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Bio-Inspired Composite Materials for Corrosion Repair in Marine Environments: A Systematic Literature Review

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Abstract: *Corrosion in marine environments is a severe issue for infrastructure and marine vessels, which makes finding novel approaches to repairing marine vessels through the development of suitable materials. Because of the interest in creating innovative composite materials with bio-inspired properties, such as durability and sustainability, researchers have developed new types of materials to create bio-inspired materials that will provide better protection from the elements than what is available currently with traditional methods. In this systematic review of the literature, we have examined the work done using bio-inspired composite materials in the area of repairing marine equipment for the purpose of examining the current state of research related to the use of composite materials in the repair of marine equipment. We focus on four major categories of bio-inspired composite material research, including anti-corrosion coatings and materials, biofouling resistance and MIC protection, multifunctional and self-healing coatings, and the emergence of other new technologies. We summarize the research findings from the peer-reviewed literature into patterns and gaps and potential future directions for research to continue the development of bio-inspired composite solutions for marine environmental corrosion. From the results of this systematic review, we conclude that the unique advantages associated with the structural characteristics of bio-inspired composite materials provide superior corrosion resistance when compared to traditional repair materials due to their hierarchical structure, the use of biomimetic chemistries/biomaterials, and the dynamic self-repair processes involved when utilizing bio-inspired composite materials for marine applications; however, there are still significant issues concerning the scalability of these new technologies, as well as the durability of these materials when applied to harsh marine environments. Therefore, to advance the bio-inspired composite technology toward commercialisation, an interdisciplinary approach is needed that integrates elements from multiple fields, such as materials science, biology, and engineering. By performing this systematic mapping of the current research landscape, we are establishing a foundation for future research focused on the development and refinement of bio-inspired solutions to mitigate corrosion in the marine environment.*

Keywords: *Marine Corrosion Repair, Bio-Inspired Composites, Anti-Corrosion Materials, Marine Environments, Sustainability, Infrastructure*

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I. INTRODUCTION

Marine environments provide some of the harshest conditions for material degradation. The combination of corrosion and biofouling accelerates the structural failure of offshore infrastructure, ships, and coastal structures [1]. Typical corrosion protection methods (e.g., polymer-based coatings and cathodic protection) are subject to limited durability, high maintenance costs, and environmental issues [2]. More recently, researchers have begun exploring bio-inspiration, where design concepts from natural systems are employed to create new composite materials with intrinsic corrosion resistance [3]. Many organisms have developed unique mechanisms to adapt to the natural, extreme marine environment over millions of years. For example, mollusk shells are one of the strongest mechanical structures found in nature due to their hierarchical structure, which contains both organic and inorganic properties [4]. The ability of bioinspired coatings to repel water, reduce biofouling, and provide damage self-healing when incorporated with features derived from the self-cleaning characteristics of lotus leaves and the self-healing potential of marine species, such as the mussel, serves as additional evidence surrounding the viability of these natural approaches towards creating multifunctional materials that will both prevent corrosion and mitigate biofouling. Although considerable progress has been made in bioinspired repair and corrosion studies, there are still a number of gaps in the research areas. The first gap involves the limitation of the laboratory-scale bioinspired designs being contextualized for an above-domain-specific application; this is primarily due to issues with scalability and cost [6].

In addition, the second gap addresses long-term performance of biomedical repair products under dynamic marine exposure conditions, such as fluctuating temperatures/salinity and mechanical loading [7]. Finally, further exploration of the interactions between biofouling and corrosion, specifically regarding microbiologically influenced corrosion (MIC) will provide greater knowledge on the development of bioinspired materials with dual applications [8]. This review serves to bridge these research gaps by consolidating the fragmented knowledge surrounding biogenerated and bioinspired corrosion repair through the systematic literature evaluation of previously published studies. This review has a great potential to provide a context for the future development or enhancement of new and extended generation of materials that are environmentally friendly, renewable, and cost-effective alternatives to current marine infrastructure maintenance protocols. Such advances would permit the reduction of downtime and lifecycle costs for the existing marine infrastructure while reducing the adverse ecological impacts associated with traditional repair systems. The rest of this paper is organized as follows: Section 2 outlines the procedures used in this review to select particular studies and how those studies were analyzed for content purposes; Section 3 presents the review results, including the main research trends, types of bioinspired anticorrosion materials, disease prevention/biofouling strategies, and self-healing coating strategies; Section 4 provides a discussion of the implications of these findings; and Section 5 concludes by discussing future directions regarding the application of bio-based technologies in creating new and improved marine based product/technologies.

