

牡蛎附着对海工混凝土的双重作用：保护机制与腐蚀机理综述

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摘 要: 在国家海洋强国战略的驱动下, 混凝土在海洋基础设施中得到了广泛应用, 其腐蚀与防护问题引起了学界的广泛关注。理解污损生物对混凝土性能的影响机制, 对于解决海洋腐蚀难题至关重要。牡蛎作为在混凝土表面形成高密度附着的优势污损物种, 已成为研究重点。因此, 本文系统梳理了以下 3 个方面: 1) 海洋环境中牡蛎附着的过程及关键影响因素; 2) 牡蛎附着对海洋工程混凝土耐久性的双重影响, 涵盖腐蚀与防护 2 种机制; 3) 当前用于防止污损或诱导有益定植的策略。基于上述综合分析, 本文最后指出了未来具有前景的研究方向。

关键词: 海洋混凝土; 污损生物; 牡蛎; 生物腐蚀; 防护与诱导

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1 Introduction

The vast volume of Earth's seawater exhibits potent corrosivity and high biological activity^[1], making marine corrosion a persistent global challenge^[2]. Within this context, the adhesion and corrosion induced by macro-fouling organisms constitute a primary constraint on marine resource development. Fouling colonization not only amplifies static and dynamic loads on offshore structures (*e.g.*, cross-sea bridge piers, oil platforms, and floating platforms), but also initiates or accelerates concrete degradation^[3]. The expansion of port infrastructure under national maritime power strategies enlarges the concrete surface area in marine environments, which elevates the overall scale and severity of macro-fouling impacts. Fig. 1 was taken at Tianjin Dongjiang Port, with a large number of oysters and barnacles attached to the bridge piers and breakwaters.

This has led to premature failure of marine engineering projects, preventing them from reaching designed service lives. Consequently, enhancing concrete durability to meet functional and longevity requirements necessitates focused research on both the corrosion mechanisms of marine macro-fouling organisms and effective protective measures^[4-6].



(a) Oysters densely coating a pier at Tianjin Port



(b) Barnacles and oysters extensively covering a breakwater in Tianjin

Fig. 1 Marine biofouling organisms colonizing concrete structures

Marine corrosion environments are classified into five distinct zones based on infrastructure positioning^[7]:

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atmospheric, splash, tidal, full immersion, and sea mud zones. Within the tidal zone, reinforced concrete structures experience cyclic wet-dry cycles under oxygen-rich conditions, elevated chloride ion concentrations, and synergistic corrosive factors, creating an exceptionally aggressive environment. Corrosion initiation in this zone significantly compromises structural durability^[8]. Oysters (Ostreidae) and barnacles (Balanidae) constitute the dominant fouling organisms on tidal concrete surfaces^[9], with barnacles predominantly colonizing the high-tide line and oysters concentrating at the low-tide line^[10–12]. Notably, oysters exhibit substantially stronger substrate adhesion than barnacles and serve as foundational substrates for barnacle settlement. Consequently, investigating oyster-concrete interactions in tidal environments holds critical scientific value. A comprehensive literature search was conducted using several academic databases, including Web of Science, Scopus, and Google Scholar. The search employed key terms such as “oyster attachment” “marine concrete” “biofouling” “biodeterioration” and “bio-protection” alone and in combination, to ensure thorough coverage of relevant studies. The inclusion criteria focused on peer-reviewed articles published in English between 1980 and 2025 that directly addressed oyster-concrete interactions. This paper elucidates: 1) oyster colonization processes and influencing factors, 2) mechanistic impacts of oyster biofouling on concrete performance, and 3) implications for developing protective strategies against marine biodeterioration, thereby advancing fundamental understanding of bio-concrete interactions in marine infrastructure.

2 Oyster attachment process and influencing factors

The ontogenetic progression from fertilized eggs to substrate attachment in oysters represents a complex biological process integrating multidisciplinary principles of developmental biology, ecology, and physiology. Elucidating this colonization trajectory and its governing factors enables deeper comprehension of oyster growth dynamics, thereby establishing a scientific foundation for conservation strategies and sustainable exploitation.

2.1 Growth and attachment of oysters

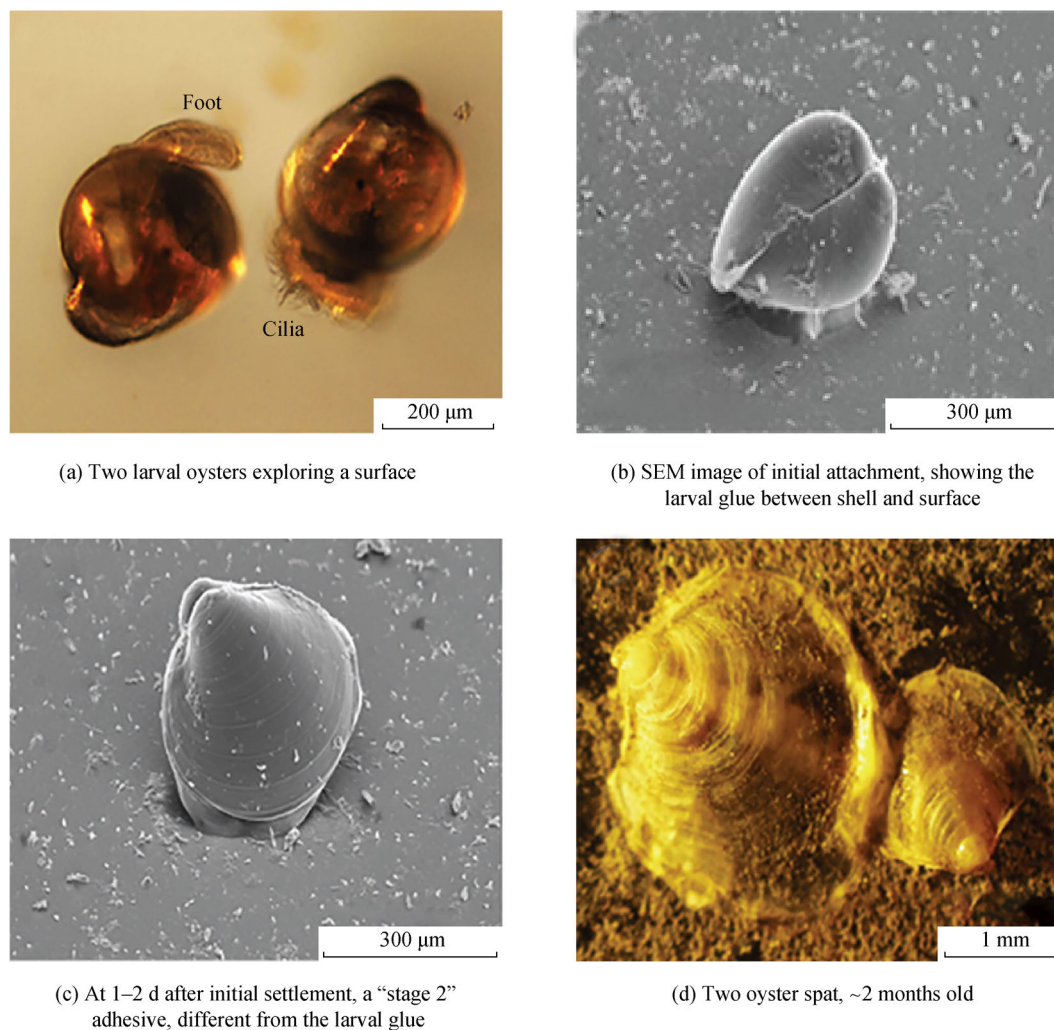
Oysters (Ostreidae), bivalve mollusks, are filter-feeding organisms characterized by dark-gray, textured shells. The dorsal valve exhibits convex morphology, while the ventral valve undergoes cementation to the substrate^[13] (Fig. 2d). As illustrated in Fig. 2, oyster ontogeny commences with fertilization, where the zygote - containing genetic blueprint - initiates developmental programming. Following embryogenesis, planktonic larvae utilize ciliary locomotion for buoyancy and planktotrophic feeding, progressing through trochophore to pediveliger stages (Fig. 2a). During settlement competence, pediveligers employ chemosensory cues to locate suitable calcified substrates (*e.g.*, rock or conspecific shells). Upon identifying an optimal site, larvae initiate permanent attachment *via* byssal secretion (Fig. 2b). Metamorphosis involves foot-mediated substrate interaction and secretory biomineralization, culminating in definitive shell formation^[14] (Fig. 2c). Post-settlement juveniles exhibit rapid growth (~30-fold size increase within 21 d), establishing microhabitats through bioenvironmental interactions.

