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REVIEW

Corrosion-Resistant Materials for Ocean Structures: Innovations, Mechanisms, and Applications

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ABSTRACT

Offshore structures such as platforms, pipelines, the hulls of ships, wind turbine foundations, etc., are constantly subjected to harsh seawater environments with high salinity, changes in temperature, humidity, biological activity, etc. These conditions promote corrosion and jeopardize the service, safety and service life. In this study, recent developments in ocean materials for corrosion resistance are extensively reviewed. It classifies

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corrosion-resistant materials as metal alloys, nanocomposites, and nanostructured hybrid materials and discusses their performance, mechanisms of protection, and applications in the field. It treats high-performance materials such as stainless steels, Ni-based alloys, and Ti alloys, polymers and composites, ceramics, or evenbio-inspired coatings. A comprehensive study including corrosion failure mechanisms, such as pitting, crevice, galvanic, microbiologically influenced, stress corrosion cracking (SCC), is provided to present a comprehensive view of the necessary selection of materials and corrosion control practices. Concurrently, the review presents protective technologies such as cathodic protection systems, anodizing, passivation, thermal spray coatings, as well as emerging ones such as plasma electrolytic oxidation and self-healing smart coatings. Advanced high entropy alloys, graphene barriers and additive manufacturing are stressed as they have the potential to disrupt marine corrosion protection. However, issues such as long-term performance verification, cost-performance ratio for optimal design, compatibility with on-line monitoring systems, and compliance with environmental standard still remain unsolved. The paper highlights significant research gaps and potential future directions in AI-enabled material design, green coatings, and development of digital corrosion management systems. In the end, this book is a great resource for engineers, researchers, and policymakers involved in the development of durable, efficient and ecologically friendly marine infrastructure.

Keywords: Marine Corrosion; Corrosion-resistant Materials; Ocean Structures; Protective Coatings; High-entropy Alloys; Offshore Engineering

1. Introduction

Marine structures have provided a key role in energy, defence, transportation and environmental observation. But the oceanic corrosive environment promotes the corrosion through electrochemical processes of chlorides, sulfates, dissolved oxygen and microorganisms. Corrosion results in loss of material, structural failure, high maintenance costs and environmental menaces. This issue demands corrosion resistant materials offering added values of specific mechanical properties, long term stability and eco-friendliness. This review compiles recent material development and technology strategies to prevent ocean structure corrosion. The global push toward sustainable energy has significantly increased interest in Ocean Renewable Energy Systems (ORES), which harness the power of waves, tides, and ocean currents to generate clean electricity [1–3]. These systems offer immense potential, particularly in coastal regions where consistent energy input can complement existing renewable infrastructures [4]. However, despite technological progress, widespread adoption of ORES remains limited due to persistent challenges. Key issues include inaccurate energy forecasting in highly dynamic marine environments, suboptimal system design and control strategies, and difficulties in maintenance and long-term reliability [5]. While recent studies have explored AI-based tools for prediction, optimization, and control, there is a lack of comprehensive reviews that consolidate these advancements in the context of real-world implementation gaps. Bridging this knowledge gap is essential to inform future research, support policy decisions, and facilitate the integration of intelligent systems into next-generation ocean energy solutions. **Figure 1** represents Corrosion Protection Strategies for Marine Structures Using Advanced Coatings and Technologies. Corrosion of metal structures in marine environments is a complex phenomenon that depends on factors like salinity, temperature, hydrodynamics and biological activity [6]. Besides the correct design of the structure, the key to successful corrosion protection is also the efficient choice, application, and preservation of corrosion protective layers, and not just in the selection of design concepts, processes, and materials [7]. It is highly demanded to develop new corrosion-resistant materials to improve the long-term durability and safety of marine structures [8]. Various techniques have been proposed in the past (and are also under research) to control the corrosion [9]. Despite their popularity, organic coatings offer considerable potential for improvement such as long-term service reliability, poor resistance to mechanical damage, and a growing concern regarding the generation of volatile organic compounds [10]. The hunt for an alternative environment friendly coating technology has been increasing and anticorrosive polymeric coatings, offer versatility of inhibiting corrosion by various methods [11]. These coatings can serve as impermeable barriers to isolate corrosive agents from the metal, including sacrificial and leaching corrosion inhibiting agents that passivate the metal and/or be self-repairing, which means the coating will heal itself after it is damaged extending the life in service [12]. Another promising direction in the development of smart coatings which have the capability to sense the environmental change and heal their own damage is reported programing to corrosion protection [13].

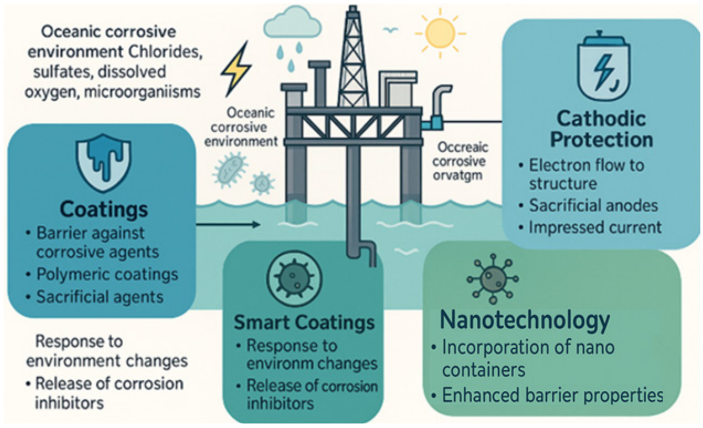

Figure 1. Oceanic Corrosive Environment.

The integration of micro- and Nano containers into coatings is essential for achieving customized responses to specific mechanical and environmental issues, as these containers hold active ingredients such as catalysts, repair monomers, and corrosion inhibitors that are released upon damage [14]. Nanotechnology has revolutionized corrosion protection through the development of smart coatings that incorporate Nano containers loaded with corrosion inhibitors [15]. These Nano containers release their contents only when corrosion is detected, providing targeted protection and extending the lifespan of the coating [16,17]. Nano coating, characterized by constituents or layers under 100 nm, effectively reduces corrosion impact due to their surface hardness, adhesive quality, and high-temperature resistance [18]. Recent advancements in polymer nanocomposite coatings have shown promise in providing anti-corrosion, anti-fouling, and self-healing properties [19]. Self-healing coatings represent a significant advancement, utilizing micro/Nano carriers to release corrosion inhibitors and polymerizable agents upon damage, thereby preventing further degradation [20]. The development of coatings with self-healing capabilities represents a significant advancement in corrosion protection, reducing maintenance and extending the lifespan of structures [21,22].

The incorporation of micro- and nano containers in coatings is crucial to tailor responses to mechanical and environmental illness, because they contain active chemicals such as catalysts, repair monomers and corrosion inhibitors that are released after damage [23]. Nanotechnology has led to better corrosion protection technology, such as smart coatings containing Nano containers filled with corrosion inhibitors [24]. They start to release their content when corrosion is perceived offering local protection and prolonging the life of the coating [25,26]. Nano coatings, the composition of which or the thickness of the layers is below 100 nm, have the potential to diminish the corrosion influence since they demonstrate surface hardness, adhesion capability and thermal endurance [27]. Recent progress in PNCCs, also as coatings, offers expectations in the respect of anti-corrosion, anti-fouling, and self-healing [28]. Self-healing films are such a major innovation that incorporates micro/Nano carriers releasing the corrosion inhibitor and polymerizable agents in response to the occurrence of damage, thereby suspending further decay [29]. The appearance of coatings possessing self-healing properties is an important development in the realm of corrosion protection, as it decreases the maintenance demands and prolongs the life of structures [30,31] **Table 1** presents the Corrosion Protection Strategies for Marine Structures.

Table 1. Corrosion Protection Strategies for Marine Structures.

