byssal on the substrate (c) barnacle permanent adhesion [59]

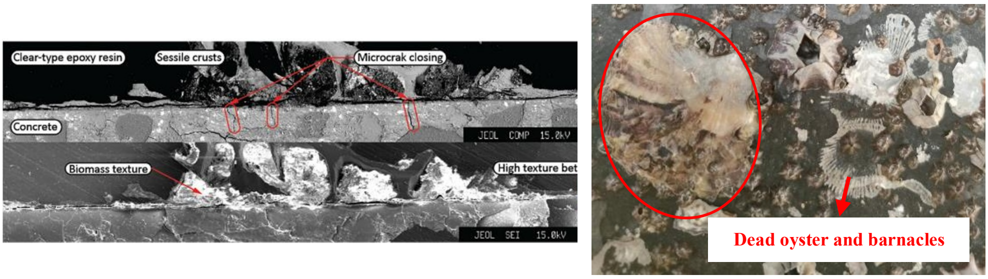
3.2.1 Biochemical Mechanism

Table 5. The Macroorganism Metabolit Activity and its Biodeterioration Activity on Concrete Surface

Macroorganisme	Biochemical process	Biodeterioration activity	Ref
Macro-algae (*Chaetomorpha antennina, Ulva fasciata*)	the presence of fatty acid (i.e. $C_{20}H_{38}O_2$ – Nonadecylenate)	The leaching of binding materials with the consequent weakening of the crystal structure	[33], [34]
Barnacles *(Megabalanus rosa, Amphibalanus Amphritite,*	The presence of amino acid compositions as adhesive proteins (993 amino acid residues, including a signal peptide)	Dissolved the cement matrix	[24], [59]–[61]

Liang et al (2019) explain the comprehensive review of the biochemistries in the life cycle of a barnacle, and revealed that the amino acid composition depends on the stage of barnacle [60]. Barnacles adhere strongly to marine concrete surfaces through the interaction of their adhesive proteins, which are rich in amino acids, with the cement matrix. This reaction results in the formation of a complex interface where amino acids chemically bind with calcium ions in the hardened cement paste, producing calcium-amino acid complexes [60]. Over time, the resulting biochemical reactions, combined with the physical pressure exerted by barnacle growth, contribute to microcrack formation and structural degradation [4].

In contrast, previous researches by Chlayon et al (2018) and Lv et al (2021) revealed the bioprotection ability of barnacles and Crassostrea gigas. Barnacles improve the concrete durability by attaching to the surface of the concrete and sealing underlying microcracks as seen in the Figure 5 (a) [62]. Another shell organisms such as Crassostrea gigas contribute to decrease the chloride ion penetration [63]. The bioprotection on concrete substrates by barnacles cannot last continuously because of their limited life cycle. Barnacles begin to have shells estimated after 7 days to 2 months then becoming adult barnacles for up to 10 months [64]. The barnacle life cycle is complete leaving a shell attached to the substrate which then peels off leaving a mark and roughness as seen in Figure 5 (b). Barnacles and Crassostrea gigas can temporarily enhance concrete durability by sealing microcracks and reducing chloride ion penetration, but their limited life cycle diminishes this bioprotective role over time.



(a) (b)

Figure 5. (a) Bioprotection role of Barnacles [37], (b) Dead Barnacle Contribute to Increase the Roughness Over the Surface of Suramadu Pile, Indonesia of Surface

The surface roughness promotes further biofouling by other organisms [10], [30], [65]. Moreover, barnacle shells and their calcareous deposits add significant weight to marine structures, with shell densities ranging from 1050 to 1325 kg/m³ [66]. Maduka et al (2023) reviewed about the hydrodynamic loading on the stable structure offshore wind turbines. The study revealed that biofouling have its intrinsic randomness and uncertainty to calculate the hydrodynamic coefficients. These coefficients depend on surface coverage percentage, relative surface roughness, roughness geometry and shape, biofouling species, and multilayering and spacing of various marine species. However, it can conclude that biofouling contribute to the change of the hydroynamic loading [67]. In the other hand, the impact of macrofouling organisms on concrete substrates not only on the structure but also affects the aquatic ecosystem due to their invasive nature. Invasive species harm native biodiversity by introducing species from outside their natural habitat. Jaberimanesh et al (2019) stated that *Amphibalanus* sp. is an invasive barnacle [68], the species also found in Indonesia specifically in the Madura Strait [43]. Based on the explanation regarding the impact of fouling organisms, it can be concluded that the presence of these organisms should be considered as one of the contributing factors to structural degradation, in addition to the effects of seawater itself.