2.2 Factors affecting oyster attachment

Oyster substrate colonization serves as the critical initial step in the biodeterioration of concrete, upon which subsequent damaging processes (*e.g.*, metabolic acid production, physical penetration) depend. Therefore, understanding the factors that influence oyster attachment provides the foundational basis for developing protective materials and is crucial for formulating effective anti-corrosion strategies. These determinants are categorized into four primary factors (as summarized in Table 1): environmental conditions, substrate properties, chemical gradients, and biological mediators.

2.2.1 Environmental conditions Oyster colonization on marine infrastructure is modulated by a suite of hydroenvironmental parameters, primarily thermal regime, hydrodynamic forces, and light availability within the water column^[15–19].

Seawater temperature exhibits a strong correlation with oyster reproductive activity and settlement competence. Governed by latitudinal and

Fig. 2 Attachment process of oysters^[14]**Table 1 Factors affecting oyster attachment**

Category	Specific Factor	Primary Effect / Influence on Attachment
Environmental conditions	Temperature	Determines reproductive activity and settlement competence, creating distinct biogeographic and seasonal recruitment patterns
	Hydrodynamic forces	Moderate flows enhance nutrient delivery; excessive turbulence dislodges larvae
	Light availability & bathymetry	Constrains vertical distribution; biomass peaks in the euphotic zone (0–40 m)
Substrate properties	Material composition & surface energy	Influences settlement selectivity; materials like limestone, gypsum, and cement-fly ash show high induction efficacy
	Surface microtopography & roughness	Textured surfaces provide tactile stimuli for larvae and promote biofilm formation, both of which induce settlement and metamorphosis
	Other attributes (Size, color)	Larger substrates provide more area for attachment; dark colors may enhance attachment success by providing crypsis
Chemical gradients	pH value	Regulates enzymatic activity and metabolic homeostasis; deviations impair development and fitness
	Ionic concentrations (K^+ , NH_4^+ , Ca^{2+})	Modulates attachment behavior in a concentration-dependent manner, <i>via</i> mechanisms such as neuronal activation or metabolic cost reduction
	Dissolved nutrients (N, P)	Optimal levels support larval health and growth; imbalances or toxic concentrations weaken larvae and inhibit
Biological mediators	Interspecific interactions (Competition, predation)	Directly governs abundance and distribution through resource competition and predation pressure
	Conspecific cues & Aggregation	Adult-derived chemical cues induce settlement; aggregative behavior improves fitness through collective benefits

seasonal variations, this thermal regime creates distinct biogeographic gradients. Tropical and subtropical regions sustain year-round recruitment due to elevated thermal optima, while temperate zones display seasonal attachment cycles aligned with thermal windows. In contrast, polar regions experience recruitment failure under cryogenic conditions^[16].

Hydrodynamic forces influence larval settlement primarily through boundary shear stress and near-substrate velocity profiles. Moderate flow regimes are beneficial as they enhance nutrient flux and particulate organic matter delivery to benthic communities. However, excessive turbulence poses a risk by inducing dislodgement of pre-settlement larvae^[20].

Light availability and bathymetry jointly constrain the vertical distribution of macrofouling biomass. In eutrophic systems, biomass peaks within the euphotic zone (0–40 m depth) where photosynthetically active radiation (PAR) and dissolved oxygen saturation are maximized. Beyond this depth, community richness declines precipitously with PAR attenuation. Empirical studies confirm that bathymetric pressure exerts additional constraints, leading to significantly reduced colonization rates on deep-sea infrastructure (>40 m)^[19].

2.2.2 Substrate properties The physical and chemical characteristics of the substrate surface are critical determinants for larval settlement and attachment strength.

The material composition and surface characteristics of the substrate significantly influence larval settlement selectivity. Key parameters include surface cleanliness, wettability, contact angle, and surface energy. For instance, Greene *et al.*^[20] demonstrated comparable larval induction efficacy between concrete and natural shell substrates. Similarly, Soniat *et al.*^[21] revealed significantly higher settlement induction on limestone (CaCO_3) and gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) compared to gravel or recycled roadbed materials, with cement-fly ash composites also demonstrating favorable induction properties.

