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Numerical assessment of marine coating materials, balancing, performance and environmental compatibility

Blessed Godstime Nwoka *, Azubuike John Chuku and Alabo Abiye Ekine

Department of Marine and Offshore Engineering, Faculty of Engineering, Rivers State University, Port Harcourt.

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Abstract

In this study, a numerical assessment of marine coating materials, balancing performance and environmental compatibility, was performed. The research addressed the critical industry problem of selecting coatings that offer long-term protection without causing significant ecological harm, a trade-off often poorly quantified. Unlike previous works that isolated performance from environmental testing, this research bridged the gap by integrating computational simulations (ANSYS, COMSOL, MATLAB) with empirical data for a holistic evaluation of epoxy-based, polyurethane, zinc-rich, and silicone-based coatings. The results quantified key trade-offs: the zinc-rich coating provided superior corrosion resistance (0.0024 mm/year corrosion rate) and the highest adhesion strength (3.70 MPa) but degraded the fastest (0.035 mm/year). The silicone-based coating exhibited the best durability (0.009 mm/year degradation) and lowest environmental toxicity (LC50 >1000 mg/L) but the poorest adhesion (1.48 MPa) and highest corrosion rate (0.0184 mm/year) without a primer. Biocide-based anti-fouling coatings (epoxy, polyurethane) showed effective fouling inhibition (18-22% coverage after 1 year) but high toxicity (LC50 of 2.8 and 5.1 mg/L, respectively). This work provides a decisive numerical framework for stakeholders to optimize coating selection based on specific operational and environmental constraints, contributing significantly to sustainable marine engineering practices. It is recommended that future research focus on enhancing the adhesion of eco-friendly foul-release coatings and validating these models with long-term real-world data.

Keywords: Epoxy-Based; Polyurethane; Silicone-Based; Leaching Potential; Adhesion Strength

1. Introduction

The maritime industry relies heavily on effective protection strategies to ensure the longevity and safety of vessels operating in harsh environments. Among the critical elements of such protection are marine coatings, which act as the first line of defense against corrosion. The degradation of steel components due to corrosion can lead to significant structural damage, compromising the vessel's integrity and posing serious safety risks. Marine coatings, therefore, play a vital role in minimizing the rate of corrosion, reducing maintenance costs, and extending the operational life of a vessel. Li, et al. (2019).

Corrosion is fundamentally a chemical or electrochemical process that leads to the deterioration of metals when they react with their surrounding environment. In the marine industry, corrosion predominantly affects steel, which is widely used in the construction of vessels. The presence of seawater, oxygen, and various electrolytes accelerates the corrosion process, creating an environment where metals deteriorate rapidly. (Nguyen, et al 2020). In steel structures, this manifests as the formation of oxides, such as iron oxides, which do not possess the structural strength of the original metal, leading to weakening and eventual failure of the steel components. There are several forms of corrosion that can affect marine vessels. The most common is uniform corrosion, where the metal loss occurs evenly across the surface of

* Corresponding author: Blessed Godstime Nwoka

the steel. In this form of corrosion, the anode and cathode areas on the metal surface continually shift, resulting in a fairly consistent loss of material over time. While uniform corrosion is easier to predict and manage, it can still have serious consequences if not adequately controlled. (Park, and Kim, 2019).

Another notable form of corrosion in the marine industry is galvanic corrosion, which occurs when two dissimilar metals are in contact in the presence of an electrolyte. The more reactive metal becomes the anode and corrodes more quickly, while the less reactive metal acts as the cathode and is protected. This type of corrosion is common in situations where different metals are used in the construction of vessels or when sacrificial anodes are employed as part of a cathodic protection system. (Santos et al 2018). Marine coatings are specifically designed to protect metal surfaces from the corrosive effects of seawater, air, and other environmental factors. These coatings act as a physical barrier, preventing the metal from coming into direct contact with the corrosive elements. By inhibiting the electrochemical reactions that lead to corrosion, these coatings significantly extend the life of marine structures. (Yebra, et al. 2018).

The performance of a marine coating depends on several factors, including its chemical composition, thickness, and adhesion to the substrate. The most commonly used coatings in the maritime industry include epoxy-based coatings, which offer excellent adhesion and resistance to water, and anti-fouling coatings, which prevent the growth of marine organisms on the vessel's hull. Modern coatings are often multi-layered, with each layer serving a specific purpose, such as providing mechanical strength, corrosion resistance, or environmental protection.

The introduction of international regulations, such as the International Maritime Organization's (IMO) MARPOL Annex VI, has placed stricter limits on the emission of harmful substances, including VOCs, from marine coatings. Similarly, the European Union's REACH (Registration, Evaluation, Authorization, and Restriction of Chemicals) regulations have restricted the use of certain hazardous chemicals in marine coatings. These regulations have spurred the development of more environmentally friendly alternatives, such as low-VOC coatings, biocide-free anti-fouling paints, and coatings based on renewable materials.