The type and growth of macrofouling are influenced by the specific marine environment, substrate characteristics, and immersion duration. These combined effects such as chemical degradation, surface roughness alteration, and additional weight highlight the need for effective strategies to mitigate biodeterioration. Protective approaches, such as antifouling coatings, surface treatments, and the use of advanced materials resistant to bioadhesion, are essential for prolonging the lifespan of marine concrete structures exposed to macrofouling.

4 Conclusion

The growth of microfouling, primarily biofilms formed by microorganisms, depends on marine environmental conditions, substrate properties, and immersion duration. These microorganisms secrete biochemical substances that initiate surface degradation. Macrofouling, including barnacles, mussels, algae, and serpulid worms, develops after biofilm formation, with surface roughness and porosity promoting their attachment. Longer immersion leads to greater macrofouling coverage.

Microfouling contributes to biodeterioration through biochemical reactions with the concrete matrix, weakening the substrate and facilitating further damage. Macrofouling causes physical and chemical impacts, such as surface roughness alteration, mechanical pressure, and increased structural load. While some macrofouling organisms temporarily seal microcracks, their life cycles result in surface roughness that promotes further fouling. Macrofouling also support the spreading of invasif aquatic species.

Such combined effects accelerate biodeterioration, emphasizing the critical need for effective mitigation strategies to enhance the durability of marine concrete structures. Protective approaches, such as antifouling coatings, surface treatments, and the development of advanced materials resistant to bioadhesion, are essential for extending the lifespan and ensuring the structural integrity of concrete exposed to both biofilm formation and macrofouling in marine environments.

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References

1. D. M. Yebra, S. Kiil, and K. Dam-Johansen, “Antifouling technology - Past, present and future steps towards efficient and environmentally friendly antifouling coatings,” *Prog. Org. Coatings*, vol. 50, no. 2, pp. 75–104, 2004, doi: 10.1016/j.porgcoat.2003.06.001.
2. L. D. Chambers, K. R. Stokes, F. C. Walsh, and R. J. K. Wood, “Modern approaches to marine antifouling coatings,” *Surf. Coatings Technol.*, vol. 201, no. 6, pp. 3642–3652, 2006, doi: 10.1016/j.surfcoat.2006.08.129.
3. M. Hayek, M. Salgues, J.-C. Souche, E. Cunge, C. Giraudel, and O. Paireau, “Influence of the Intrinsic Characteristics of Cementitious Materials on Biofouling in the Marine Environment,” 2021, doi: 10.3390/su13052625.
4. A. I. Railkin, *Marine biofouling; colonization process and defenses*. 2004.
5. P. Vuong, A. McKinley, and P. Kaur, “Understanding biofouling and contaminant accretion on submerged marine structures,” *npj Mater. Degrad.*, vol. 7, no. 1, pp. 1–11, 2023, doi: 10.1038/s41529-023-00370-5.
6. G. Gizer, U. Önal, M. Ram, and N. Sahiner, “Biofouling and Mitigation Methods: A Review,” *Biointerface Res. Appl. Chem.*, vol. 13, no. 2, pp. 1–25, 2023, doi: 10.33263/BRIAC132.185.
7. I. K. A. P. Utama, Y. A. Hermawan, R. C. Ariesta, S. Risdiyanto, M. Sitinjak, and W. Ardhiyanto, “Protecting the Country from Bio-invasion, a Case Study of Biofouling Management in Indonesia,” *IOP Conf. Ser. Earth Environ. Sci.*, vol. 1250, no. 1, 2023, doi: 10.1088/1755-1315/1250/1/012022.
8. C. Bressy and M. Lejars, “Marine fouling : An overview marine fouling,” *J. Ocean Technol.*, vol. 9, no. 4, pp. 19–28, 2014.
9. T. Yan and W. X. Yan, “Fouling of Offshore Structures in China-a Review,” *Biofouling*, vol. 19, no. sup1, pp. 133–138, 2003, doi: 10.1080/0892701021000057927.
10. M. L. Hakim, B. Nugroho, M. N. Nurrohman, I. K. Suastika, and I. K. A. P. Utama, “Investigation of fuel consumption on an operating ship due to biofouling growth and quality of anti-fouling coating,” *IOP Conf. Ser. Earth Environ. Sci.*, vol. 339, no. 1, 2019, doi: 10.1088/1755-1315/339/1/012037.
11. H. C. Flemming and J. Wingender, “The biofilm matrix,” *Nat. Rev. Microbiol.*, vol. 8, no. 9, pp. 623–633, 2010, doi: 10.1038/nrmicro2415.