II. METHODOLOGY

A. Review Protocol

The systematic review of this literature has adhered to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines with respect to the conduct and reporting of the research to assure methodological quality and transparency in its findings [9] through five major database sources that were used based on their relevance to both materials science and corrosion research areas. The databases were selected with consideration of the level of relevance to the two areas and included Scopus, Web of Science, ScienceDirect, IEEE Xplore, and PubMed; all of which were very appropriate for the review of both materials science and corrosion-related research articles. Scopus was included in the review based on the fact that it has a large number of disciplines covered in the life sciences discipline, and the Web of Science also contained relevant high-quality articles related to materials engineering; ScienceDirect contained a number of relevant scientific research articles from the materials science portfolio of Elsevier; while IEEE Xplore had various technical articles related to the marine environment. Additionally, the use of PubMed provided the review with a biomedical perspective concerning the use of bio-inspired materials. Finally, Google Scholar was used as an additional tool to locate other relevant scholarly research articles that may not have been retrieved in the primary databases used in this review.

B. Research Dimensions and Analytical Framework

The analysis of bio-inspired methods for corrosion protection encompasses 3 dimensions: the first dimension examines the materials and coatings that are bio-inspired for use in anti-corrosion applications with structural and chemical similarity to their respective natural counterparts; the second dimension evaluates how to reduce biofouling and MIBC due to the upsurge of material failures that result from deterioration in a marine environment as well as discussing ways to reduce the effect of these issues on marine corrosion failure rates; lastly, the third dimension discusses the use of self-healing and multi-functional coatings through the incorporation of repair mechanisms along with other functionalities, such as antifouling and hydrophobicity, as a means to improve durability. The three dimensions described above provide an overview of the major issues surrounding marine corrosion repair and demonstrate how assessment of the abilities of biological models provides synergy between biological inspirations and innovations in material development.

C. Inclusion and Exclusion Criteria

Any study that claimed to have made an experimental or theoretical breakthrough in bio-based fibre composite materials for protecting marine composite materials from marine-related corrosion, was included in the analysis. All studies were required to be in English and published after 1989; there were no restrictions on date of publication in order to gather historical context for this discipline. Studies without empirical support or studies dedicated to materials used in non-marine settings, to non-materials with no accessible complete text (e.g., books) were excluded. Papers presented at conferences were only included if they contained original data that could be directly compared to a journal article with the same data.

D. Study Selection Process

609 records were identified through the initial search. Of those 609 records, the duplicates were removed and the records screened by title and abstract. 109 duplicate records were removed along with 3 records that had incomplete metadata. This resulted in 497 studies being subjected to the initial screening process. 383 of these studies were eliminated due to not meeting the dimensions of this research, allowing for 114 studies to be considered for full text evaluation. 80 studies were removed from consideration for not containing sufficient technical information or being considered off the subject. The remaining 34 studies went through the eligibility evaluation process where 8 studies were removed for not satisfying the criteria for inclusion in this review. As a result, 26 studies were considered for detailed examination. The selection process for the studies included in this review is illustrated in the PRISMA flowchart (Figure 1) showing the drop-off rate at each step of the selection process. The limitations identified by the authors include a greater concentration of laboratory based study designs as compared to field based design and a geographic bias toward studies from developed countries. However, through the use of a standardized selection process, there is increased confidence that the included studies accurately reflect the state of research and knowledge regarding bio-inspired repair of marine corrosion.