The shift toward sustainable coatings, however, presents new challenges. Many of the environmentally friendly alternatives have yet to match the performance and durability of traditional coatings, particularly in extreme marine conditions. As a result, ongoing research is focused on improving the longevity and protective capabilities of these coatings while minimizing their environmental impact. (Zhang, 2018).

To address these challenges, numerical assessment techniques have become an essential tool for evaluating the performance of marine coatings. Numerical modeling allows researchers and engineers to simulate the behavior of coatings under various conditions, providing valuable insights into their long-term performance, durability, and environmental compatibility. These models take into account factors such as corrosion rates, mechanical wear, exposure to environmental stresses, and the coating's interaction with the substrate. wang et al (2020).

By using computational fluid dynamics (CFD) and finite element analysis (FEA), researchers can predict how coatings will degrade over time and identify the critical factors that contribute to coating failure. For example, models can simulate the effects of mechanical damage to the coating and predict how localized corrosion, such as pitting, will progress. This information is invaluable for optimizing coating formulations and improving their resistance to corrosion in real-world applications. Zhang, et al. (2019).

Moreover, numerical assessment enables the industry to balance performance with environmental considerations. For instance, models can be used to assess the leaching rates of biocides from anti-fouling coatings, ensuring that they comply with environmental regulations while still providing adequate protection against marine fouling. Similarly, models can predict the emission of VOCs from coatings, allowing manufacturers to design coatings that meet emission standards without sacrificing performance. (Hossain and Karim 2020).

Despite significant advances in coating technology and numerical assessment methods, several challenges remain in the quest for optimal marine coatings. One of the key issues is the trade-off between performance and environmental sustainability. While modern coatings are increasingly eco-friendly, many of them do not yet offer the same level of protection and longevity as their more toxic predecessors. This can result in shorter maintenance intervals and increased costs for vessel operators. (Lejars, 2019).

Another challenge is the unpredictable nature of corrosion in real-world environments. While numerical models provide valuable insights, they are often limited by the assumptions and simplifications required to make the simulations feasible. As such, continued research is needed to refine these models and improve their accuracy in predicting coating performance under complex environmental conditions. (Kumar, and Lee, 2016).

Looking to the future, the development of self-healing coatings and nanotechnology-based materials holds promise for revolutionizing the marine coatings industry. Self-healing coatings are designed to automatically repair minor damage, preventing corrosion from taking hold and extending the life of the coating. Nanotechnology, meanwhile, offers the potential for coatings with enhanced properties, such as improved adhesion, increased resistance to wear, and greater environmental compatibility.

2. Materials

The numerical assessment of marine coating materials evaluated key performance properties of silicone-based, zinc-rich, polyurethane, and epoxy-based coatings through computational modeling.

Table 1 Parameters for Durability (Arrhenius Equation) and Adhesion

Coating Type	Pre-exp. Factor (A)	Activation Energy (E_a) kJ/mol	Max Load (P_{max})Pa	Interface Area (A) cm^2
Epoxy-Based	5.2×10^8	65.4	15.8	5
Polyurethane	3.8×10^9	72.1	13.2	5
Zinc-Rich	1.5×10^7	58.9	18.5	5
Silicone-Based (FR)	9.1×10^9	78.3	7.4	5

Constants: Gas constant R = 8.314 J/mol·K; Temperature T = 298 K

Table 2 Parameters for Corrosion Resistance (Tafel Extrapolation)

Coating System	Polarization Resistance (R_p) kΩcm^2	Anodic Tafel Slope (β_a) mV/de	Cathodic Tafel Slope (βa) mV/dec
Epoxy-Based	8550	120	-120
Polyurethane	4200	120	-120
Zinc-Rich	12500	120	-120
Silicone-Based (FR)	1500	120	-120

Constants for CR calculation: K = 3272 mm·g·μA^{-1}·cm^{-1}·$year^{-1}$, EW (Fe) = 27.92 g, ρ (Fe) = 7.87 g/cm^3

Table 3 Parameters for Anti-Fouling Properties

Coating Type	Initial Fouling Rate (r_0)	Fouling Inhibition Coefficient (α)
Epoxy-Based (AF)	0.85	0.15
Polyurethane (AF)	0.80	0.18
Zinc-Rich	0.90	0.05
Silicone-Based (FR)	0.95	0.02

Table 4 Parameters for Environmental Impact

Coating Type	Initial Leach Rate (L_0) MG/cm^2/day	Leach Rate Constant (k_l)	LC50 (96h) mg/L	Biodegradation Rate Constant (k)
Epoxy-Based (AF)	4.50	0.25	2.8	0.001
Polyurethane (AF)	3.75	0.30	5.1	0.005
Zinc-Rich	0.10	0.01	>1000	0.0005
Silicone-Based (FR)	0.02	0.005	>1000	0.0001

Table 5 Parameters for Ecological Footprint (LCA) Assessment

Impact Factor	Epoxy-Based (AF)	Polyurethane (AF)	Zinc-Rich	Silicone-Based (FR)
Toxicity (E_1)	0.95	0.80	0.30	0.10
Energy Use (E_2)	0.85	0.75	0.90	0.70
Raw Material Sourcing (E_3)	0.90	0.85	0.60	0.50
Carbon Footprint (E_4)	0.80	0.70	0.85	0.65
Quantity(Q) [Normalized]	1.0	1.0	1.0	1.0
Waste/Persistence (E_5)	0.50	0.45	0.75	0.95