Surface microtopography and roughness play a crucial role in larval settlement through dual

mechanisms. As established by Yang *et al.*^[22], larvae prefer rigid, textured surfaces because surface microtopography provides tactile stimuli that enhance larval crawling and substrate retention, thereby increasing settlement rates; and enhanced surface roughness promotes microbial colonization, creating biofilms rich in polysaccharides and glycoproteins. These biomolecules bind to larval surface lectins, triggering metamorphosis^[23]. Concurrently, microbial supernatants containing bioactive NH_3 further induce larval settlement and metamorphosis^[23].

Other physical attributes, such as substrate dimensions and chromaticity, further modulate larval settlement behavior^[24–25]. Fan *et al.*^[26] documented positive correlations between substrate size and juvenile density, but inverse relationships with shell height, indicating density-dependent growth inhibition. Wang *et al.*^[27] attributed the larval preference for dark substrates to the crypsis advantages they provide against visual predators. Additional facilitators in the microenvironment include microbial exometabolites and bioavailable trace elements^[28]. In summary, it is the interplay of these diverse physical and chemical substrate characteristics that ultimately determines the success and intensity of larval settlement.

2.2.3 Chemical factors Chemical parameters—specifically pH, ionic concentrations, and dissolved nitrogen-phosphorus nutrients—serve as critical determinants modulating oyster ontogeny and reef-based ecosystem stability.

The pH value exerts direct regulatory control over enzymatic activity in oysters. As biological catalysts, enzymes orchestrate metabolic reactions *in vivo*. Deviation from physiological pH value optima induces conformational changes that impair catalytic efficiency, leading to enzyme inhibition or denaturation. This cascade disrupts metabolic homeostasis and ontogenetic development^[29]. Elevated pH value (8.50) upregulates expression of fucosylated antigens (*e.g.*, Fuca1-2Gal epitopes), enhancing antiviral defense mechanisms^[30]. Conversely, reduced pH value impairs metabolic flux, compromises locomotor performance, and suppresses filtration efficiency^[31].

Ionic gradients (K^+ , NH_4^+ , Ca^{2+}) exert concentration-dependent induction or inhibition of oyster larval settlement. Yool *et al.*^[32] demonstrated that physiological K^+ concentrations depolarize cellular membranes, accelerating larval settlement and metamorphosis. Coon *et al.*^[33] established that NH_4^+ -mediated intracellular alkalization induces neuronal depolarization, triggering settlement responses. The foot-secreted protein dopamine mediates substrate adhesion, with empirical evidence confirming its dual role in promoting both primary settlement and reattachment behavior^[34–35], indicating dopaminergic regulation of larval settlement. Qi *et al.*^[36] documented significantly enhanced settlement induction in *Crassostrea angulata* within optimal seawater Ca^{2+} thresholds. Mechanistically, Ca^{2+} functions as a second messenger activating metamorphosis pathways^[37–38] and a biomineralization substrate reducing calcification energy costs by ~40%, thereby theoretically freeing metabolic resources that could be allocated to other physiological processes^[39]. However, it is crucial to distinguish this potential energetic benefit from measurable growth outcomes. Deviations from optimal Ca^{2+} concentrations induce physiological stress: hypocalcic conditions suppress respiratory and predatory activities to conserve energy for shell formation, while hypercalcic environments disrupt osmotic homeostasis, impairing settlement competence. Liu *et al.*^[40] further confirmed Ca^{2+} toxicity at elevated concentrations. Substrate calcium speciation critically modulates settlement efficiency, exhibiting the hierarchy: organic calcium > calcium carbonate $\approx$ calcium sulfate^[41]. Maximum induction occurs at 20% $CaCO_3$ content. Notably, the observed lack of a significant correlation between calcium availability and larval shell height suggests that the metabolic resources conserved by reduced calcification costs are likely prioritized for critical processes including shell formation, attachment, and metamorphosis, rather than being directly translated into enhanced linear shell growth.

Marine microorganisms mediate the biogeochemical mineralization of organic detritus and metabolic wastes, generating bioavailable inorganic nutrients

including nitrates (NO_3^-), nitrites (NO_2^-), and phosphates (PO_4^{3-})^[42]. Wang's spectroscopic analysis^[43] identified trace amino acids and crystalline calcium phosphate within oyster shell matrices. Adductor muscle growth exhibited significant positive correlation with dissolved inorganic nitrogen concentrations, with optimal N:P ratios enhancing somatic growth rates^[43]. Conversely, elevated nitrite exposure inhibits cytochrome c oxidase activity, induces immunosuppression through hemocyte apoptosis, and disrupts reproductive endocrinology. Acute toxicity manifests *via* methemoglobinemia-induced hypoxia^[44].

2.2.4 Biological factors Biological mechanisms—particularly interspecific interactions and conspecific aggregation dynamics—constitute fundamental drivers governing the spatiotemporal heterogeneity of oyster settlement patterns.

Interspecific interactions—encompassing competition, predation, and symbiosis—directly govern the abundance and distribution of fouling organisms. Within tidal environments, oysters exhibit planktotrophic feeding on diverse microalgal communities, with elevated phytoplankton densities enhancing larval growth and settlement^[45]. Spatial and trophic competition occurs between oysters and co-occurring invertebrates (*e.g.*, barnacles, mussels), wherein competitive exclusion between oysters and barnacles manifests as negatively correlated cumulative attachment due to resource partitioning^[46]. Concurrently, oyster populations experience predation pressure from keystone predators including the sea star *Asterias amurensis*, whelk *Rapana venosa*, and crab *Charybdis japonica*, which significantly regulate oyster survival rates^[47]. Sun's research^[48] demonstrated an inverse proportionality between oyster size and predation vulnerability, indicating size-dependent refugium effects.

Oyster larvae exhibit aggregative settlement patterns, demonstrating conspecific aggregation behavior^[49–51]. This density-dependent strategy enhances individual fitness through improved filtration efficiency, competitive advantage, and predation dilution effects while reducing ontogenetic mortality.

Ke *et al.*^[52] established that adult-derived chemical cues significantly induce larval settlement and metamorphosis. Jiang *et al.*^[53] observed significantly enhanced settlement induction on novel shell substrates compared to weathered counterparts throughout the oyster life cycle. Grant *et al.*^[54] further confirmed that conspecific aggregations trigger larval searching behavior and substrate commitment. Additionally, inverse relationships exist between mean shell height and settlement density, while larval abundance positively correlates with substrate colonization rates^[55].