S.No.	Corrosion Challenge	Strategy/Approach	Technology or Material Used	Key Benefits
1	Corrosion from oceanic salts, microbes, oxygen	Need for corrosion-resistant materials	Alloys, eco-friendly materials	Long-term stability, durability
2	High salt concentration exposure	Advanced protective fluids	Water-based inhibitors	Eco-friendly corrosion control
3	Mechanical scratches and environmental stimuli	Responsive protection	Smart Coatings	Self-healing, environment sensing
4	Global corrosion with climate effects	Sustainable corrosion control	Green materials, improved coatings	Reduced impact, improved protection
5	Electron loss in structures	Electrochemical balance	Cathodic protection	Restores electron flow, protects metal
6	Complex marine environment (salinity, biology)	Holistic approach to protection	Protective layers + design	Enhanced life and performance
7	Demand for durability in marine structures	Material innovation	New corrosion-resistant materials	Extended life, improved safety
8	Organic coating limitations	Alternative coatings	Anticorrosive polymeric coatings	Less VOCs, more flexibility
9	Physical damage to coatings	Barrier and healing coatings	Self-healing polymers	Damage recovery, extended service
10	Localized corrosion from mechanical/environmental triggers	Encapsulated chemical delivery	Nano/Micro containers	Responsive inhibitor release
11	Surface-level corrosion	Ultrathin layer protection	Nano coatings <100nm	Hardness, adhesion, thermal endurance
12	Multifunctional needs	Advanced coating systems	PNCCs, self-healing films	Anti-fouling, corrosion, healing

In preparing this review, a systematic methodology was employed to ensure the relevance, rigor, and comprehensiveness of the selected literature. Sources were retrieved from leading academic databases including Scopus, Web of Science, IEEE Xplore, and Science Direct, focusing on publications from 2010 to 2025 to capture contemporary developments. The keyword combinations used in the search included marine corrosion, anticorrosive coatings, bio-inspired materials, smart coatings, additive manufacturing, and predictive maintenance in marine systems. Preference was given to peer-reviewed articles, experimental studies, simulation-based analyses, and industry reports that offered field-relevant insights. Studies lacking marine context, technical depth, or empirical support were excluded. This review methodology ensured that the article draws upon high-quality and up-to-date sources to present a critical and application-focused perspective on corrosion-resistant materials and intelligent maintenance strategies in marine environments.

2. Classification of Corrosion-Resistant Materials

The corrosive sea environment – high humidity, salinity, bio-fouling and temperature changes – calls for materials with admirable corrosion resistance. These materials are generally divided into three main categories according to their constitution and function. **Figure 2** categorizes corrosion-resistant materials for marine structures into three groups: metallic alloys, non-metallic materials, and advanced hybrid materials. Metallic alloys like stainless steel, titanium, and nickel-based alloys offer strength and corrosion resistance in harsh marine conditions. Non-metallic materials, including fiber-reinforced polymer (FRP) composites and polymer coatings, provide lightweight, non-corrosive alternatives. Advanced hybrid materials, such as bio-inspired coatings and ceramic-metal matrix composites, combine the benefits of natural design and engineered strength, offering improved durability, antifouling properties, and long-term performance in marine environments.

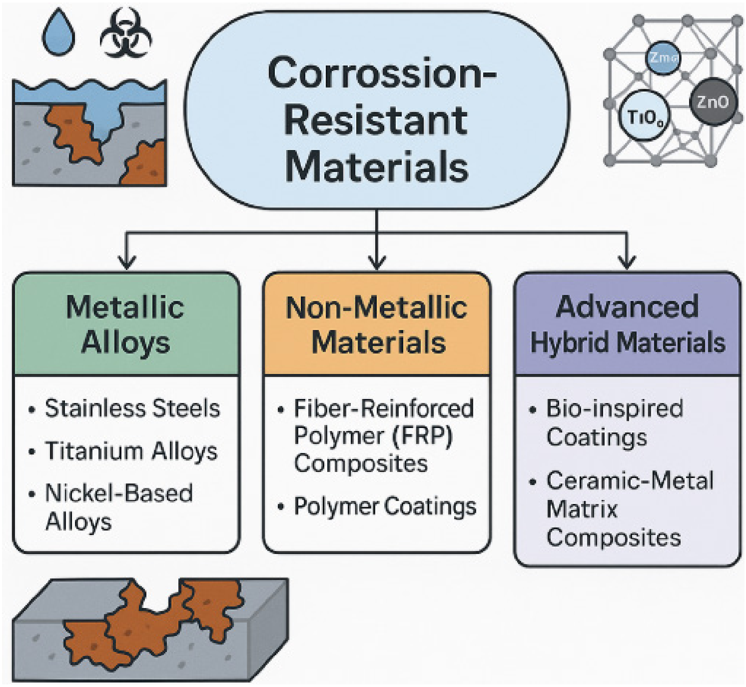

Figure 2. Classification of Corrosion-Resistant Materials for Marine Structures.

2.1.Metallic Alloys

Because of their good mechanical properties and good corrosion resistance, metallic alloys are indispensable materials for marine structures. In seawater systems, the resistance may be due to passivation, which is the rapid formation of a thin, protective oxide film or to the presence of corrosion-inhibiting elements.

2.1.1. Stainless Steels

As known, the presence of a “stainless” phase (20–35 wt % chromium) highlights the so-called “triplex” microstructure in both SSs that have a high chromium (≥16%) content and therefore form a passive oxide film, allowing a s/p transition, also being Mo used to enhance the pitting resistance in the presence of chlorides. For seawater systems, 316L is commonly employed in piping and storage tanks, while higher in strength and corrosion resistance duplex steels like 2205 are applied for offshore platforms and load-carrying structures in marine environments. Excellent corrosion resistance is imparted by nickel-based alloys such as Inconel and Hastelloy, which are alloyed with molybdenum along with a substantial amount of nickel and chromium. These alloys are used in a variety of applications including subsea pipelines, heat exchangers and chemical processing applications where pitting, crevice and stress corrosion cracking resistance is required.

2.1.2. Titanium Alloys

Corrosion-resistant TiO2 layer on the surface to provide immunity from harsh marine corrosion, such as crevice and pitting corrosion. Such alloys are widely used in heat exchangers, desalination units, and marine condenser tubing. Titanium and titanium alloys have high specific strength and corrosion resistance as they form a stable titanium dioxide layer.

2.1.3. Nickel-Based Alloys

Nickel-Based Alloys such as Inconel & Hastelloy are designed to withstand high temperature, high salt environment and acid attacks. Their superior resistance to oxidation and stress-corrosion cracking makes them suitable for demanding applications such as deep-sea diving, marine turbines, and high-performance exhaust systems. The resistance of nickel alloys to localized corrosion is extremely important to the oil and gas upstream industry, chemical process industry, and exposure to seawater [32]. Nickel-based alloys strengthened by dispersion of particles are used widely due to their high resistance to corrosion and high strength as well as used in fabrication of complex drilling/finishing equipment and components for equipment used in active media containing high levels of chlorides, carbon dioxide and hydrogen sulfides at temperatures of up to 250°C [33]. Nickel based coatings are valued due to their high hardness, wear resistance and corrosion resistance and as such are well suited for marine, power generation, chemical and automotive sectors [34].

2.2.Non-Metallic Materials

Non-metallic materials play a crucial role in marine applications due to their inherent resistance to corrosion and reduced maintenance needs.

2.2.1. Fiber-Reinforced Polymer (FRP) Composites

FRP Composites, such as Fiber-Reinforced Polymer (FRP) Composites, which offer lightweight and high corrosion resistant properties are widely used as structural elements, including such structural components as decking, grating, and handrails in marine surroundings. Their hydrolytically stable responses in saline environment should be maintained for a long time with the sense of no degradation influence.