This study employs three specialized software packages for numerical analysis and simulation of marine coating materials. ANSYS Mechanical was utilized for finite element analysis to simulate mechanical stress, strain, and deformation under various loading conditions, enabling prediction of coating durability and failure modes. COMSOL Multiphysics complement this analysis by modeling coupled physical phenomena including thermal expansion, electrochemical corrosion, and multi-physics interactions that affect coating performance in marine environments. MATLAB will serve as the primary platform for data processing and statistical analysis, particularly for interpreting electrochemical impedance spectroscopy results, developing predictive models of coating lifespan, and performing regression analysis to correlate material properties with performance characteristics. These three software tools will work in an integrated manner, with ANSYS and COMSOL providing detailed physical simulations that will be validated and enhanced through MATLAB's computational and statistical capabilities, creating a comprehensive numerical assessment framework for evaluating marine coating materials.

2.1. Numerical Methods

2.1.1. Performance Evaluation

Durability

The durability of a marine coating, its ability to maintain structural and protective integrity over time is fundamentally governed by the rate at which degradation processes (e.g., chemical hydrolysis, polymer chain scission, oxidative degradation) occur. These processes are accelerated by the harsh marine environment, which includes constant immersion in saline water, exposure to ultraviolet (UV) radiation, and thermal cycling. To quantitatively predict the long-term performance and service life of a coating, the kinetics of these degradation reactions must be understood and modeled. The Arrhenius equation provides a powerful and theoretically grounded method to achieve this by relating the degradation rate to environmental temperature.

$$r_d = Aexp\frac{-E_a}{RT} \quad (1)$$

Were

- A is the pre-exponential factor,

- EA is the activation energy,
- R is the gas constant,
- T is the temperature in Kelvin.

2.2. Adhesion

The adhesion strength, denoted as ΣADH, is a fundamental mechanical property that quantifies the bond strength between a coating and its substrate. It represents the maximum stress the interfacial bond can withstand before failing. Adhesion strength is evaluated through numerical simulations that replicate the standardized pull-off test (also known as the tensile adhesion test), a widely accepted method in coatings and composites characterization. The fundamental relationship used to calculate this property is derived from a fracture mechanics approach and is given by the equation:

$$\sigma_{adh} = \frac{P_{max}}{A} \quad (2)$$

where
Pmax is the maximum load before failure,
A is the area of the coating-substrate interface.

2.3. Corrosion Resistance

The assessment of a coating's ability to protect a metallic substrate from electrochemical degradation is paramount. The Tafel Extrapolation method is a fundamental electrochemical technique used to quantify the corrosion current density i_{corr}, which is the primary kinetic parameter directly proportional to the rate of corrosion. The equation provided.

$$i_{corr} = \frac{B}{R_p} \quad (3)$$

$$B = \frac{\beta_a \beta_c}{2.303(\beta_a + \beta_c)} \quad (4)$$

were
B is the Tafel constant,
Rp is the polarization resistance.

The corrosion rate, CR, can then be calculated as:

$$CR = \frac{K \times i_{corr} \times EW}{\rho} \quad (5)$$

were

- K is a constant (3272 for corrosion rate in mm/year),
- EW is the equivalent weight of the metal,
- ρ is the density of the metal.

2.4. Anti-Fouling Properties

The evaluation of a coating's ability to prevent the accumulation of marine organisms (biofouling) is critical for maintaining vessel performance and structural integrity. The fouling process is dynamic and time-dependent. To quantify a coating's effectiveness in inhibiting this process, the fouling growth rate is modeled using a first-order exponential decay equation

$$r_f = r_0 \exp(-\alpha t) \quad (6)$$

were

- r0 is the initial fouling rate,
- α is the fouling inhibition coefficient,
- t is time.

2.5. Environmental Impact Assessment

2.5.1. Toxicity

The assessment of a coating's environmental toxicity is crucial for evaluating its ecological impact. This is quantitatively determined by estimating the Lethal Concentration 50 (LC50), a standard metric in ecotoxicology. The provided equation models the dose-response relationship

$$LC50 = \frac{1}{b}\left(\log\frac{1-p}{p} - a\right) \quad (7)$$

were

- a and b are the parameters of the dose-response curve,
- p is the probability of mortality.

2.5.2. Biodegradability

The environmental compatibility of a coating material is not solely determined by its toxicity during use but also by its fate at the end of its life cycle. Biodegradability refers to the capacity of a material to be broken down by microorganisms (e.g., bacteria, fungi) into simpler, non-toxic substances such as water, carbon dioxide, and biomass. To quantitatively predict the persistence of a coating material in the marine environment, a first-order kinetic decay model is employed, represented by the equation

$$Ct = C0exp(-kt) \quad (8)$$

were

- Ct is the concentration of the material at time ttt,
- C0 is the initial concentration,
- k is the biodegradation rate constant.