3 Influence mechanism of oyster attachment on concrete

Upon attachment to concrete surfaces, oysters elicit alterations in the material properties, with effects varying across their growth stages. However, the ultimate consequence for concrete durability remains debated. Some studies suggest that the biogenic secretions released during larval settlement, combined with foraging/excretion during growth, gamete release at maturity, and decomposition products post-mortem, can induce corrosion of the concrete matrix^[55–62]. Conversely, other research indicates that the biofilm formed by the biological adhesives generated during oyster growth may exert a protective effect on the concrete surface^[63–72].

3.1 Corrosion mechanism

During larval settlement, oysters secrete biological adhesives. Wang *et al.*^[55] propose that the released adhesives contain bioacids which react with surface $\text{Ca}(\text{OH})_2$ to form gypsum. This reaction decomposes calcium silicate hydrate (C-S-H), yielding non-cementitious SiO_2 colloid. Furthermore, the formed gypsum reacts with hydration products (*e.g.*, C_3A) in the concrete to generate ettringite (AFt), inducing concrete cracking. Currently, research on the corrosion effects of excreta and reproductive secretions secreted during the growth and mature stages is lacking.

Similarly, while direct studies on post-mortem concrete corrosion by oyster remains are absent, inferences can be drawn from relevant literature^[56–61]. Following death, microbial decomposition and

oxidation of proteins in the carcass under aerobic conditions produce SO_4^{2-} , which corrodes the concrete. Subsequent microbial biochemical activity generates acidic substances and CO_2 , further reducing the pH value at the concrete surface. When this pH value is sufficiently low and the free CO_2 concentration exceeds the equilibrium level, carbonate corrosion occurs, continuously consuming and dissolving CaCO_3 to form soluble $\text{Ca}(\text{HCO}_3)_2$. Concurrently, microbial consumption of O_2 facilitates the production of H_2S through metabolism. This H_2S corrodes concrete *via* a mechanism analogous to that of aggressive carbonic acid. Although the free acids themselves may not be highly corrosive, they dissolve the protective calcium carbonate film on the concrete surface, thereby accelerating the corrosion process.

Moreover, the dissolution of surface CaCO_3 reduces the concrete's internal alkalinity. When alkalinity falls below the threshold required for the stability of skeleton-forming hydrated minerals (*e.g.*, calcium silicate), these minerals decompose, leading to concrete degradation. As the surface pH value decreases into the acidic range, aerobic sulfur-oxidizing bacteria proliferate, oxidizing H_2S to produce biosulfuric acid that causes further corrosion.

Additionally, endogenous microorganisms and enzymes initiate decomposition of the carcass, releasing organic matter and acidic substances that penetrate and corrode the concrete structure. These decomposition products also attract further colonization by marine organisms, amplifying the corrosive impact. Collectively, these synergistic factors within the marine environment eventually lead to accelerated deterioration of the concrete material^[62].

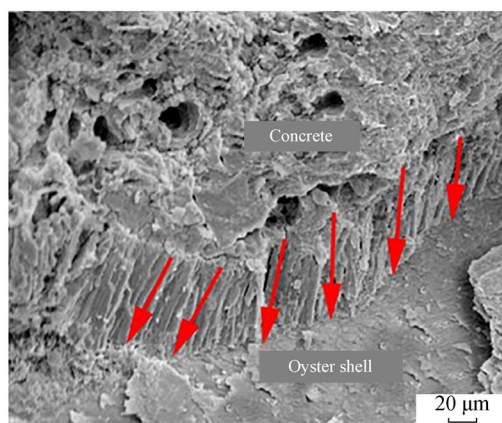
3.2 Protection mechanism

Beyond the potential corrosive effects of oysters discussed previously, their attachment can also confer a protective effect on concrete structures. The efficacy of this protection is critically dependent on the density of oyster coverage. Kawabata *et al.*^[63], through a ten-year field exposure test in a marine environment, demonstrated that the protective effect exhibits no significant correlation with exposure duration. Their

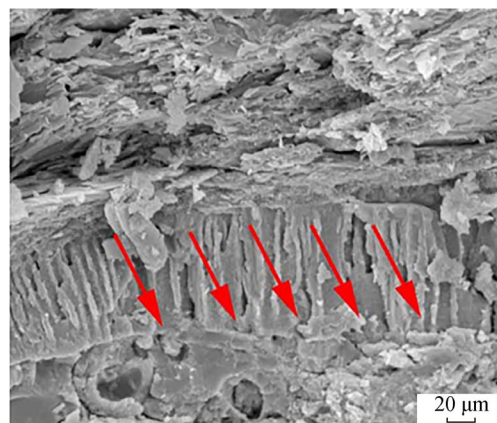
findings indicate that the greater the total coverage are, the stronger the protective effect imparted to the concrete. The composite layer formed by the oyster biofilm and shells serves a dual protective function: it impedes the diffusion of oxygen (O_2) and chloride ions (Cl^-) to the concrete surface^[64], while simultaneously mitigating the scouring and abrasive impact of water flow and suspended particles. This barrier effect contributes to enhanced concrete durability. Conversely, low-density oyster attachment provides substantially reduced protection to the concrete surface^[65] and may even accelerate its deterioration.

Fig. 3 presents the electron microscopy image of the oyster-concrete interface. As illustrated in Fig. 3a and Fig. 3b, the oyster biofilm exhibits continuous penetration into the concrete surface, concurrently

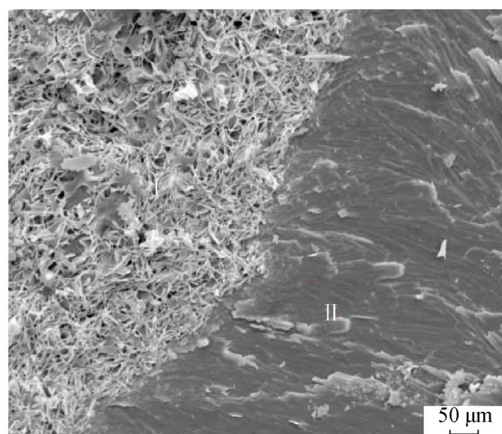
depositing calcium carbonate. This process facilitates the repair of visible concrete cracks and effectively seals surface pores. Consequently, both the maximum pore size and the total porosity of the surface concrete are reduced, thereby enhancing the material's durability^[65-68]. The oyster shell structure comprises two distinct layers: the inner chalk layer (I) and the outer foliated layer (II), with a pronounced transition zone observed between them (Fig. 3c). During attachment, the chalk layer establishes direct contact with the concrete substrate, while the foliated layer forms the upper shell structure. Notably, the chalk layer contains a significant number of tortuous pores (Fig. 3d). Crucially, the degree of pore tortuosity within the concrete is positively correlated with its resistance to chloride-ion permeability^[66].