12. L. Karygianni, Z. Ren, H. Koo, and T. Thurnheer, “Biofilm Matrixome: Extracellular Components in Structured Microbial Communities,” *Trends Microbiol.*, vol. 28, no. 8, pp. 668–681, 2020, doi: 10.1016/j.tim.2020.03.016.
13. S. Karačić, O. Modin, P. Hagelia, F. Persson, and B. M. Wilén, “The effect of time and surface type on the composition of biofilm communities on concrete exposed to seawater,” *Int. Biodeterior. Biodegrad.*, vol. 173, no. July, 2022, doi: 10.1016/j.ibiod.2022.105458.
14. H. F. Mohamed, A. Abd-Elgawad, R. Cai, Z. Luo, L. Pie, and C. Xu, “Microbial community shift on artificial biological reef structures (ABRs) deployed in the South China Sea,” *Sci. Rep.*, vol. 13, no. 1, pp. 1–15, 2023, doi: 10.1038/s41598-023-29359-5.
15. W. Ding *et al.*, “Anaerobic thiosulfate oxidation by the Roseobacter group is prevalent in marine biofilms,” *Nat. Commun.*, vol. 14, no. 1, pp. 1–14, 2023, doi: 10.1038/s41467-023-37759-4.
16. K. Nandakumar, H. Matsunaga, and M. Takagi, “Microfouling Studies on Experimental Test Blocks of Steelmaking Slag and Concrete Exposed to Seawater off Chiba, Japan,” *Biofouling*, vol. 19, no. 4, pp. 257–267, 2003, doi: 10.1080/0892701032000077158.
17. P. Hughes *et al.*, “Microscopic study into biodeterioration of marine concrete,” *Int. Biodeterior. Biodegrad.*, vol. 79, pp. 14–19, 2013, doi: 10.1016/j.ibiod.2013.01.007.
18. A. S. Natanzi, B. J. Thompson, P. R. Brooks, T. P. Crowe, and C. McNally, “Influence of concrete properties on the initial biological colonisation of marine artificial structures,” *Ecol. Eng.*, vol. 159, no. November 2020, p. 106104, 2021, doi: 10.1016/j.ecoleng.2020.106104.
19. M. Harilal, B. Anandkumar, B. B. Lahiri, R. P. George, J. Philip, and S. K. Albert, “Enhanced biodeterioration and biofouling resistance of nanoparticles and inhibitor admixed fly ash based concrete in marine environments,” *Int. Biodeterior. Biodegrad.*, vol. 155, no. August, p. 105088, 2020, doi: 10.1016/j.ibiod.2020.105088.
20. M. Georges, A. Bourguiba, D. Chateigner, N. Sebaibi, and M. Boutouil, “The study of long-term durability and bio-colonization of concrete in marine environment,” *Environ. Sustain. Indic.*, vol. 10, no. December 2020, p. 100120, 2021, doi: 10.1016/j.indic.2021.100120.
21. P. Y. Qian, A. Cheng, R. Wang, and R. Zhang, “Marine biofilms: diversity, interactions and biofouling,” *Nat. Rev. Microbiol.*, vol. 20, no. 11, pp. 671–684, 2022, doi: 10.1038/s41579-022-00744-7.
22. P. J. Schnurr and D. G. Allen, “Factors affecting algae biofilm growth and lipid production: A review,” *Renew. Sustain. Energy Rev.*, vol. 52, no. May, pp. 418–429, 2015, doi: 10.1016/j.rser.2015.07.090.
23. C. C. Gaylarde and B. O. Ortega-Morales, “Biodeterioration and Chemical Corrosion of Concrete in the Marine Environment: Too Complex for Prediction,” *Microorganisms*, vol. 11, no. 10, pp. 1–17, 2023, doi: 10.3390/microorganisms11102438.
24. E. Bastidas-Arteaga, M. Sánchez-Silva, A. Chateauneuf, and M. R. Silva, “Coupled reliability model of biodeterioration, chloride ingress and cracking for reinforced concrete structures,” *Struct. Saf.*, vol. 30, no. 2, pp. 110–129, 2008, doi: 10.1016/j.strusafe.2006.09.001.
25. A. Lence, “Investigation of Best Practices for Maintenance of Concrete Bridge Railings,” 2015.
26. C. Gaylarde, M. Ribas Silva, and T. Warscheid, “Microbial impact on building materials: An overview,” *Mater. Struct. Constr.*, vol. 36, no. 259, pp. 342–352, 2003, doi: 10.1617/13867.