Polymeric Materials Polymeric materials, including high density polyethylene and polyvinyl chloride, provide low-cost answers for piping, cable insulation and coatings. They are resistant to chemical breakdown and are ideal for having to be exposed to seawater. Coatings and Linings (epoxy, polyurethane and rubber linings that are used as a barrier to protect steel from marine corrosion).

HDPE is used in a wide variety of applications including plastic bottles, milk jugs, shampoo bottles, bleach bottles, cutting boards, and piping and is valued for its natural resistance to chemicals and corrosion in seawater while maintaining its strength, durability and lasting performance. Polymer composites reinforced with fibres are known for their high strength-to-weight ratio, corrosion resistance, and design freedom. They are sought after for their limited hardness, wear resistance and corrosion resistance with harsh chemicals, which often allows their use as coatings, sensor housings, and bearings in a variety of marine equipment. The use of ceramics provides an effective defence against wear, erosion, and chemical attacks to extend the life of key components of marine systems [35].

2.2.2. Polymer Coatings

Polymers (such as epoxy, polyurethane, and vinyl ester resins) serve as barrier layers to impede water and penetration of ions. Such coatings are widely used to provide protection to metal-based substrates in seawater from corrosive elements and to lengthen the life of marine structures. Surface finishes and coatings are essential in preventing corrosion in these materials, for they serve as a barrier between the material and the aggressive environment [36]. These coatings consist of, but are not limited to, inorganic coatings such as zinc-rich paints, organic coatings including epoxies and also polyurethanes and more sophisticated coatings such as self-healing polymers. Coating is a complicated system, and its performance relies on raw materials, as well as an application onto the film, drying, and curing. The growing concerns for environmental protection laws have limited chemical biocides uses, so antifouling and anti-corrosion coatings have been developed [37]. The antifouling coatings from marine organisms' adhesive and corrosion [38].

2.3.Advanced Hybrid Materials

Advanced hybrid materials are increasingly being developed to enhance the performance and longevity of marine structures by combining unique functional properties.

Hybrid materials, particularly ceramic-metal matrix composites (CMMCs), offer a promising combination of the high-temperature resistance and hardness of ceramics with the toughness and ductility of metals. This unique synergy enables superior performance in harsh environments, making them ideal for applications such as turbine blades, brake discs, cutting tools, and aerospace structural components. For example, TiC-reinforced aluminium matrix composites are used in automotive engine components due to their lightweight and wear-resistant nature, outperforming conventional aluminium alloys under thermal cycling. Similarly, SiC-Ti6Al4V composites are gaining traction in aerospace propulsion systems for their ability to maintain mechanical integrity at elevated temperatures where monolithic metals fail.

In comparison to pure metallic materials, CMMCs demonstrate enhanced creep resistance, reduced thermal expansion, and improved oxidation resistance. A notable case is the use of Al_2O_3-Ni composites in marine heat exchangers, where their corrosion resistance surpasses traditional copper-based alloys, especially in saltwater environments. Despite their advantages, challenges such as interfacial bonding, cost of production, and processing complexity still hinder their large-scale adoption. However, advancements in powder metallurgy and additive manufacturing are gradually overcoming these limitations, making CMMCs a realistic option for next-generation high-performance applications.

2.3.1. Bio-inspired Coatings

Bio-inspired coatings, modelled after natural surfaces like nacre, lotus leaves, and fish skin, offer advanced functionalities such as self-healing, antifouling, and water repellence. These coatings naturally resist marine growth and corrosion, effectively preventing biofouling and reducing maintenance requirements. Self-healing variants are particularly valuable, as they can autonomously repair damage from mechanical stress or environmental factors, thereby prolonging the lifespan and integrity of structures. This is achieved through the incorporation of microcapsules or Nano containers filled with repair monomers, catalysts, or anticorrosive agents [39]. On a microscopic scale, such coatings exhibit superior mechanical strength, chemical resistance, and barrier performance. Furthermore, the inclusion of nanoparticles like TiO_2, ZnO, and graphene enhances coating properties by improving hardness, UV resistance, and antioxidant capacity [40].

Non-toxic antifouling paints and coatings are formulated with environmentally safe substances and surface textures that prevent the attachment of marine organisms, thereby reducing drag and metal corrosion. Understanding the interactions between fouling organisms and surface materials is crucial for improving the natural repellence of antifouling compounds [41]. Hydrogels, when applied as direct coatings, can effectively minimize the initial adhesion of proteins and polysaccharides—key early-stage biofuels—thus mitigating biofouling across various applications [42]. This antifouling effect is further enhanced by surface microstructures and mucus-like secretions, similar to those found on marine animal skin.

2.3.2. Ceramic-Metal Matrix Composites

Ceramic-Metal Matrix Composites combine the ductility and toughness of metals with the excellent corrosion and thermal resistance of ceramics. These composites find use especially when both mechanical strength and chemical resistance are desired, for example, in corrosive marine environments. Bioactive ceramic coatings, such as those containing copper, silver, zinc, and titanium, can be coated on carbon steel to prevent microorganism-induced corrosion in offshore floating wind farms [43].

The inclusion of hydrolysable units in hydrophobic PDMS segments can lead to self-polishing coatings with a good compromise between hydrophobicity and hydrolytic features [40]. Adding nanoparticles in organic materials proved to give the materials a modified aesthetic appearance, anti-corrosion ability, thermal stability, mechanical strength, and nano-architectural cross-linking [44]. Nanocoating can be deposited in much thinner and more smooth thicknesses; this improves the flexibility in the design of devices, resulting in energy savings, cheaper fuel consumption, lower CO2 footprints and reduced maintenance and operating costs [45].

Materials that can resist corrosion are important for the long-term use of ocean structures. Marine structures can therefore be easily designed to last long, with low-maintenance by utilizing conventional alloys along with newer non-metal and hybrid materials. The possibilities for protecting metals from corrosion in aggressive marine environments have further been extended as a result of new work, which is actively being researched in the areas of bio-mimicry, coatings and composites. **Table 2** represents Corrosion-Resistant Materials for Marine Structures.

Table 2. Materials Used in Marine and Offshore Structures with Compositional and Mechanical Properties.

Material Type	Example	Typical Applications	Corrosion Resistance	Chemical Composition	Mechanical Properties
Steel Alloy	ASTM A36	Offshore platforms, hulls	Moderate to Low	Fe-C alloy with ~0.26% C, Mn, Si	UTS: ~400 MPa, YS: ~250 MPa, Elongation: 20%
Stainless Steel	316L	Pipes, risers	High	Fe–17Cr–12Ni–2.5Mo	UTS: ~485 MPa, YS: ~170 MPa, Elongation: 40%
Aluminium Alloy	5083	Ship hulls	Good (with anodizing)	Al–4.5Mg–0.7Mn–0.15Cr	UTS: ~330 MPa, YS: ~215 MPa, Elongation: 12%
Epoxy Resin	DGEBA-based	Composite coatings	Excellent (barrier type)	(C21H24O4)n	Tensile Strength: ~70 MPa, Modulus: ~3 GPa
Polyurethane	PU Coatings	Ship decks, hulls	Good (UV + corrosion)	–(RNHCOOR')n–	Tensile Strength: ~35–60 MPa, Elongation: ~300%
Vinyl Ester	FRP Composites	Wind blades, panels	Very High	Modified Epoxy with unsaturated esters	Tensile Strength: ~80–90 MPa, Flexural Strength: ~140 MPa
Zinc-rich Coating	Zn dust in epoxy	Sacrificial coating	Excellent	>85% Zn by wt.	NA (coating), acts anodically
Thermal Spray Al	Al coating	Subsea pipelines	Excellent	Pure Al	NA (coating), corrosion potential: –0.80 V (SCE)

3. Corrosion Mechanisms in Marine Structures

Corrosion in marine environments occurs due to the synergistic effects of salinity, dissolved oxygen, temperature, and microbial activity. Among various corrosion types, Stress Corrosion Cracking (SCC) is a critical concern for marine structural alloys. For example, Austenitic stainless steels (e.g., 304L, 316L), widely used in ship hulls and offshore platforms, are particularly vulnerable to chloride-induced SCC in warm, oxygenated seawater environments. Similarly, high-strength aluminium alloys, such as AA7075, exhibit SCC under cyclic mechanical loading and prolonged seawater exposure. This type of localized corrosion often leads to sudden and brittle failure without significant prior deformation, making it highly dangerous for load-bearing marine structures.