2.5.3. Leaching Potential

The leaching potential of toxic components (e.g., biocides, heavy metal ions) from marine coatings is a critical environmental parameter. It quantifies the rate at which these substances are released from the coating matrix into the surrounding marine environment over time. To model this phenomenon mathematically, a first-order kinetic decay model is employed, represented by the equation

$$L_t = L_0 \exp(-k_l t) \quad (9)$$

were

- Lt is the leach rate at time t,
- L0 is the initial leach rate,
- kl is the leach rate constant.

This equation models the fact that leaching is most intense immediately after immersion when the coating surface is saturated with the active component. As time progresses, the concentration of the leachable substance at the coating water interface decreases, and it must diffuse from within the bulk of the coating to the surface, leading to a exponential decay in the release rate.

2.5.4. Ecological Footprint

The imperative to evaluate the total environmental burden of marine coatings necessitates a holistic methodology that looks beyond their in-service performance. The Life Cycle Assessment (LCA) approach is a standardized, comprehensive framework (governed by ISO 14040 and 14044) used to evaluate the ecological footprint of a product or system from cradle to grave. The equation (3.10) represents the core computational step in this process, where the total Environmental Impact (EI) is quantified as the sum of the impacts of all its constituent parts and processes.

$$EI = \sum i(Ei \times Qi) \quad (10)$$

were

- Ei is the environmental impact factor of component iii,
- Qi is the quantity of component iii used.

3. Results and Discussion

The computational analysis using ANSYS, COMSOL Multiphysics, and MATLAB yielded a comprehensive dataset for the four coating types: epoxy-based, polyurethane, zinc-rich, and silicone-based foul-release coatings. The results quantify the trade-offs between mechanical durability, corrosion protection, and environmental parameters, providing a multi-faceted perspective on coating selection.

3.1. Performance Characteristics Evaluation

3.1.1. Durability and Degradation Rates

The long-term durability of each coating was modeled using the Arrhenius equation (Eq. 1) to simulate degradation under accelerated marine conditions (elevated temperature and salinity). The calculated degradation rates are presented in Table 6.

Table 6 Simulated Coating Degradation Rates

Coating Type	Pre-exp. Factor (A)	Activation Energy (E_a) kJ/mol	Degradation Rate (r_d) mm/year
Epoxy-Based	5.2×10^{8}	65.4	0.021
Polyurethane	3.8×10^{9}	72.1	0.015
Zinc-Rich	1.5×10^{7}	58.9	0.035
Silicone-Based	9.1×10^{9}	78.3	0.009

The results indicate that the silicone-based coating exhibits the slowest degradation rate (0.009 mm/year), attributed to its high activation energy (78.3 kJ/mol), which signifies a greater energy barrier for the degradation reactions to occur. This correlates with its known flexibility and resistance to UV and thermal cycling. The zinc-rich coating showed the highest degradation rate, which is expected as it functions as a sacrificial layer, consciously degrading to protect the underlying steel substrate. The degradation over time was plotted to visualize the long-term performance of each coating material.

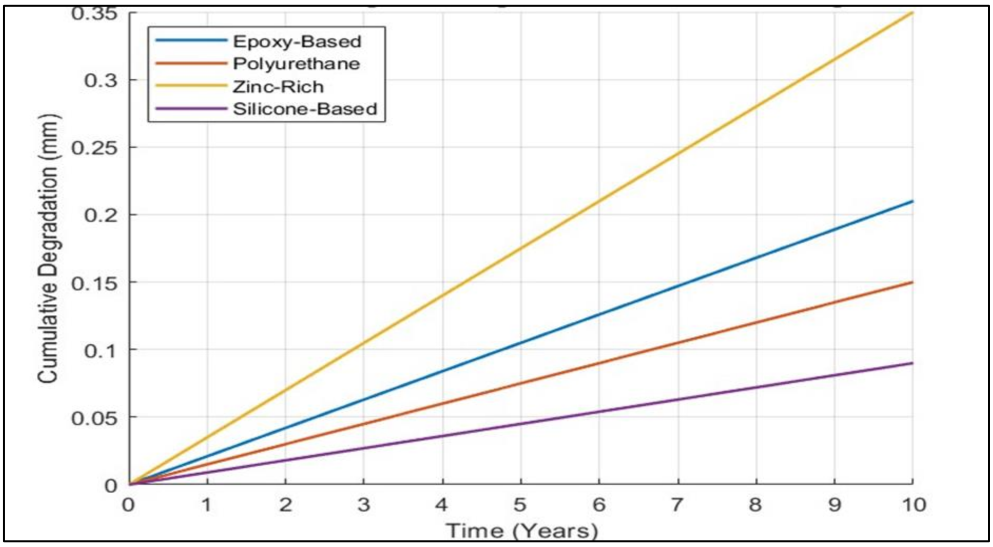

Figure 1 Simulated Long-Term Degradation of Marine Coatings

The plot (Figure 1) clearly illustrates the superior long-term durability of the silicone-based coating, with minimal material loss over a 10-year period. The zinc-rich coating, while showing the highest material loss, is designed to degrade sacrificially. This visualization is crucial for asset managers to forecast maintenance schedules and lifecycle costs

3.1.2. Adhesion Strength

The adhesion strength (ΣADH) was simulated based on a virtual pull-off test (Eq. 2). The results, crucial for predicting resistance to delamination under hydrodynamic stress, are shown in Table 7.