27. J. Sempere-Valverde *et al.*, "Location and building material determine fouling assemblages within marinas: A case study in Madeira Island (NE Atlantic, Portugal)," *Mar. Pollut. Bull.*, vol. 187, no. December 2022, 2023, doi: 10.1016/j.marpolbul.2022.114522.
28. W. Al-Kautsar, R. A. Perdanawati, and Noverma, "Laju penempelan macrofouling pada tiang pancang jembatan Suramadu," *J. Ilmu Kelaut. Kepul.*, vol. 3, no. 2, pp. 211–221, 2020.
29. S. P. Putro, M. D. Al Haqi, F. Muhammad, R. Hariyati, and M. Helmi, "The influence of different substrate types on the diversity of macrofouling organisms at the submerged coastal ecosystem of Karimunjawa Islands, Indonesia," *Biodiversitas*, vol. 25, no. 8, pp. 3394–3400, 2024, doi: 10.13057/biodiv/d250810.
30. A. Isdianto, O. M. Luthfi, S. T. Thaeraniza, and A. Soegianto, "Biofouling colonization on cubic artificial reefs in pantai damas, trenggalek, Indonesia," *Ecol. Environ. Conserv.*, vol. 26, no. November, pp. S84–S90, 2020.
31. A. R. Syam, S. T. Hartati, and K. Krismono, "Komunitas Biota Penempel Pada Terumbu Buatan Di Perairan Pulau Ganteng Dan Pulau Rakit, Teluk Saleh, Nusa Tenggara Barat," *J. Penelit. Perikan. Indones.*, vol. 13, no. 2, p. 157, 2007, doi: 10.15578/jppi.13.2.2007.157-166.
32. J. Lv, M. Wang, X. Hu, Z. Cao, and H. Ba, "Experimental study on the durability and microstructure of marine concrete covered with barnacles," *Constr. Build. Mater.*, vol. 317, p. 125900, Jan. 2022, doi: 10.1016/J.CONBUILDMAT.2021.125900.
33. S. Jayakumar and R. Saravanane, "Detrimental effects on coastal concrete by Ulva fasciata," *Proc. Inst. Civ. Eng. Constr. Mater.*, vol. 163, no. 4, pp. 239–246, 2010, doi: 10.1680/coma.900028.
34. S. Jayakumar and R. Saravanane, "Biodeterioration of coastal concrete structures by macro algae - chaetomorpha antennina," *Mater. Res.*, vol. 12, no. 4, pp. 465–472, 2009, doi: 10.1590/S1516-14392009000400015.
35. Y. Kawabata, E. Kato, and M. Iwanami, "Enhanced long-term resistance of concrete with marine sessile organisms to chloride ion penetration," *J. Adv. Concr. Technol.*, vol. 10, no. 4, pp. 151–159, 2012, doi: 10.3151/jact.10.151.
36. M. El-Hawary, H. Al-Khaiat, and S. Fereig, "Performance of epoxy-repaired concrete in a marine environment," *Cem. Concr. Res.*, vol. 30, no. 2, pp. 259–266, 2000, doi: 10.1016/S0008-8846(99)00242-2.
37. T. Chlayon, M. Iwanami, and N. Chijiwa, "Impacts from concrete microstructure and surface on the settlement of sessile organisms affecting chloride attack," *Constr. Build. Mater.*, vol. 239, p. 117863, 2020, doi: 10.1016/j.conbuildmat.2019.117863.
38. M. A. Coombes, H. A. Viles, L. A. Naylor, and E. C. La Marca, "Cool barnacles: Do common biogenic structures enhance or retard rates of deterioration of intertidal rocks and concrete?," *Sci. Total Environ.*, vol. 580, pp. 1034–1045, 2017, doi: 10.1016/j.scitotenv.2016.12.058.
39. H. G. Sonjaya, *Cat Antifouling Untuk Penanganan Kerusakan Struktur Jembatan Akibat Biota Penempel*. 2016.
40. G. Priyotomo, L. Nuraini, H. Gunawan, J. Triwardono, S. Sundjono, and S. Prifiharni, "A Preliminary field study of antifouling paint perfomance after short exposure in Mandara Bali, Indonesia," *Int. J. Eng. Trans. A Basics*, vol. 34, no. 4, pp. 976–986, 2021, doi: 10.5829/ije.2021.34.04a.24.
41. O. Guillitte, "Bioreceptivity: a new concept for building ecology studies," *Sci. Total Environ.*, vol. 167, no. 1–3, pp. 215–220, 1995, doi: 10.1016/0048-9697(95)04582-L.
42. S. Romimohtarto, Kasijan; Juwana, *BIOLOGI LAUT: Ilmu Pengetahuan Tentang Biota Laut*. Djambatan, 2009.
43. A. Iswadi, J. S. Porter, and M. C. Bell, "Biofouling Observation In Tropical Waters Of