To enhance clarity, **Figure 3** illustrates uniform corrosion, pitting, crevice corrosion, galvanic corrosion, and SCC can be added. These visuals can depict the progression of damage in materials like stainless steel in chloride-rich waters or galvanic coupling between steel and aluminium in ship fittings. Diagrams should include labels for electrochemical reactions, anodic/cathodic regions, and microstructural changes under stress to strengthen conceptual understanding.

The corrosion mechanisms section is conceptually strong but can be improved by adding real-world examples and supporting literature. For instance, stress corrosion cracking (SCC) is discussed, but specific marine alloys like 316L stainless steel or AA7075 aluminium, which are prone to SCC in seawater, should be mentioned. Including case-based references and diagrams illustrating key mechanisms—such as SCC, galvanic corrosion, and pitting—would enhance clarity. These visuals should show electrochemical behaviour, material degradation, and stress effects to better link theory with practical marine applications.

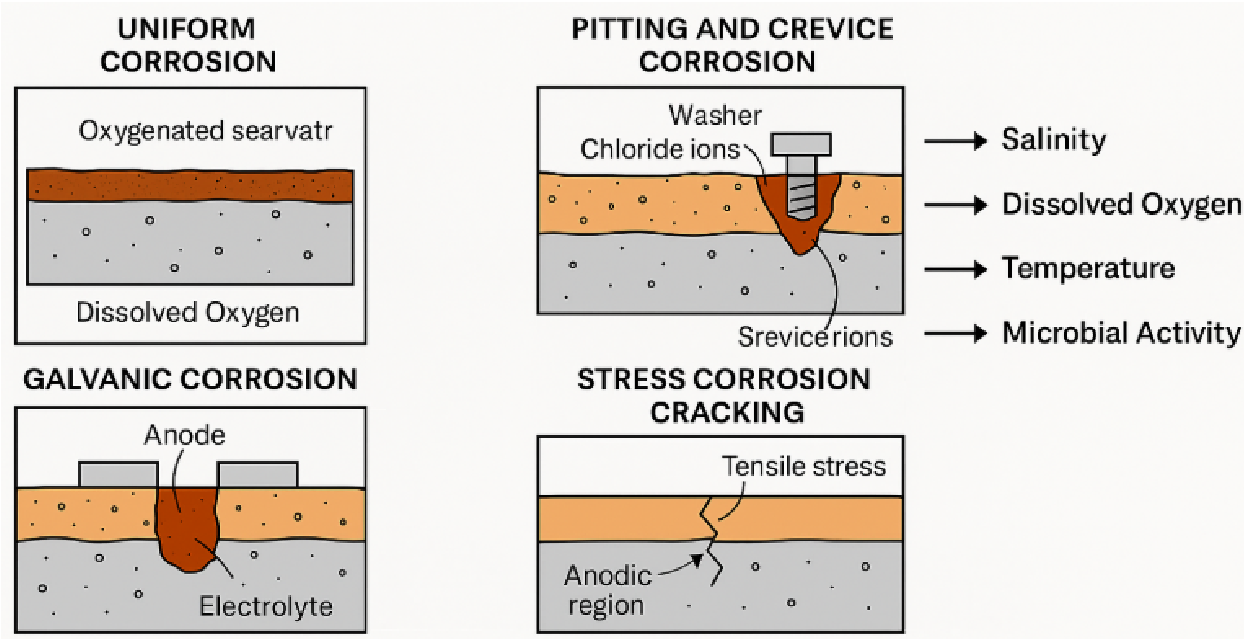

Figure 3. Corrosion Mechanisms in Marine Structures and Their Environmental Triggers.

3.1.Uniform Corrosion

This is the simplest type of corrosion, in which metal surfaces react uniformly to oxygenated seawater and deteriorate. This produces uniform reduction spreading across wide areas and is rather predictable. It is more easily detected and controlled, but still causes slow material loss leading to decreased structural integrity. The electrochemical reactions involve the dissolution or oxidation of the metal, coupled with the reduction of oxygen [46]. For instance, stainless steels' uniform corrosion rate intensifies with temperature increases, with pitting corrosion becoming more apparent under severe conditions [47]. In contrast, metals higher in the electrochemical series tend to corrode more [48]. To mitigate this, high-loaded solid inhibitors could be used, but marine engineering usually uses coatings and cathodic protection instead [2]. Corrosion is an active process affecting various sectors like industrial equipment, marine industry, oil and gas, and infrastructure [49]. The metal's electrochemical potential can be altered through cathodic or anodic protection to make it less susceptible to oxidation [23].

3.2.Pitting and Crevice Corrosion

These are types of localized corrosion. Pitting attack results from formation of small deep pits on metal surfaces due to chloride ion action, whereas crevice corrosion takes place in confined areas (under gaskets, washers, or biofilm areas), where stagnating seawater and a scarce amount of oxygen make the environment extremely aggressive. Both are hazardous because it can be hard to identify them and they can cause structural collapses without warning. The effects of galvanic corrosion are system-specific, making it difficult to prevent without assessing each case individually [50]. Corrosion in carbon dioxide environments is referred to as sweet corrosion, whereas corrosion in environments containing hydrogen sulfide is known as sour corrosion [51]. Understanding and controlling corrosion requires not only knowledge of the materials involved but also a nuanced awareness of electrochemical processes and environmental factors [52].

3.3.Galvanic Corrosion

This phenomenon is driven by the galvanic effect, which occurs when two dissimilar metals in electrical contact generate an electric potential, particularly in the presence of an electrolyte like seawater. In such cases, the less noble (more anodic) metal corrodes at an accelerated rate, while the more noble (cathodic) metal is safeguarded from corrosion. This effect is commonly observed in mixed-metal assemblies—such as screws, fasteners, or structural joints—unless they are properly insulated or protected using sacrificial anodes. Corrosion inhibitors are commonly used to mitigate uniform and localized corrosion by interacting with the material's surface to improve its corrosion resistance [53]. Corrosion inhibitors function by adsorbing onto the metal surface, thereby impeding electrochemical processes at the metal-solution interface [28]. Coatings are another method of preventing corrosion by forming a physical barrier that prevents aggressive substances from reaching the metallic interface [28]. Organic compounds containing oxygen, sulfur, and nitrogen have been shown to be very effective corrosion inhibitors by creating protective films. Smart inhibitors, which activate only when corrosion is detected, can be integrated into coatings as microcapsules, enabling self-healing properties [23].

3.4.Stress Corrosion Cracking

SCC is a very destructive type of corrosion that occurs due to tensile stress in a corrosive environment. It results in the generation of cracks that can propagate even without deformation and can cause catastrophic failures. SCC is especially troublesome in high strength alloys which are employed in structural marine applications. Anodic dissolution, hydrogen-induced cracking, and combined anodic dissolution and hydrogen-induced cracking mechanisms are the currently prevalent stress corrosion cracking theories [46]. The microstructure, presence of pores, micro-cracks, and macro-cracks can favour electrolyte penetration, leading to galvanic corrosion, coating degradation, and substrate weakening [54]. The prediction of corrosion is challenging but crucial for the design and maintenance of marine structures, as corrosion can compromise structural integrity and lead to environmental pollution [55]. The presence of hydrogen sulfide and carbon dioxide in marine environments can exacerbate corrosion, particularly in oil and gas infrastructure, necessitating careful material selection and corrosion management strategies [56,57]. Self-healing coatings, which include corrosion inhibitors, can be applied to the metal to protect it from corrosion by either cathodic or anodic protection [23,24]. These coatings contain microcapsules and Nano containers with active ingredients like catalysts and corrosion inhibitors that are released upon damage, allowing for customized responses to specific environmental and mechanical issues [23,28].