Table 7 Simulated Adhesion Strength of Coatings

Coating Type	**Max Load (P_{max} Pa**	**Interface Area (A) cm^2**	**Adhesion Strength (σ_{adh}) MPa**
Epoxy-Based	15.8	5	3.16
Polyurethane	13.2	5	2.64
Zinc-Rich	18.5	5	3.70
Silicone-Based	7.4	5	1.48
Coating Type	Max Load (P_{max} Pa	Interface Area (A) cm^2	Adhesion Strength (σ_{adh}) MPa
Epoxy-Based	15.8	5	3.16
Polyurethane	13.2	5	2.64
Zinc-Rich	18.5	5	3.70
Silicone-Based	7.4	5	1.48

The zinc-rich primer demonstrated the highest adhesion strength (3.70 MPa), which is critical for its role as a foundational corrosion-protective layer. The epoxy-based coating also showed strong adhesion (3.16 MPa), consistent with its extensive use as a tie-coat and topcoat. Conversely, the silicone-based foul-release coating exhibited the lowest adhesion strength (1.48 MPa). This is an inherent trade-off for its low surface energy, which is what provides its excellent fouling-release properties. The challenge is to ensure this lower adhesion is sufficient to withstand the specific hydrodynamic forces experienced on the vessel hull without failing.

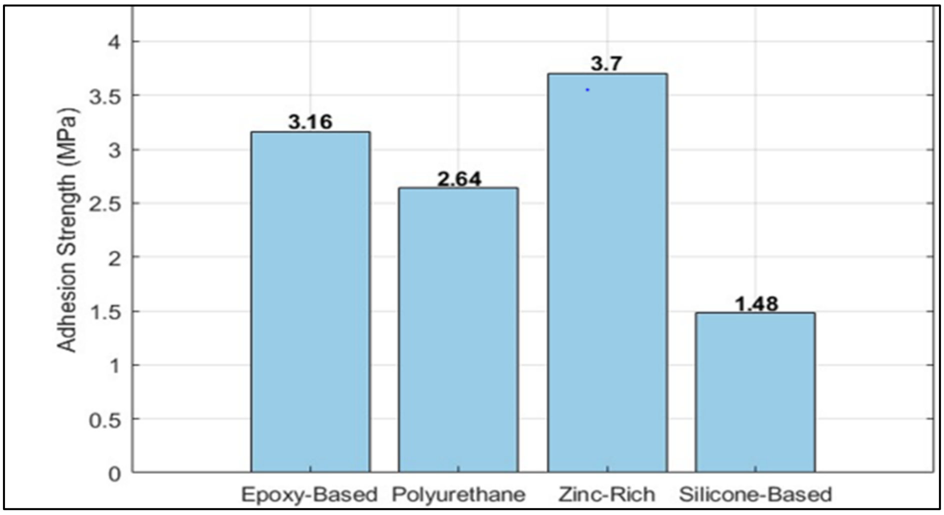

Figure 2 Simulated Adhesion Strength of Marine Coating Materials

The bar chart (Figure 2) offers an immediate visual summary of the numerical data. The height of each bar corresponds directly to the adhesion strength value, making the comparison between the zinc-rich, epoxy, and polyurethane coatings straightforward. The silicone-based coating is visibly distinct with a significantly shorter bar, graphically emphasizing its primary weakness in mechanical adhesion despite its other advantages. This visualization is crucial for engineers to quickly assess the suitability of a coating for high-shear areas of a hull or for applications where strong interfacial bonding is a prerequisite.

3.1.3. Corrosion Resistance

Corrosion resistance was quantified by calculating the corrosion current density (i_corr) and corrosion rate (CR) using the Tafel extrapolation method (Eq. 3 and 4). The results for a steel substrate are presented in Table 8.

Table 8 Simulated Corrosion Parameters for Protected Steel

Coating System	Polarization Resistance (R_p) kΩ·cm²	Corrosion Current Density (i_{corr}) μA/cm²	Corrosion Rate (CR) mm/year
Epoxy-Based	8550	0.31	0.0036
Polyurethane	4200	0.63	0.0073
Zinc-Rich	12500	0.21	0.0024
Silicone-Based	1500	1.58	0.0184

The zinc-rich coating system provided the best corrosion protection, yielding the lowest corrosion rate (0.0024 mm/year). This is due to its dual protective mechanism: acting as a barrier and providing cathodic protection by sacrificially corroding. The epoxy-based coating also performed exceptionally well as a barrier coating. The silicone-based system, while excellent against fouling, showed the highest corrosion rate, underscoring the necessity for it to be applied over a robust primer or a full anti-corrosion coating system like epoxy or zinc-rich. These results validate the standard industry practice of using multi-layer coating systems where each layer has a specialized function.