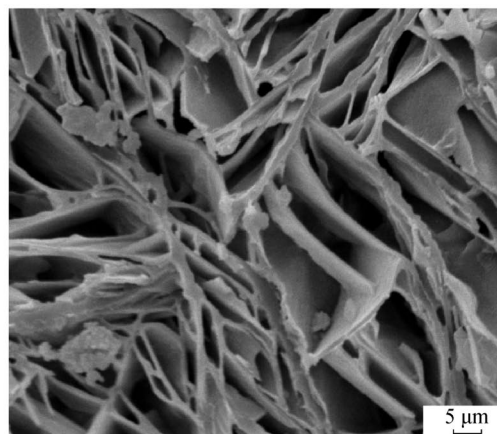
(a) Morphology of the concrete-oyster joint surface



(b) Cross-sectional view of the oyster-concrete interface



(c) Stratified structure of oyster shell showing chalk layer (I) and foliated layer (II)



(d) Microstructure of the oyster chalk layer

Fig. 3 SEM micrographs of the oyster-concrete interface^[66]

Lv *et al.*^[69] demonstrated that oyster adhesion reduces concrete surface pore size, resulting in a 39.83% lower porosity compared to bare concrete.

Supporting this finding, Hu *et al.*^[66] observed that oyster-derived adhesives penetrate the concrete surface layer, effectively blocking the majority of pores within

the 10–100 nm range. This penetration leads to a significant decrease in the most probable pore size within the surface layer, and the associated improvement in pore structure becomes more pronounced over time. Kawabata *et al.*^[63] further reported that concrete colonized by sessile organisms exhibits lower chloride ion (Cl^-) content than non-colonized concrete. Notably, this reduced Cl^- content persisted even after the attached organisms were removed. Consistent with these protective effects, An *et al.*^[70] found that concrete surfaces with oyster attachment in the upper intertidal zone exhibit enhanced resistance to chloride ion penetration.

Oyster attachment to concrete surfaces not only reduces surface layer porosity and refines its pore structure, thereby enhancing resistance to chloride ion penetration, but also improves concrete impermeability. Furthermore, it significantly influences the concrete carbonation rate. Hong *et al.*^[71] demonstrated that concrete colonized by viable oyster biofilms exhibits superior impermeability compared to concrete with non-viable biofilms. Supporting this observation, Lv *et al.*^[69] documented that oyster attachment forms a dense biofilm. This biofilm adheres firmly to and penetrates the concrete surface, reducing water absorption; crucially, the reduction effect intensifies with increasing colonization density. Regarding carbonation, Hu *et al.*^[66] found that prior to biofilm maturation, oyster-colonized concrete exhibited a higher degree of carbonation than non-colonized concrete. However, following complete biofilm establishment, the carbonation rate of colonized concrete decreased, ultimately falling below that of biofilm-free concrete.

In summary, oyster attachment enhances concrete durability primarily by modifying the surface layer *via* biofilm formation. This beneficial effect intensifies temporally and requires the maturation of a dense, stable biofilm to achieve a significant durability improvement.

3.3 Critical conditions governing the dual effects of oyster attachment

The preceding sections have established that oyster attachment can lead to either concrete corrosion

or protection. The transition between these opposing outcomes is governed by a hierarchy of interdependent factors, among which the coverage density, maturity, and viability of the oyster population are paramount. Empirical evidence consistently demonstrates that low-density, patchy attachment fails to form an effective barrier, thereby allowing localized corrosive processes—such as acid secretion from bioadhesives and metabolites, as well as the decomposition products following oyster death—to dominate and accelerate material degradation, as detailed in Section 3.1 and supported by studies on biochemical corrosion^[55–62]. Conversely, the protective mechanisms outlined in Section 3.2, including the impediment of chloride ion diffusion and the physical sealing of surface pores, are contingent upon the establishment of a high-density, mature, and stable oyster population^[63–71]. This dense biofilm-shell composite structure effectively isolates the concrete surface from the bulk marine environment. The temporal dimension is intrinsic to this relationship, as the protective effect intensifies with biofilm maturation and the development of continuous coverage^[66, 69]. A critical aspect of population viability is its mortality status; a mass die-off can catastrophically shift the equilibrium from protection back to corrosion, as the concentrated decomposition of organic matter releases a pulse of aggressive compounds directly onto the substrate, a process inferred from post-mortem corrosion studies^[56–61].

The local hydrodynamic regime serves as a crucial secondary factor that modulates these core interactions. In high-energy environments, a dense oyster assemblage confers significant benefits by reducing the effective surface area of concrete exposed to direct hydrodynamic impact and abrasive suspended particles^[64]. Furthermore, higher flow rates promote the dissipation of locally excreted corrosive metabolites, thereby reducing their contact time with the substrate and mitigating their damaging potential. In contrast, under quiescent, poorly flushed conditions, the accumulation of these acidic byproducts beneath even a low-density attachment can be exacerbated, heightening the risk of corrosion.

In summary, the manifestation of net corrosion

versus net protection is primarily determined by the achievement of a critical threshold in oyster population density and maturity. Environmental conditions, particularly hydrodynamics, act as important modulators by influencing both the physical erosion forces and the mass transfer of chemical species at the concrete-surface interface.

4 Strategies for preventing and facilitating oyster attachment

The management of oyster colonization on marine concrete structures presents a dualistic challenge, necessitating strategies that are either preventive or facilitative, depending on the specific engineering objectives and environmental context. For critical infrastructure where biofouling compromises structural function, operational safety, or maintenance access (*e.g.*, pipelines, ship hulls, water intake systems), preventive measures to inhibit oyster attachment are paramount. Conversely, for submerged components where enhancing long-term durability is the primary goal and biofouling can be tolerated, inductive measures to promote the formation of a dense, protective oyster reef layer offer a promising bio-protective approach. This section reviews the current state-of-the-art for both strategic directions.

4.1 Adhesion prevention measures

Current studies indicate that strategies to inhibit oyster larval attachment and eradicate established oysters encompass concrete modification, physical removal, and protective coatings.

4.1.1 Modification of concrete Concrete modification entails the strategic selection of raw materials to enhance concrete properties such as acid resistance, impermeability, and crack resistance. For instance, incorporating volcanic ash into concrete leverages the pozzolanic reaction, which refines the interfacial transition zone (ITZ) between cement paste and aggregate, consequently improving the concrete's resistance to corrosion^[72]. Similarly, the addition of ground granulated blast-furnace slag (GGBS) facilitates crack remediation through the formation of calcium silicate hydrate (C-S-H) gel during hydration, sealing cracks induced by concrete deterioration.