Various corrosion types in marine atmospheres are of great threat to the stability and safety of structure elements. Full knowledge of these will allow engineers and material scientists to choose appropriate materials and coatings for these purposes and to design suitable maintenance programs that ensure the long and safe service of marine structures. **Table 3** indicates the corrosion mechanism in marine structures.

Table 3. Corrosion Mechanisms in Marine Structures.

S.No.	Corrosion Type	Description	Causes	Impact on Structures
1	Uniform Corrosion	Uniform metal loss across surface due to reaction with oxygenated seawater.	High salinity, dissolved oxygen	Predictable material thinning and reduction of structural integrity.
2	Pitting and Crevice Corrosion	Localized corrosion forming deep pits or under crevices (gaskets, biofilms).	Chloride ions, stagnant seawater, low oxygen	Difficult to detect; may cause sudden failures.
3	Galvanic Corrosion	Corrosion when dissimilar metals are in contact in seawater.	Electrical potential differences, mixed-metal installations	Accelerated corrosion of anodic metal; structural weakening.
4	Corrosion Affected by Micro-organisms (CABM)	Corrosion caused by microbial activity, especially sulfate-reducing bacteria.	Biofilms, anaerobic zones, hydrogen sulfide production	Increased corrosion rate in subsea structures and pipelines.
5	Stress Corrosion Cracking (SCC)	Crack formation due to tensile stress in corrosive environment.	Tensile stress, high-strength alloys, corrosive agents	Can lead to catastrophic failures without visible deformation.

3.5. Corrosion and Damage in Offshore Wind Turbine Blades

Offshore wind turbine blades are typically fabricated using fiber-reinforced polymer composites (FRPs), which are valued for their lightweight and corrosion-resistant properties. However, their exposure to harsh marine conditions—salt spray, UV radiation, humidity, and high mechanical stress—makes them prone to specific degradation mechanisms such as surface erosion, delamination, and moisture-induced fatigue. Recent studies have reported accelerated blade damage due to salt fog environments, biofouling, and micro crack propagation under cyclic loading. Additionally, lightning strikes and UV degradation contribute to matrix cracking and fiber-matrix deboning.

Interlayer hybrid fibre composites are also being explored to improve damage tolerance and maintain structural integrity, potentially supplementing or replacing existing glass fibres. Such materials can optimize stacking arrangement, number of plies, and fibre orientation to improve mechanical properties [58]. With the increasing capacity of offshore wind turbines, some reaching 12–15 MW and rotor diameters of up to 236 m, the demand for robust and reliable blade materials is greater than ever. These advancements aim to address the growing challenges of waste management and the need for sustainable solutions in the wind energy sector [59]. Research is also focusing on the development of combined structures of offshore monopile wind turbines and aquaculture cages in waters, but reference materials applicable to engineering practice are extremely limited [60]. Digital healthcare engineering frameworks are being developed to facilitate early fault detection and health assessments, contributing to the safety and sustainability of ageing offshore wind turbines [61]. As offshore wind capacity expands, with projections reaching 85 GW in Europe, innovative designs such as tension-leg dual-module systems are being explored to ease installation and maintenance [62,63]. Further research into towing stability and the implementation of new evaluation methods are essential for ensuring the reliability of floating wind turbines, as are risk assessment frameworks tailored for retrofitting ship structures to enhance eco-friendliness [64,65].

The study investigates the influence of impact velocity, angle, and duration on raindrop erosion of GFRP wind turbine blades, comparing bare and polyurethane-coated samples using Taguchi's DOE approach. Results showed that coatings significantly reduced erosion, with impact velocity being the most influential factor, and advanced techniques like SEM, XRD, and hardness testing provided insights into erosion mechanisms and material characteristics [66]. The study aims to evaluate and optimize the erosion performance of coated and uncoated GFRP wind turbine blade materials using Taguchi's L25 design by varying impact velocity, angle, and run time. Experimental results confirmed lower erosion in coated samples, with impact velocity being the most influential factor, and advanced characterization tools (SEM, XRD, EDXS) were used to analyze erosion mechanisms and surface morphology [67].

To counter these effects, advanced coatings (e.g., hydrophobic, UV-stable, and erosion-resistant layers) and nano-engineered composite materials are being researched. Furthermore, sensor-embedded smart blades are emerging to enable real-time health monitoring and predictive maintenance of wind turbines. The development of AI-based blade damage prediction models based on acoustic emission and strain monitoring data is another frontier in offshore wind energy reliability.

4. Recent Innovations and Material Developments

The development of advanced materials and protection technologies for improved corrosion resistance, durability and performance is an aspect of interest due to the harsh marine environment it faces. These advances are expected to enable to overcome drawbacks of traditional materials by integrating new functionalities like self-healing, enhanced barrier and smart structural concept. **Figure 4** represents Recent Innovations and Material Developments for Marine Corrosion Protection.

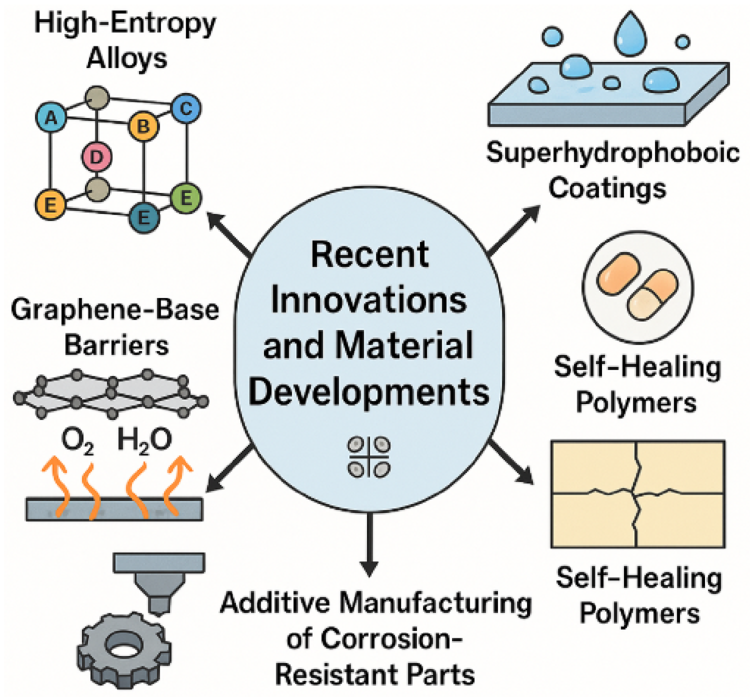

Figure 4. Recent Innovations and Material Developments for Marine Corrosion Protection.

4.1.High-Entropy Alloys (HEAs)

High-Entropy Alloys belong to a new form of alloys containing several (usually five at minimum) principal elements in near-equimolar ratios. It is this interesting material combination which results in slow atomic diffusion and stable passive oxide films that contribute to enhanced corrosion resistance in a highly aggressive environment, such as seawater. Their intrinsic structural stability, high mechanical strength, and excellent corrosion resistance indicate that HEAs might be eligible materials for above-mentioned marine components that are placed under joint influence of mechanical stressing and corrosion. Nevertheless, further studies are still required for the tribological properties of HEAs [68].