Indonesia For Marine Renewable Energy Sector," *2nd GEF-UNDP-IMO GloFouling R&D Forum Exhib. Biofouling Prev. Manag. Marit. Ind.*, 2022.

44. A. Bertron, "Understanding interactions between cementitious materials and microorganisms: a key to sustainable and safe concrete structures in various contexts," *Mater. Struct. Constr.*, vol. 47, no. 11, pp. 1787–1806, 2014, doi: 10.1617/s11527-014-0433-1.
45. B. Cwalina, "Biodeterioration of concrete," *Archit. Civ. Eng. Environ.*, vol. 4, pp. 133–140, 2008, doi: 10.1201/9781315119557.
46. D. Trejo, P. De Figueiredo, M. Sanchez, C. Gonzalez, S. Wei, and L. Li, "ANALYSIS AND ASSESSMENT OF MICROBIAL BIOFILM-MEDIATED CONCRETE DETERIORATION 5. Report Date 13. Type of Report and Period Covered Unclassified," vol. 7, no. 2, pp. 8–72, 1700.
47. P. Monteiro, "Durability of concrete: ability to resist weathering action, chemical attack, abrasion, or any process of deterioration.," 2015.
48. I. N. Amini and J. J. Ekaputri, *The Effect of GGBFS and Additional Cement, Water, and Superplasticizer on the Mechanical Properties of Workable Geopolymer Concrete*, vol. 289. Springer Nature Singapore, 2023.
49. L. Procópio, "The role of biofilms in the corrosion of steel in marine environments," *World J. Microbiol. Biotechnol.*, vol. 35, no. 5, 2019, doi: 10.1007/s11274-019-2647-4.
50. R. E. Melchers, "Long-term durability of marine reinforced concrete structures," *J. Mar. Sci. Eng.*, vol. 8, no. 4, 2020, doi: 10.3390/JMSE8040290.
51. R. E. Melchers and I. A. Chaves, "Durable steel-reinforced concrete structures for marine environments," *Sustain.*, vol. 13, no. 24, 2021, doi: 10.3390/su132413695.
52. F. Qu, W. Li, W. Dong, V. W. Y. Tam, and T. Yu, "Durability deterioration of concrete under marine environment from material to structure: A critical review," *J. Build. Eng.*, vol. 35, no. June 2020, p. 102074, 2021, doi: 10.1016/j.jobe.2020.102074.
53. T. Noeiaghaei, A. Mukherjee, N. Dhami, and S. R. Chae, "Biogenic deterioration of concrete and its mitigation technologies," *Constr. Build. Mater.*, vol. 149, no. May, pp. 575–586, 2017, doi: 10.1016/j.conbuildmat.2017.05.144.
54. T. Mori *et al.*, "Microbial corrosion of concrete sewer pipes, H2S production from sediments and determination of corrosion rate," *Water Sci. Technol.*, vol. 23, no. 7–9, pp. 1275–1282, 1991, doi: 10.2166/wst.1991.0579.
55. Y. Wang *et al.*, "Extracellular Polymeric Substances and Biocorrosion/Biofouling: Recent Advances and Future Perspectives," *Int. J. Mol. Sci.*, vol. 23, no. 10, 2022, doi: 10.3390/ijms23105566.
56. E. Joseph, *Microorganisms in the deterioration and preservation of cultural heritage*. 2021.
57. Y. Li and C. Ning, "Latest research progress of marine microbiological corrosion and bio-fouling, and new approaches of marine anti-corrosion and anti-fouling," *Bioact. Mater.*, vol. 4, no. January 2019, pp. 189–195, 2019, doi: 10.1016/j.bioactmat.2019.04.003.
58. J. R. Bone, R. Stafford, A. E. Hall, and R. J. H. Herbert, "Biodeterioration and bioprotection of concrete assets in the coastal environment," *Int. Biodeterior. Biodegrad.*, vol. 175, no. February, p. 105507, 2022, doi: 10.1016/j.ibiod.2022.105507.
59. X. Li, S. Li, X. Huang, Y. Chen, J. Cheng, and A. Zhan, "Protein-mediated bioadhesion in marine organisms: A review," *Mar. Environ. Res.*, vol. 170, no. October 2020, 2021, doi: 10.1016/j.marenvres.2021.105409.
60. C. Liang, J. Strickland, Z. Ye, W. Wu, B. Hu, and D. Rittschof, "Biochemistry of Barnacle Adhesion: An Updated Review," *Front. Mar. Sci.*, vol. 6, no. September, pp.