Furthermore, marine concrete containing GGBS not only reduces the leaching of metallic ions into seawater but also impedes chloride ion (Cl^-) diffusion into the concrete matrix, thereby enhancing its overall durability in marine environments^[73].

4.1.2 Physical removal Physical removal primarily encompasses methods such as manual/mechanical cleaning, filtration, and ultrasonic techniques^[74].

The manual/mechanical cleaning method is primarily employed for removing fouling organisms attached to surfaces. This approach represents the earliest and a relatively mature anti-fouling strategy. Currently, specialized machinery for pipeline and equipment descaling is utilized in practical operations. A significant limitation of this method is its inability to prevent fouling formation; it can only address existing deposits, resulting in substantial processing costs.

The filtration method employs granular media such as soil and gravel to remove eggs, larvae, and spores of fouling organisms from seawater. Typically applied as a primary seawater treatment, this method is commonly combined with other anti-fouling approaches.

The ultrasonic technique utilizes electronic devices to generate ultrasonic waves that disrupt the physiological processes or living environment of fouling organisms, thereby preventing fouling^[75].

4.1.3 Novel protective coatings Novel protective coating technologies have emerged as a prominent research focus in marine antifouling. Characterized by their environmental compatibility, these coatings effectively inhibit the adhesion of fouling organism larvae through precise modulation of surface physicochemical properties^[76]. Currently, however, most novel protective coating technologies remain at the experimental stage, with limited practical engineering applications. Based on their primary antifouling mechanisms, these coatings can be categorized into three distinct pathways: natural antifouling agent-based coatings, surface property-tuning coatings, and stimuli-responsive intelligent coatings. Yet, due to technical bottlenecks such as complex preparation processes and inadequate long-term stability, the majority of research

outcomes are still confined to laboratory validation, exhibiting a considerable gap to large-scale industrial implementation.

1) Natural antifouling agent-based coatings.

Numerous organisms in nature—including bacteria, algae, celery, ginger, and eucalyptus—produce active substances capable of repelling or killing sessile invertebrate larvae. These substances are predominantly biodegradable and exhibit low or negligible toxicity, rendering them environmentally friendly materials. For instance, Liu *et al.*^[77] demonstrated that cardenolide extracted from *Nerium indicum* effectively kills barnacles, while Almeida *et al.*^[78] showed that chalcone and its derivatives, extracted and synthesized from celery, strongly inhibit the attachment of mussel larvae. However, the extraction of such natural antifouling compounds from plants and animals faces significant challenges. The processes involved are often complex, leading to low yields and high production costs^[79], and may entail potential risks. Furthermore, compared to traditional antifouling coatings, higher concentrations of these natural substances are typically required to achieve comparable efficacy. Therefore, for large-scale application, artificial synthesis methods that preserve their bioactivity must be developed.

The adhesive secretions of organisms such as oysters are predominantly proteinaceous; consequently, proteases can degrade these proteins. Wang *et al.*^[80] isolated bacteria from sea mud whose secreted proteases significantly inhibited the attachment of barnacles, mussels, and other fouling organisms. Tasso *et al.*^[81] developed a coating utilizing poly (2-ethyl acrylate) (PEMA) copolymer and protease to maintain enzymatic activity. Krishnan *et al.*^[82] proposed that nanomaterials could be employed to construct micro-support structures for enzyme stabilization, noting that such nano-support structures have minimal impact on coating performance^[83]. Maintaining the activity, stability, and controlled release of enzymes represents a critical challenge for the widespread application of such coatings.

2) Surface property-tuning coatings

This category leverages tailored surface

physicochemical properties—including microstructure, wettability, and surface energy—to prevent fouling adhesion. It primarily encompasses two approaches: biomimetic microstructure coatings and amphiphilic coatings.

Biomimetic microstructure coatings are designed to replicate the topographical features of natural antifouling surfaces. These coatings typically exhibit superhydrophobicity and low surface energy, creating a physical barrier that inhibits larval adhesion. For instance, Haghdoost *et al.*^[84] developed a superhydrophobic coating mimicking the cauliflower morphology. Similarly, Jiang *et al.*^[85] engineered a robust antifouling superhydrophobic surface by incorporating microneedle-like materials onto regularly arranged micropillars, replicating the surface structure of lotus leaves. Drawing inspiration from the slippery surface of *Nepenthes* (pitcher plant), Zou *et al.*^[86] fabricated a self-healing antifouling coating by dispersing lubricant within a PDMS supramolecular precursor. This coating demonstrated rapid recovery after damage, sustaining over 300 healing cycles. Recently, coral-inspired antifouling coatings have garnered significant attention. Corals have evolved sophisticated antifouling strategies^[87], such as fouling-release effects and tissue shedding. Fig. 4 illustrates the antifouling mechanism mediated by coral soft tentacles.

Amphiphilic coatings constitute another major strategy for tuning surface properties. Inspired by desert beetles and lotus petioles^[88–89], synthetic amphiphilic coatings exhibit adaptive surface energy and wettability in response to environmental changes. Koc *et al.*^[90] demonstrated that in mixed charge-balanced self-assembled monolayers (SAMs), dipole orientation significantly influences protein adsorption and marine biofouling. They found that biofouling was minimized when the anionic and cationic groups were positioned at an equivalent distance from the substrate surface. Gudipati *et al.*^[91] developed amphiphilic coatings by combining polyethylene glycol (PEG) with low surface energy fluorinated polymers (HBFP). Krishnan *et al.*^[92] fabricated a comb-like polymer coating incorporating amphiphilic branched chains.

These synthetic coatings adapt their surface energy and wettability properties dynamically to environmental variations, offering broad applicability

and environmental compatibility. Future research should focus on evaluating their long-term stability and antifouling efficacy.