HEAs offer exceptional strength, corrosion resistance, and thermal stability, yet their industrial application remains limited due to high production costs, complex processing requirements, and limited standardization. Most HEA research is still at the lab scale, with only a few pilot implementations in aerospace and marine fasteners. Similarly, graphene coatings demonstrate excellent barrier properties and antifouling potential in laboratory tests; however, scalability, coating uniformity, long-term adhesion in seawater, and cost remain significant barriers to commercial use. Industrial adoption is still in its early stages, and widespread application in marine infrastructure has yet to be realized. Expanding this discussion with insights from pilot trials and current limitations in manufacturing and lifecycle performance would offer a more realistic view of their readiness for deployment.

4.2.Super hydrophobic Coatings

They're engineered to frustrate water, imitating surfaces in nature such as lotus leaves. Based on nanostructured silica, fluoropolymers, or finally textured composites, super hydrophobic coatings significantly suppress water adherence, salt accretion, and biofouling on a marine interface. Due to their low surface energy and high contact angle, water adhesion is low, which inhibits corrosion and microbial growth. These coatings are well suited for ship hull, offshore platform, and, underwater sensor etc.

4.3.Graphene-Based Barriers

Graphene, a one-atom-thick layer of carbon atoms in a honeycomb lattice, has also demonstrated superior permeability to gases and liquids. Graphene coatings create a barrier that virtually no oxygen, water, or harmful ions can surpass. Such coatings tend to improve resistance to oxidation when applied to metallic substrates, and reduce corrosion rates without substantially increasing component weight. They are very effective in shielding electronics, as well as marine or low volume structural devices. Corrosion resistance can be significantly enhanced by the addition of graphene Nano powder in the range of 0.5–1.0 wt. % [69].

4.4.Self-Healing Polymers

Self-healing coatings containing microcapsules or filled with corrosion inhibitors or healing agents and some kind of a liquid-releasing mechanism. Upon physical damage of the coating, but at any rate upon the further growth of a corrosion initiation expansion, these encapsulated materials would be released in the exposed area to build a fresh protective layer. This mimicking of natural healing processes prolongs the life of coatings on underwater or splash zone structures and decreases the frequency of maintenance required. However, the limited healing ability of healing agents could hinder their efficiency for repeated damage [70]. Such inhibitors are able to be included in self-healing coatings, to protect the metals by cathodic and/or anodic protection, by the creation of a protective layer or by neutralizing aggressive substances such as sulfur or chloride compounds [71].

4.5.Additive Manufacturing of Corrosion-Resistant Parts

The 3D printing or additive manufacturing process allows custom-designed parts to be produced from materials resistant to corrosion, such as stainless steel, titanium or a nickel-based alloy. AM provides the ability to steer micro-structures and grain boundaries, thereby improving the stability against corrosion and mechanical properties. This process becomes very advantageous to deliver components with intricate profiles such as those employed in heat-exchangers, impellers, and structural-brackets for marine applications. Additive manufacturing has the potential to form complex internal ducting and geometries for conformal cooling, light weighting, and mechanical performance tailoring.

While Additive Manufacturing (AM) enables the fabrication of geometrically complex and lightweight components tailored for marine applications, several limitations affect its effectiveness in corrosion-prone environments. One key issue is porosity, often introduced during the layer-wise deposition process, which can lead to microstructural voids that serve as initiation sites for pitting and crevice corrosion. Additionally, anisotropy in AM-produced parts results in directional dependency of mechanical and corrosion properties, making certain build orientations more vulnerable to degradation under marine exposure. Surface roughness and residual stresses, typically present in as-built parts, further reduce corrosion resistance unless adequately addressed. As a result, post-processing steps such as heat treatment, hot isostatic pressing (HIP), and surface polishing or coating are essential to enhance uniformity, reduce surface defects, and improve corrosion performance. Despite these challenges, ongoing research is exploring tailored alloy compositions and in-situ monitoring techniques to reduce defects and improve the corrosion behavior of AM parts. A comprehensive understanding of these limitations is crucial before wide-scale deployment of AM technologies in critical marine structural applications.

However, traditional material design approaches face limitations due to the complexity of compositions, structures, and desired properties [72]. Modern engineering requires materials that are multifunctional and optimized for mass and volume [73]. As such, additive manufacturing has emerged as a transformative technology, enabling the creation of complex, customized objects with precision [74]. Freedom of design, mass customization, waste minimization, and rapid prototyping are some of the major advantages of additive manufacturing [75]. This technology facilitates simultaneous control of component geometry and material properties at the local level, opening new frontiers for engineering applications across various industries [76]. The integration of smart materials with additive manufacturing techniques is particularly promising, enabling the fabrication of dynamic structures with the capacity to respond to environmental changes [77]. These advancements are answering critical issues in construction and material development, allowing architects to act as builders and designers [78]. The convergence of additive manufacturing with materials science has enabled the fabrication of functional materials and structures with intricate geometries and multi-phase distributions [79]. Additive manufacturing constructs physical objects by adding material layer upon layer based on a digital model, using desktop design software [80]. This approach allows for the creation of customized implants and scaffolds with intricate geometries suited to individual patient needs [81]. Additive manufacturing reduces expenses and production time [82]. Additive manufacturing is considered an advanced digital manufacturing technique that directly creates a physical model of complex structures and geometries from CAD models by adding materials layer by layer [83]. This method contrasts with subtractive manufacturing and formative manufacturing [84]. Metal additive manufacturing utilizes lasers to melt powdered materials layer-by-layer [85]. Subtractive methods are limited by the cutting tool's motion range and size, causing material waste and potential microscopic cracks [86]. Additive manufacturing offers advantages such as better time efficiency and similar or superior mechanical properties compared to subtractive manufacturing [87]. Recent developments in additive manufacturing techniques have enabled the design and production of almost any product from a wide variety of materials [88]. The rise of additive manufacturing has introduced a versatile production process that supports new product design and material concepts, which has led to customized products [89]. One of the most accessible methods of 3D printing is fused filament fabrication, which works with polymeric materials [90]. Other techniques include selective laser sintering and stereo lithography, each offering unique advantages depending on the application [91]. Sintering, an essential process in many additive manufacturing techniques, consolidates particles into desired shapes, offering a cost-effective approach for near-net-shape manufacturing [92].

These advanced material technologies are therefore leading to the development of smart, adaptive and efficient marine engineering solutions. Using advanced alloys, smart coatings and more precise manufacturing, the industry is working towards corrosion mitigation strategies that have a longer life span and are more sustainable. **Table 4** shows Recent Innovations and Material Developments in Marine Corrosion Protection.

Table 4. Recent Innovations and Material Developments in Marine Corrosion Protection.

S.No.	Innovation	Description	Key Materials/Components	Marine Applications
1	High-Entropy Alloys (HEAs)	Multi-element alloys offering stable passive oxide films and strong corrosion resistance.	Equimolar metal elements, stable oxide films	Marine components under mechanical stress and corrosion.
2	Super hydrophobic Coatings	Nature-inspired coatings repelling water, reducing salt and biofouling accumulation.	Nanostructured silica, fluoropolymers, textured composites	Ship hulls, offshore platforms, underwater sensors.
3	Graphene-Based Barriers	Graphene layers form nearly impermeable shields against oxygen, water, and ions.	Graphene Nano sheets, 0.5–1.0 wt.% in coatings	Electronics, marine devices, lightweight protective barriers.
4	Self-Healing Polymers	Contain microcapsules with healing agents that release upon coating damage.	Encapsulated inhibitors, cathodic/anodic protective agents	Splash zone structures, submerged metals, high-maintenance zones.
5	Additive Manufacturing (AM)	3D printing of corrosion-resistant components with tailored microstructures.	Stainless steel, titanium, nickel alloys	Heat exchangers, impellers, brackets with complex geometries.

5. Protective Techniques and Surface Treatments

In order to improve the long-term stability and durability of marine structures in corrosive environment, many types of protection methods and surface treatments have been proposed. Those methods are intended to either provide the material with a protection against corrosive agents or to change its surface properties to withstand external corrosive attacks better. The selection of method is based on factors such as exposure, material and structural importance. **Figure 5** shows the Protective Techniques and Surface Treatments for Corrosion Resistance in Marine Structures.