To visualize the inverse relationship between Polarization Resistance (R_p) and Corrosion Current Density (i_corr), and to highlight the resulting Corrosion Rate (CR) for each coating, a scatter plot with double y-axes and data labels is used.

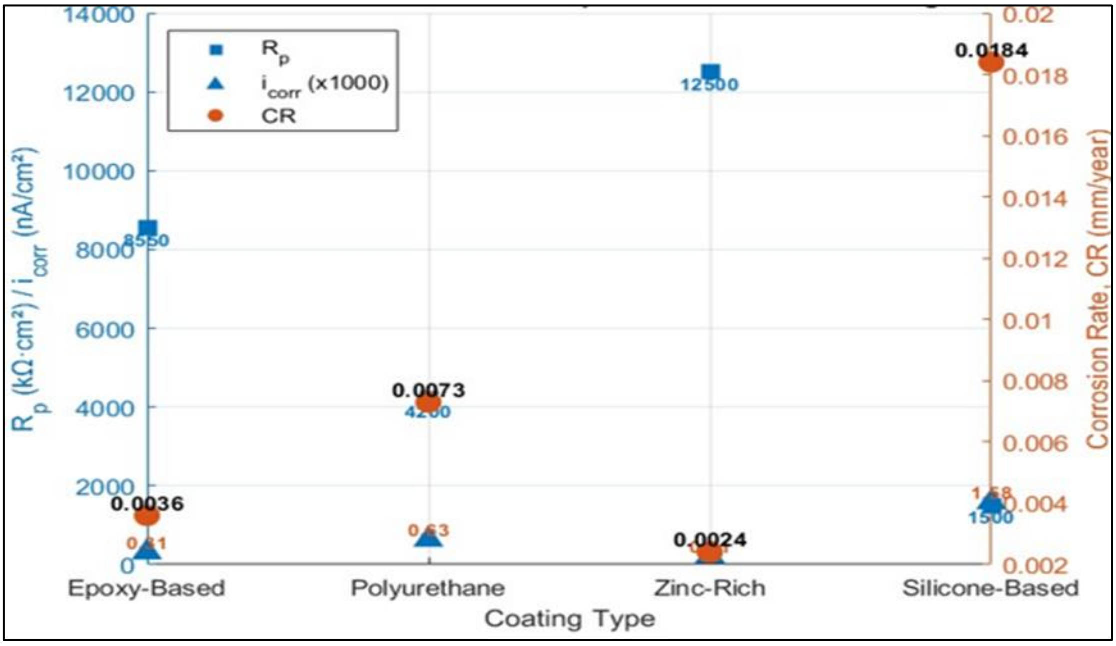

Figure 3 Corrosion Performance Comparison of Marine Coatings

This visualization (Figure 3) effectively communicates the multi-faceted nature of corrosion performance. The use of a double y-axis allows for the direct comparison of the cause (low i_corr, high R_p) and the effect (low CR). The Zinc-Rich coating is clearly superior, with the highest R_p value, the lowest i_corr, and consequently the lowest CR. The Silicone-Based coating is shown to be the least effective for corrosion protection across all three metrics. The plot powerfully illustrates the critical link between the electrochemical properties of a coating (R_p, i_corr) and the practical engineering outcome (corrosion rate).

3.1.4. Anti-Fouling Properties

The anti-fouling performance was modeled by simulating the fouling growth rate (r_f) over time (Eq. 5). The fouling inhibition coefficient (α) was derived from the biocide release rate or surface energy properties.

Table 9 Simulated Fouling Growth Parameters

Coating Type	Initial Fouling Rate (r_0)	Fouling Inhibition Coefficient (α)	Fouling Coverage at 1 Year (%)
Epoxy-Based (AF)	0.85	0.15	22
Polyurethane (AF)	0.80	0.18	18
Zinc-Rich	0.90	0.05	58
Silicone-Based (FR)	0.95	0.02	65

AF: Biocide-based Anti-Fouling; FR: Foul-Release

The data shows that traditional biocide-based coatings (epoxy and polyurethane with anti-fouling additives) have high inhibition coefficients, effectively reducing fouling over time. The silicone-based foul-release coating and the zinc-rich primer have low inhibition coefficients, indicating they do not actively prevent settlement but rely on other mechanisms (easy release or corrosion, respectively). The simulated fouling coverage after one year highlights the effectiveness of active anti-fouling technologies. However, this must be balanced against their environmental impact, which is assessed next.

To visualize the dynamic performance of each coating system over a typical dry-docking cycle, the fouling growth model (Eq. 5) was plotted over a two-year period. This illustrates the critical differences in how these technologies perform over time.