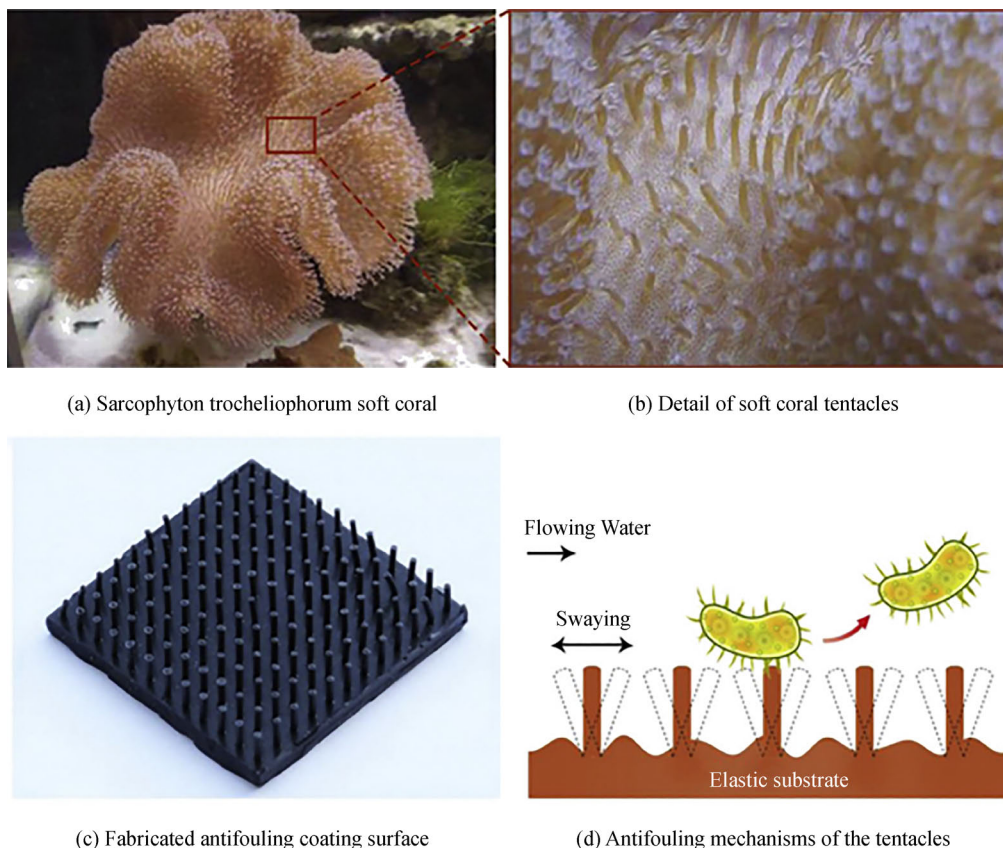


Fig. 4 Coral-inspired antifouling coating and mechanism^[87]

3) Stimuli-responsive intelligent coatings.

This class of materials is capable of altering their antifouling properties dynamically in response to external triggers such as pH, light, or temperature, offering an "on-demand" antifouling capability.

For instance, Mo *et al.*^[93] encapsulated a healing agent within microcapsules blocked by acid- and strong alkali-soluble nano-ZnO. Upon dissolution of the ZnO, the healing agent is released, enabling the preparation of a self-healing coating. Radulovic *et al.*^[94] incorporated photosensitive TiO₂ into a water-based silane emulsion. Under sunlight irradiation, TiO₂ induces protein denaturation, thereby disrupting the adhesion of fouling organisms to concrete substrates^[95] and enhancing the coating's mechanical properties. However, a significant challenge lies in precisely controlling the concentration of photosensitive materials. Excessive amounts lead to material inhomogeneity, while

insufficient concentrations yield negligible effects^[96]. Furthermore, the efficacy of such systems is severely constrained by the incident angle and radiation intensity of ultraviolet light^[97-98]. Research into stimuli-responsive materials (*e.g.*, thermosensitive and photosensitive types) forms the foundation for developing advanced intelligent coatings.

4) Composite and intelligent coating systems.

To maximize the advantages of diverse protective coatings, researchers have pursued strategies for integrating multiple functional coatings. Zhao^[99] fabricated a superhydrophobic-self-healing dual-effect intelligent coating *via* a bilayer design, spraying a nano-composite epoxy resin as the outermost layer onto a self-healing base coating. The coating's self-healing capability and service performance were evaluated under multi-factor coupled corrosion simulation tests. Currently, most composite coatings are achieved by simply superimposing or directly

incorporating two or three functional layers. A key future trend involves developing coatings with four or more synergistic functionalities and deeper intelligence, building upon the foundation of stimuli-responsive material research.

4.1.4 Summary and comparative analysis The three primary antifouling strategies discussed—concrete modification, physical removal, and novel protective coatings—offer distinct advantages and limitations, positioning them for different application scenarios. Concrete modification represents a mature and commercially established approach that enhances the intrinsic durability of new infrastructure, providing a long-term, cost-effective, and passive resistance. However, its antifouling efficacy is fundamentally limited. In contrast, physical removal is a curative, post-attachment measure with well-developed methodologies, capable of directly eradicating established biofouling but suffering from high recurring costs and operational inefficiencies. Novel protective coatings constitute an advancing field of research, with laboratory studies demonstrating considerable efficacy through active surface modulation; however, they currently face significant challenges in long-term durability and scalable manufacturing, which restricts their widespread practical application. Future advancements are expected to focus on hybrid systems that combine the bulk resilience of modified concrete with the high-performance, preventive action of advanced coatings, alongside ongoing efforts to improve the durability and scalability of the coating technologies themselves.

4.2 Measures to induce oyster attachment

Oyster shells represent a preferred substrate for oyster larval attachment. This preference is generally attributed to either chemical cues associated with conspecifics or the strong inductive effect of calcium-containing substrates on larval settlement [36–39]. Specifically, Ca^{2+} within the substrate has been shown to effectively induce oyster larval attachment. Consequently, optimizing the concrete mix proportion is necessary to enhance this larval attachment induction effect.

The incorporation of different substances into

concrete exerts distinct inductive effects on oyster larval attachment. Hu^[66] demonstrated that utilizing two types of calcium-containing inducers significantly enhanced the settlement rate of oyster larvae on concrete surfaces. Notably, the synergistic combination of these inducers more than doubled oyster settlement, and concrete exhibiting dense oyster colonization demonstrated superior durability. Fan *et al.*^[100] investigated the influence of calcium sources within the substrate by adding calcium carbonate, bovine bone powder, and gypsum powder to concrete. Their findings revealed that bovine bone powder possessed a greater capacity to induce oyster larval attachment compared to calcium carbonate and gypsum. Lv *et al.*^[101] reported that incorporating approximately 8% calcium carbonate increased the oyster attachment rate by about 50%, whereas adding approximately 8% bovine bone powder resulted in an increase exceeding 200%. Furthermore, Huang^[102] showed that combining calcium carbonate with bovine bone powder could elevate the adhesion rate by 206%.