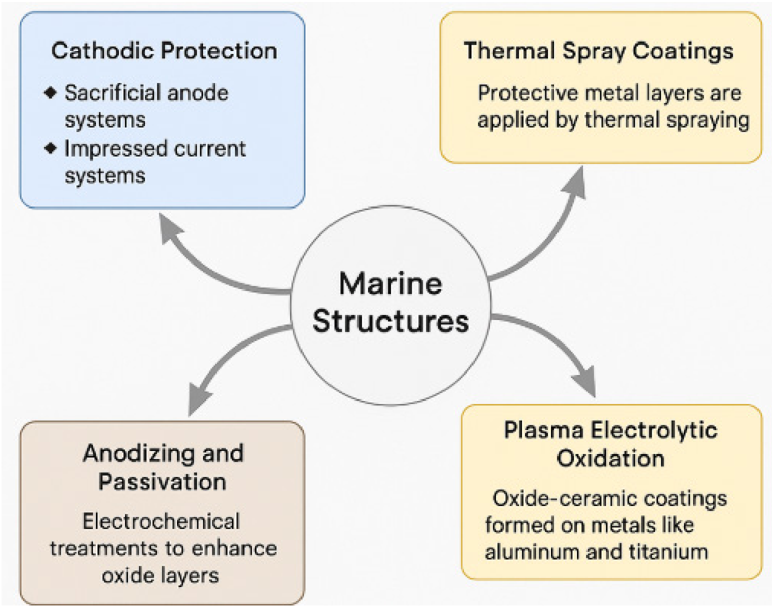

Figure 5. Protective Techniques and Surface Treatments for Corrosion Resistance in Marine Structures.

5.1.Cathodic Protection

Cathodic protection is well known electrochemical technique, which protects metal from the action of corrosion on the metal, by making the metal surface to be protected act as the cathode of an electrochemical cell. Cathodic protection is one of the most durable corrosion mitigation methods for both new and existing reinforced concrete structures [62]. ICCPT is applicable for wide coverage, particularly in reinforced concrete structure. There are two main types:

- Sacrificial anode systems: Employ highly reactive metals such as zinc, aluminium or magnesium that, in essence, will corrode in place of the structure being protected. These anodes are in electrical communication with the structure for a generation of electrons, and the electrons can foil oxidation reactions.
- Impressed Current Systems (ICCP): Employ an independent power supply to force current between inert anodes, ideal for providing controlled protection to larger structures. It is widely used in pipelines, ship hulls, offshore platforms, and submerged metallic structures.

Coatings and linings Organic and inorganic coatings form a physical barrier between the metal substrate and the corrosion agent.

5.2.Thermal Spray Coatings

In this method, protective metals like zinc or aluminium are melted and sprayed onto the substrate to produce a dense, adherent layer. Being physical barriers as well as sacrificial layers, these metallic layers would also corrode selectively, serving to preserve the underlying structural layer. Thermal spray coatings are often used on bridge decks, off-shore rigs and exposed structures in oceanic atmospheres. Surface engineering methods include any of the techniques used to alter the properties of a material without changing the bulk composition, such as a surface coating, in order to increase wear and corrosion resistance [93]. Such methods involve the application of thermal spray coating and bronzed coatings, in which the passive anti-wear property of materials is enhanced by the formation of interstitial solid solutions or novel compounds on the surface, respectively [94].

5.3.Anodizing and Passivation

The electrochemical methods apply oxidative treatments to the native oxide layer of the metals to enhance its corrosion resistance. Anodizing is used to increase surface durability and corrosion resistance, and to create a decorative surface. Passivation is generally utilized for stainless steel and consists of chemical treatment to remove surface contaminants and to formulate a protective chromium oxide layer. Stainless steel is passivated using nitric acid or other oxidizing substances, creating the self-repairing chromium oxide layer, which prevents both iron oxide and the chromium-reducing effects of oxygen present in the moly date test [95]. These processes are common in marine hardware, instrumentation and light-weight structural applications.

5.4.Plasma Electrolytic Oxidation (PEO)

PEO is a sophisticated surface coating technique that is employed for metals such as titanium and aluminium. It means, that a crust is built on delicate oxide ceramic like coating during high voltage ECPLD in plasma assisting regime. These films have good wear, corrosion, and thermal shock resistance. PEO-processed surfaces are well-suited for high performance marine parts like propellers, valves and sensor housings operated under harsh seawater conditions. PEO is a potential technique since it forms a protective oxide layer and minimizes the rate of corrosion attack [96–102].

These protective measures help to prolong the life and structural integrity of marine structures. The combined multiple methods – cathodic protection and high-performance coatings – will supplement each other and provide better and long-term corrosion protection in aggressive marine environments [103–108]. Electrolytic plasma processing technology is an eco-friendly process that employs non-hazardous aqueous solutions to clean metal surfaces, in contrast to worrying about environmental health impacts of acid pickling.

All of these protective measures are necessary to ensure a long service life of maritime constructions. When properly specified and utilized, these coatings provide an excellent cost-benefit ratio by minimizing maintenance, increasing safety, and providing reliable performance in harsh oceanic environments.

6. Challenges and Research Gaps

Although there are several corrosion-resistant materials and protective technologies that have been developed, there are still numerous challenges and research gaps that are preventing their full application in marine environments. These issues must be resolved to enhance long-term structural integrity, economic viability, and environmental compliance in ocean applications. **Figure 6** represents the Challenges and Research Gaps in Advancing Marine Corrosion Protection Technologies.

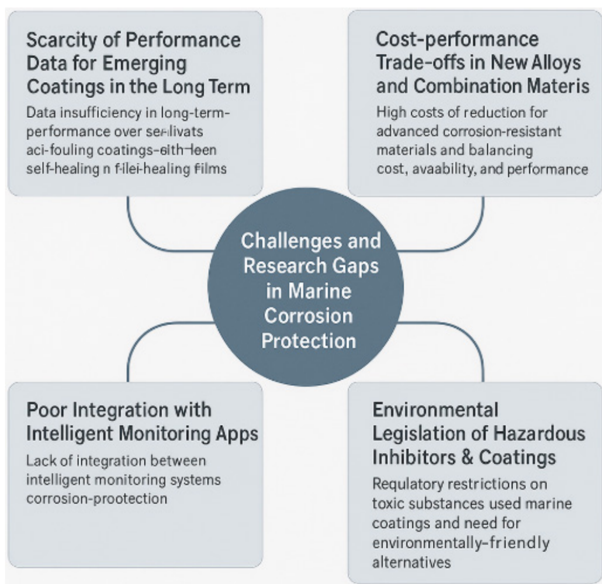

Figure 6. Challenges and Research Gaps in Advancing Marine Corrosion Protection Technologies.

6.1.Scarcity of Performance Data for Emerging Coatings in the Long Term

Innovative coatings like graphene-based, super hydrophobic, and self-healing films have shown great potential as next-generation antifouling solutions in laboratory settings. However, there is limited data on their long-term performance in real marine environments. Factors such as UV radiation, saltwater exposure, biofouling, and mechanical wear may degrade their effectiveness over time. The absence of extensive field testing and life-cycle assessments creates uncertainty, making it difficult for engineers and policymakers to confidently adopt and implement these technologies in critical infrastructure applications.

6.2.Cost-performance Trade-offs in New Alloys and Combination Materials

Advanced materials such as high-entropy alloys, titanium composites or ceramic-metal hybrids can provide excellent resistance to corrosion and mechanical properties, but their manufacturing cost can be high. A good balance between cost, availability and long-term performance in large marine structures should be obtained for such a material to become widespread. Further studies are therefore required to find the methods of fabrication that are more cost-effective, to tune (if necessary) the formulation of the materials to fulfil the specifications in terms of performance and cost.