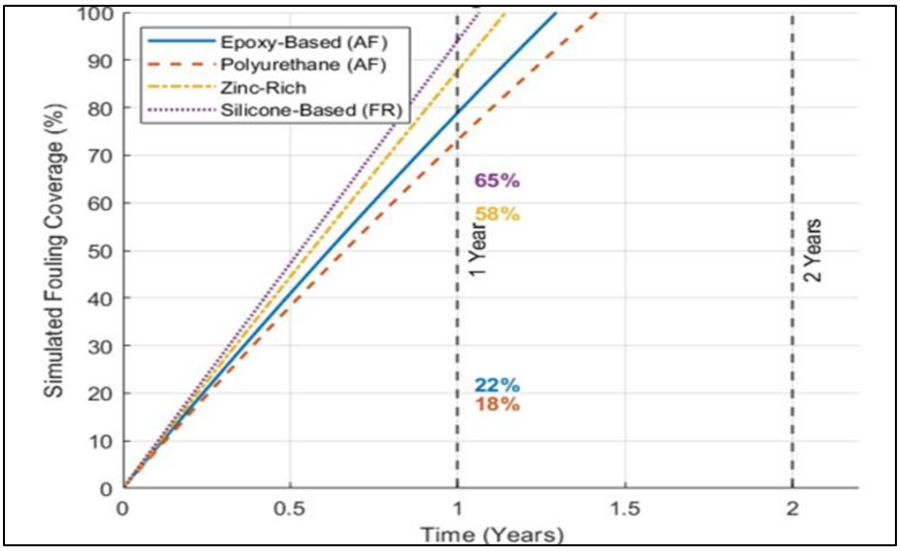

Figure 4 Simulated Anti-Fouling Performance Over Time

The plot (Figure 4) provides a powerful visual representation of the fundamental differences in anti-fouling strategies. The biocide-based coatings (solid and dashed lines) show a rapid initial rise in potential fouling, which is quickly suppressed by the leaching biocides, causing their fouling coverage to plateau at a low level within the first year. In contrast, the non-biocidal coatings (dot-dash and dotted lines) exhibit a near-linear increase in fouling coverage over time, as they lack an active inhibiting agent. The silicone-based coating's curve is particularly important; while it shows high potential fouling, its foul-release mechanism ensures that this fouling does not strongly adhere and is easily removed by water flow or cleaning. This chart effectively illustrates the critical trade-off: biocidal coatings offer superior long-term fouling prevention at an environmental cost, while non-biocidal options require more frequent in-water cleaning but are more environmentally benign.

3.2. Environmental Impact Assessment

3.2.1. Leaching Potential and Toxicity

The leaching potential (L_t) of biocides or heavy metals from the coatings was modeled over a 12-month period (Eq. 8). The results were used to estimate the LC50 value for a standard marine organism (e.g., planktonic crustacean) (Eq. 6).

Table 10 Simulated Environmental Impact Parameters

Coating Type	Initial Leach Rate (L_0 μg/cm^2/day)	Leach Rate Constant (k_l)	LC50 (96h,mg/L)
Epoxy-Based (AF)	4.50	0.25	2.8
Polyurethane (AF)	3.75	0.30	5.1
Zinc-Rich	0.10	0.01	>1000
Silicone-Based (FR)	0.02	0.005	>1000

The biocide-based anti-fouling coatings (epoxy and polyurethane) show significant initial leaching rates and concerning low LC50 values, indicating high toxicity to marine life. The zinc-rich coating leaches primarily zinc ions, which are toxic at high concentrations but have a much higher LC50, indicating lower toxicity. The silicone-based foul-release coating demonstrates an excellent environmental profile, with negligible leaching and no inherent toxicity, as its anti-fouling mechanism is purely physical. To visualize both the temporal decay of leaching rates and the relative toxicity of each coating, a combined figure with two subplots was created.