Furthermore, substrate surface characteristics—including roughness, color, and size—significantly influence oyster larval attachment. Chlayon *et al.*^[73] demonstrated that rougher concrete surface textures enhance oyster settlement. Hu^[66] found that increasing the darkness of the concrete background color improves its ability to induce oyster adhesion. Specifically, Xu^[103] reported that using dark pigments deepens concrete chroma and promotes oyster adhesion. Fan^[26] indicated that at low larval densities, substrate size exhibits a significant positive correlation with juvenile oyster attachment density.

5 Conclusion and prospect

The adhesion of oysters on concrete surfaces and the subsequent corrosion process represent a complex system involving microorganisms and sessile communities. This phenomenon spans multiple disciplines, posing challenges for integrated knowledge synthesis. This review systematically elaborates the oyster attachment process and its key influencing factors, provides an in-depth discussion of the "corrosion-protection" dual role and mechanisms of

oyster colonization on concrete, and summarizes current strategies for either inhibiting or inducing oyster attachment. However, the evolutionary dynamics of oysters as dominant sessile organisms on concrete substrates, along with their lifecycle impacts on concrete integrity, remain incompletely understood and subject to ongoing debate. Consequently, the underlying mechanisms of oyster-induced concrete corrosion require further investigation. Specific research directions include:

1) The complex interplay of diverse marine environmental factors significantly influences oyster attachment dynamics. Variations in seasonal and developmental phases lead to differential growth patterns and distinct impacts on concrete substrates. Future research should prioritize conducting *in-situ* oyster adhesion trials within authentic marine environments. This approach will accelerate experimental timelines, enhance variable control, and enable more precise mechanistic analysis of oyster adhesion/corrosion processes. Ultimately, this will facilitate quantitative assessment of oyster lifecycle impacts on concrete durability.

2) While oyster attachment can be detrimental, the formation of stable, dense biofilms may confer protective benefits to concrete substrates. Future investigations should explore this protective mechanism. By integrating biological principles, selective breeding and behavioral conditioning of target oyster species could enable rapid colonization of intertidal concrete surfaces. This approach aims to engineer cohesive biofilms that provide effective material protection.

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Dual Role of Oyster Fouling on Marine Concrete: A Review of Protection and Corrosion Mechanisms

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Extended Abstract

Marine biofouling poses a significant threat to the durability of coastal infrastructure, with the attachment of macroorganisms such as oysters inducing complex effects on concrete substrates. This review systematically examines the attachment process of oysters on marine concrete, the multifaceted factors governing this process, and the subsequent influence on material durability, distinguishing between corrosive and protective mechanisms. The analysis further evaluates current strategies for either inhibiting or facilitating oyster colonization to support targeted management of marine structures.

The review begins by elucidating the biological attachment process of oysters, from larval settlement through metamorphosis, highlighting the critical role of substrate selection. Key determinants of attachment are systematically categorized into environmental conditions, substrate properties, chemical gradients, and biological mediators. Environmental conditions including thermal regime, hydrodynamic forces, and light availability establish broader colonization patterns. Substrate properties such as surface microtopography, material composition, roughness, and color, critically influence larval settlement selectivity and adhesion strength. Chemical gradients, particularly pH value and specific ions, modulate larval behavior and enzymatic activity. Biological mediators, including conspecific cues and interspecific interactions, govern the spatial distribution and density of oyster populations. These factors collectively determine the settlement density and adhesion strength of oysters on concrete surfaces.

The core of this review addresses the dual impact of oyster attachment on concrete performance. Corrosion can occur, driven by bioacids in larval adhesives that react with cement hydrates to form expansive products, leading to matrix cracking. Post-mortem decomposition of oyster tissue further produces aggressive species that lower surface pH and facilitate biogenic acid attack. Conversely, a protective mechanism operates when a high-density, mature oyster community establishes a durable biofilm-shell composite. This layer physically seals surface pores, refines pore structure, and significantly impedes the ingress of aggressive agents such as chloride ions and oxygen, while also mitigating physical erosion from water flow. The transition from net corrosion to net protection is critically governed by the achievement of a threshold oyster coverage density and biofilm maturity, with low-density attachment providing insufficient protection and potentially exacerbating localized degradation.

The review further summarizes strategies to manage oyster attachment. Preventive measures include modifying concrete mix designs with pozzolans or slag to enhance inherent durability, physical removal methods such as manual cleaning and ultrasonic techniques, and the development of advanced protective coatings. These coatings encompass natural antifouling agent-based coatings, surface-property-tuning coatings including biomimetic and amphiphilic designs, and stimuli-responsive intelligent coatings that offer targeted, environmentally benign alternatives. However, they face challenges in long-term stability and scalable application. Conversely, inductive measures to promote protective oyster colonization focus on optimizing concrete as a settlement substrate through the incorporation of calcium-based inducers such as bovine bone powder and calcium carbonate, and tailoring surface characteristics including roughness and dark color to significantly enhance larval attachment rates and aim to engineer stable, high-density biofilms for long-term concrete preservation.

Summary and prospects Although significant progress has been achieved in understanding oyster-concrete interactions, the dualistic corrosion-protection mechanisms of oyster attachment remain complex and incompletely understood, with the evolutionary dynamics of oysters as dominant sessile organisms on concrete substrates and their lifecycle impacts on concrete integrity subject to ongoing debate owing to the intricate interplay of diverse marine environmental factors, seasonal variations, and developmental

phases that lead to differential growth patterns and distinct effects on concrete durability. Future research should prioritize conducting systematic in situ field trials within authentic marine environments to enable precise mechanistic analysis of adhesion and corrosion processes, facilitate quantitative assessment of oyster life-cycle effects on concrete performance, and establish comprehensive models capable of predicting the transition between corrosive and protective outcomes based on critical thresholds of coverage density, biofilm maturity, and local hydrodynamic regimes. Furthermore, although oyster attachment can be detrimental under conditions of low-density colonization, the formation of stable, dense biofilms may confer significant protective benefits to concrete substrates by impeding aggressive agent ingress, refining surface pore structure, and mitigating physical erosion, warranting in-depth investigations into this protective mechanism through integration of biological principles such as selective breeding and behavioral conditioning of target oyster species to promote rapid colonization of intertidal concrete surfaces and engineer cohesive fouling communities capable of providing effective long-term material preservation, ultimately contributing to the development of controllable, large-scale bioprotective strategies for sustainable marine infrastructure management.

Keywords marine concrete; fouling organisms; oyster; biocorrosion; protection and induction