6.3.Poor Integration with Intelligent Monitoring Apps

Despite the developments of sensor technologies and AI empowered systems, there are still a number of corrosion protection solutions that act as stand-alone solutions without connection to digital monitoring systems. Monitoring and real-time knowledge of coating degradation, corrosion initiation, and structural integrity are of paramount importance for predictive maintenance and failure avoidance. The development of intelligent materials, which are capable of interacting with monitoring systems, or the integration of sensors in coatings, could help to fill this gap and improve the efficiency of corrosion management plans.

6.4.Environmental Legislation of Hazardous Inhibitors & Coating

Environmental regulation has made the application of toxic compounds in marine coatings, such as tributyltin (TBT), heavy metals, and some biocides, much more difficult with respect to the detrimental environmental effects. This has spurred the development of environmentally friendly, low-toxic replacements which do not sacrifice performance. However, far too many eco-friendly solutions are not as long lasting and efficient as synthetic alternatives. It is of paramount importance to develop environmentally friendly and long-term protection, sustainable inhibitors and coatings.

An interdisciplinary approach among material science, environmental engineering, ecology, economics and digital technology is needed to solve these challenges. Closing these gaps would open doors to more sustainable, smart, and effective corrosion protection systems in marine settings. **Table 5** shows Challenges and Research Gaps in Marine Corrosion Protection.

Table 5 presents a comparative overview of selected advanced coatings based on cost-performance ratio, estimated field life, and resistance to key degradation factors such as biofouling, UV exposure, and mechanical wear.

Table 5. Quantitative Comparison of Selected Marine Coatings.

Coating Type	Approx. Cost ($/m^2)	Estimated Field Life (Years)	Biofouling Resistance	UV Resistance	Mechanical Durability	Self-Healing Capability
Epoxy-Based Coating	10–20	3–5	Moderate	Low	Moderate	No
Graphene Coating	80–100	10–15	High	High	High	No
Self-Healing Polymer	50–70	8–12	High	Moderate	Moderate	Yes
Fluoropolymer Coating	40–60	7–10	Very High	Very High	High	No
Bio-Inspired Coating	60–90	10–15	Very High	High	High	Yes (in some cases)

This quantitative comparison reveals the trade-offs between cost, durability, and performance. For example, while graphene coatings have high resistance and long service life, their cost limits large-scale adoption. Bio-inspired and self-healing coatings, although still under development, show strong potential in balancing performance and longevity if production costs can be reduced. Inclusion of such data supports better material selection and lifecycle planning in marine applications.

7. Future Outlook

The development of multifunctional materials, the next generation of marine corrosion protection technology, extends beyond property enhancement. These new generation materials need not only to withstand corrosion, but also to enhance mechanical properties, trigger self-assessment, and match global sustainability targets. The future research and innovation in this area are believed to go some certain directions as:

7.1.Green Materials and Eco-Friendly Coatings

Increased stringency on environmental regulation and awareness of environmental impact are motivating the need for more environmentally friendly corrosion inhibitors and coatings. Read more new developments will focus on natural-source based materials, low-VOC formulations and non-toxic, biodegradable polymers. Coatings that are useful and good for the environment will rely heavily on bio-based resins, plant-based additives, and naturally occurring minerals.

7.2.Integration with AI and IoT for Predictive Maintenance

The integration of Artificial Intelligence (AI), Internet of Things (IoT), and smart coatings in predictive maintenance is transforming how marine systems are monitored and maintained. Current state-of-the-art solutions include AI-powered health monitoring platforms that use real-time data from embedded sensors (e.g., vibration, temperature, corrosion potential) to predict component degradation before failure. For example, Rolls-Royce's "Intelligent Awareness" system integrates AI and IoT to monitor ship engines and propulsion components, enabling predictive diagnostics and reducing unscheduled maintenance. Similarly, companies like DNV and ABB Marine offer AI-based fleet management solutions that assess corrosion rates, biofouling levels, and structural fatigue using historical and real-time data analytics.

Smart coatings, embedded with sensors or self-reporting functionalities, are also under development to detect corrosion onset or mechanical damage. However, barriers to large-scale deployment include high implementation costs, data standardization issues, limited sensor durability in marine conditions, and the need for skilled personnel to interpret AI outputs. Moreover, regulatory gaps and cybersecurity risks associated with IoT-based maritime systems further complicate adoption.

To fully leverage these technologies, future research must focus on improving sensor robustness, developing interoperable platforms, and validating AI models with long-term marine field data. Industry-wide collaboration and policy support will also be essential to standardize predictive maintenance protocols across the global maritime sector.

7.3.Development of AI-Assisted Material Design

AI and machine learning are anticipated to be a pivotal technology in speeding up discovery and optimization of corrosion-resistant materials. By sifting through large experimental and simulated datasets, artificial intelligence (AI) can flag ideal compositions, predict how materials may behave, and even suggest new alloy or coating recipes. Such a materials design method expedites the process and lowers the cost of trial-and-error material research.

7.4.Bio-Derived and Biodegradable Coatings

As environmental pressure grows, the coatings of the future will have to minimize ecological damage as well as deliver on performance. Materials such as chitosan, lignin, and tannins are becoming popular among researchers, as they confer corrosion protection and are also biodegradable, not to mention non-toxic. Such coatings could provide a solution for temporary constructions, low impact installations, and use in environmentally protected marine environments.

In summary the future engines shall have to empower the intelligent, sustainable and adaptive corrosion resistance. Leveraging advancements in green chemistry, digital integration and material design guided by AI, the marine industry can construct infrastructure that is simultaneously tough, affordable and future compatible from an environmental and regulatory perspective.

8. Conclusions

The paper finishes by highlighting a developing need for the integration of different material categories to provide an overall corrosion resistance and structural life in the oceans. A blend of traditional metal alloys with non-metallic and hybrid materials has been successful in achieving durability, strength, and meeting requirements of environmental regulations. In this regard, the development of smart (self-healing and biofouling resistant) coatings and nano/micro structured systems represents a revolutionary strategy towards reducing maintenance and lengthening the lifetime of assets. High performance materials such as HEAs, Ni-systems and Ti-composites shows excellent resistance in harsh marine environments but cost effectiveness and field verification are to be fine tuned. Conventional surface protection methods, such as cathodic protection, anodization and plasma electrolytic oxidation, are still essential for protecting metallic structures in the marine environment when subjected to heavy operating conditions.

Furthermore, development is fueled by sensors, particularly artificial intelligence (AI) analytics, IoT-enabled sensors, and digital twin models that enable predictive maintenance and lifecycle optimization, incorporated with these materials to bring the next level of structural monitoring technology. They are also becoming a move towards non-toxic, biodegradable and bio-based coatings as a result of stringent environmental regulations and enabling eco-design without sacrificing performance. Additive manufacturing (AM) can help by producing corrosion-resistant parts with custom geometries and properties to fit this demanding marine environment. However, significant obstacles remain, especially with regard to obtaining performance data over the longer term, enhanced cost effectiveness and holistic smart system architectures. Filling these gaps requires interdisciplinary collaboration between materials, environmental engineering and digital technologies. In the end, the new frontier of corrosion protection in ocean structures is all about balancing sustainability and resilience with smart design, green materials, and data-driven innovations.

Author Contributions

Literature review, classification of corrosion-resistant materials, and manuscript formatting: D.S.; Content development for corrosion mechanisms, technical editing, and review of environmental impacts: U.S.; Analysis of polymer coatings and ceramic-metal matrix composites, reference curation: H.H.A.; Contributions to sections on protective techniques and surface treatments, graphical representation: M.M.D.; Compilation of recent innovations in material development and preparation of comparison tables: S.M.C.; Drafting of sections on corrosion mechanisms and data visualization figures: S.A.D.; Conceptualization, methodology design, supervision, final manuscript review, and corresponding author responsibilities: A.S.K.

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Conflict of Interest

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