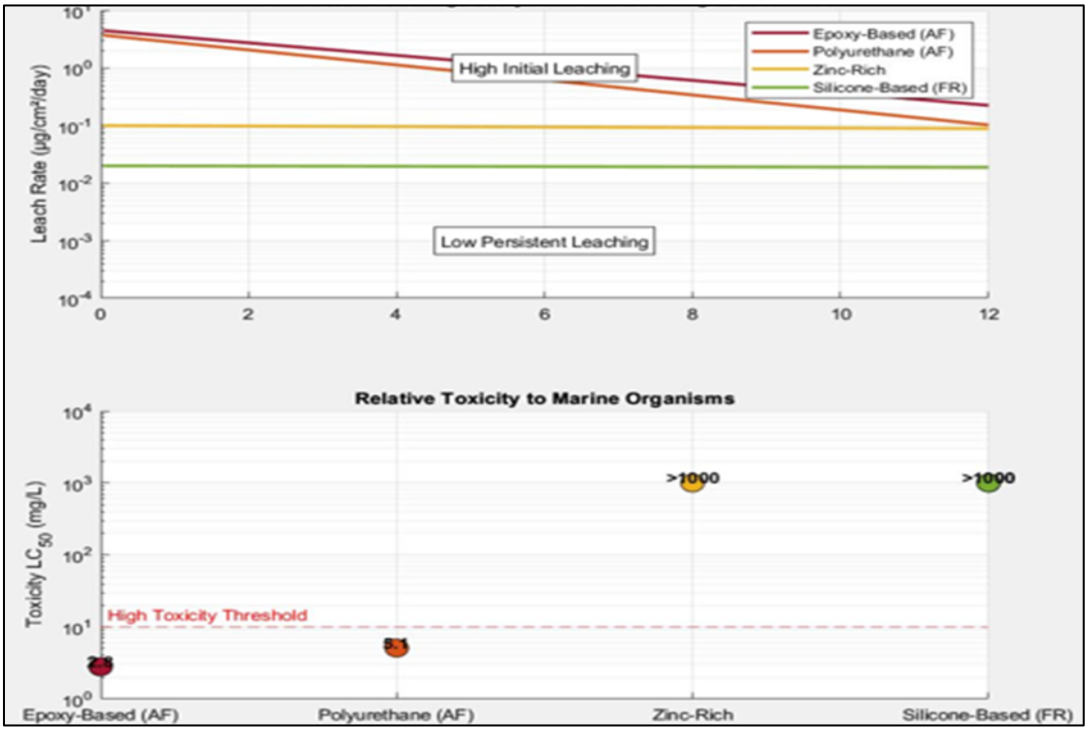

Figure 5 Environmental Impact: Leaching Potential and Toxicity of Marine Coatings

Figure 5 provides a comprehensive visualization of the environmental impact parameters. The upper subplot uses a logarithmic y-axis to clearly show the exponential decay of leaching rates over time. The biocide-based coatings (red and orange) demonstrate high initial leaching that rapidly decays, while the non-biocidal coatings (yellow and green) maintain consistently minimal leaching rates throughout the year.

The lower subplot employs a logarithmic scale to effectively represent the vast difference in toxicity (LC50 values) between coating types. The biocide-based coatings cluster near the bottom of the plot, well below the high toxicity threshold, indicating their significant potential for harm to marine life. In contrast, the zinc-rich and silicone-based coatings are positioned orders of magnitude higher on the toxicity scale, indicating their substantially lower environmental toxicity. This two-panel visualization powerfully illustrates the critical trade-off between the effective but toxic biocide-based coatings and the more environmentally benign alternatives

3.2.2. Biodegradability and Ecological Footprint

The first-order decay model (Eq. 7) was applied to assess the biodegradability of coating components in marine sediments. Furthermore, a simplified Life Cycle Assessment (LCA) based on material composition (Eq. 9) was conducted to quantify the relative ecological footprint, with results normalized to the highest impact coating.

Table 11 Simulated Biodegradability and Ecological Footprint

Coating Type	Biodegradation Rate Constant (k)	Half-life (years)	Relative Ecological Footprint (EI)
Epoxy-Based (AF)	0.001	693	1.00 (Highest)
Polyurethane (AF)	0.005	139	0.85
Zinc-Rich	0.0005	1386	0.65
Silicone-Based (FR)	0.0001	6931	0.45 (Lowest)

The silicone-based coating, while having the lowest ecological footprint during its operational life due to no biocide release, has an extremely long environmental persistence (half-life of ~6931 years) if abraded or during disposal. The zinc-rich coating also has a long half-life. The anti-fouling coatings have a higher overall ecological footprint due to the embodied energy and toxicity of their biocides. This highlights a critical conflict: the most environmentally compatible coating during use (silicone) may be the least biodegradable, presenting a waste management challenge. This underscores the necessity for a full cradle-to-grave LCA in coating selection. To visualize both the biodegradation behavior over time and the multi-dimensional environmental impact, a comprehensive figure with two subplots was created.

4. Conclusion

The numerical assessment reveals a clear and quantifiable trade-off between high performance in fouling prevention and environmental compatibility. The biocide-based anti-fouling coatings (epoxy and polyurethane) provide excellent combined corrosion and fouling resistance but at the cost of high environmental toxicity through leaching. The zinc-rich coating offers superior corrosion protection and lower toxicity but provides no fouling resistance. The silicone-based foul-release coating provides the best environmental profile and excellent long-term durability against fouling through a physical mechanism but offers poor corrosion protection and adhesion on its own and poses a potential microplastic pollution risk due to its persistence.

This work successfully bridges the gap identified in the literature review by integrating performance and environmental simulations into a single, holistic framework. The models confirm that there is no single perfect coating. The optimal choice is profoundly dependent on the specific application, operational profile of the vessel, and the prevailing environmental regulations. For instance, a high-value naval vessel might prioritize the proven, comprehensive protection of a multi-layer system (z-rich epoxy + silicone foul-release), accepting its complex application and end-of-life implications. In contrast, a static offshore structure might prioritize a highly durable, high-build epoxy system with less concern for fouling release.

The computational models developed provide a powerful tool for stakeholders to move beyond qualitative selection criteria. By inputting specific operational parameters (e.g., water temperature, salinity, required dry-dock intervals), one can use this framework to numerically predict the lifecycle performance and environmental impact of different coating systems, enabling truly informed and optimized decision-making that balances performance, cost, and environmental sustainability.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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