1–20, 2019, doi: 10.3389/fmars.2019.00565.

61. K. Kamino, K. Inoue, T. Maruyama, N. Takamatsu, S. Harayama, and Y. Shizuri, "Barnacle Cement Proteins," *J. Biol. Chem.*, vol. 275, no. 35, pp. 27360–27365, 2000, doi: 10.1016/s0021-9258(19)61519-x.
62. T. Chlayon, M. Iwanami, and N. Chijiwa, "Combined protective action of barnacles and biofilm on concrete surface in intertidal areas," *Constr. Build. Mater.*, vol. 179, pp. 477–487, 2018, doi: 10.1016/j.conbuildmat.2018.05.223.
63. J. F. Lv, J. Z. Mao, and H. J. Ba, "Influence of Crassostrea gigas on the permeability and microstructure of the surface layer of concrete exposed to the tidal zone of the Yellow Sea," *Biofouling*, vol. 31, no. 1, pp. 61–70, 2015, doi: 10.1080/08927014.2014.999235.
64. D. Maruzzo, N. Aldred, A. S. Clare, and J. T. Høeg, "Metamorphosis in the cirripede Crustacean Balanus amphitrite," *PLoS One*, vol. 7, no. 5, 2012, doi: 10.1371/journal.pone.0037408.
65. J. R. Bone, R. Stafford, A. E. Hall, and R. J. H. Herbert, "The intrinsic primary bioreceptivity of concrete in the coastal environment – A review," *Dev. Built Environ.*, vol. 10, no. April, p. 100078, 2022, doi: 10.1016/j.dibe.2022.100078.
66. R. Miller and A. Macleod, "Marine Growth Mapping and Monitoring: Feasibility of Predictive Mapping of Marine Growth March. A report by SAMS Research Services Ltd to the Offshore Renewable Energy Catapult.," no. March, p. 69, 2016.
67. M. Maduka, F. Schoefs, K. Thiagarajan, and A. Bates, "Hydrodynamic effects of biofouling-induced surface roughness – Review and research gaps for shallow water offshore wind energy structures," *Ocean Eng.*, vol. 272, no. January, 2023, doi: 10.1016/j.oceaneng.2023.113798.
68. Z. Jaberimanesh, M. Oladi, A. Nasrolahi, and F. Ahmadzadeh, "Presence of Amphibalanus eburneus (Crustacea, Cirripedia) in Gomishan Wetland: Molecular and morphological evidence of a new introduction to the southern Caspian Sea," *Reg. Stud. Mar. Sci.*, vol. 25, p. 100469, 2019, doi: 10.1016/j.rsma.2018.100469.