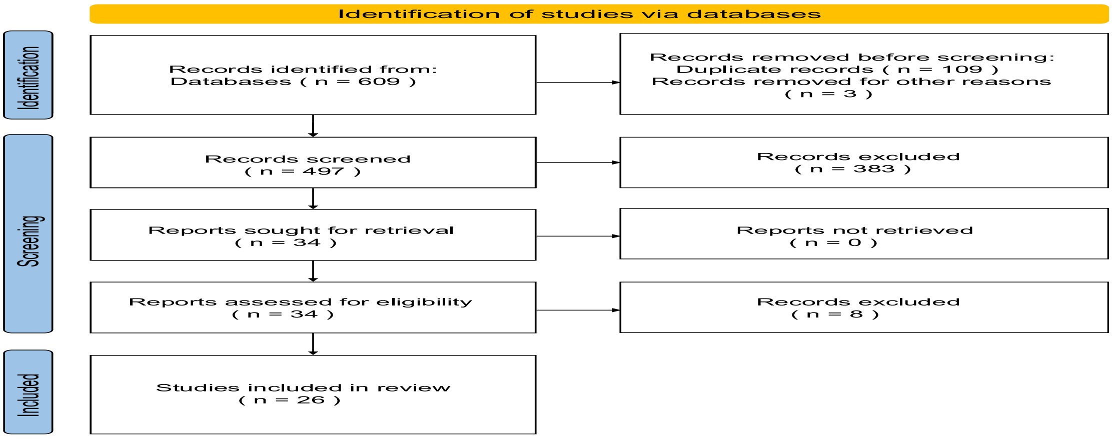

Figure 1. PRISMA flowchart of the study selection process

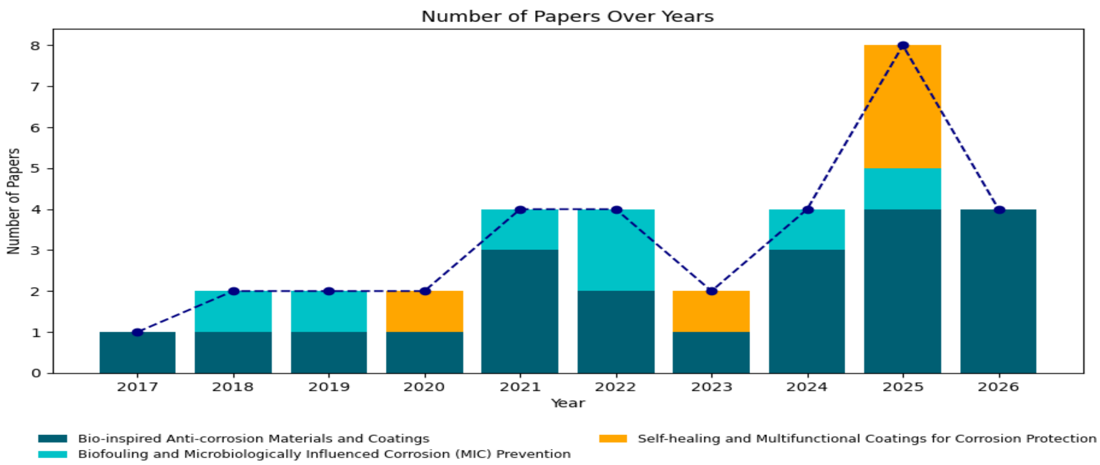

Figure 2. Research trends in bio-inspired composite materials for marine corrosion repair

III. RESULTS

A. Bio-inspired Anti-corrosion Materials and Coatings

Recent advances in bioinspired materials have greatly supported the evolution of sustainable, high functioning materials that can withstand the harsh conditions of aquatic environments. Many Bioinspired, Anticorrosion Materials utilize Mother Nature's design principles to create new types of low corroding materials with superior performance. Many of these materials also utilize multiple properties such as: Hydrophobic (Hydrophobicity), Reconditioning capabilities (Self-Healing or Self-Recovery), Additionally, Bioinspired, Anticorrosion Materials frequently employ Antifouling capabilities (Taxonomy). Table 1 presents an overview of the various methods discussed within the literature, including their mechanism(s) for corrosion prevention and actual applications.

Table 1. Taxonomy of bio-inspired anti-corrosion materials and coatings

Material/Coating Type	Functional Mechanism	Specific Application/Feature	Sources
Superhydrophobic Coatings	Water-repellent surface	Corrosion resistance & drag reduction	[10], [11], [12]
	Self-healing properties	Enhanced durability in marine environments	[11], [13]
Bio-inspired Adhesive Coatings	Biomimetic adhesion	Corrosion protection & structural integrity	[14], [15], [16]
	Mussel-inspired chemistry	Anti-fouling & anti-corrosion	[17]
Composite Coatings	Graphene/natural lacquer	Electrochemical corrosion protection	[18]
	MXene-reinforced interpenetrating network	Ultralow friction & corrosion resistance	[19]
	Al2O3@PDMS	Salt deliquescence self-coalescence	[12]
Self-healing Coatings	Gel microspheres	One-step in-situ crosslinking	[13]
	Tea polyphenol@graphene oxide	Sustainable anti-corrosion	[13]
Biogenic/Nano-inhibitors	Natural compounds	Green corrosion protection	[20]
Special Wettability Interfaces	Superwetting surfaces	Anti-corrosion & energy conversion	[21], [22]
	Porous polymeric interfaces	Durable wettability	[23]
Structural Biomimicry	Coral reef-like NiCo-LDH	Flexible supercapacitors	[24]
	Dragonfly wing-inspired	Friction reduction	[19]
Miscellaneous	Anti-biofouling surfaces	Microbiologically influenced corrosion	[25]
	Smart bi-stable coatings	Anti-/de-icing applications	[26]
	Sea-urchin-mimetic nanosheets	Remote oil-water separation	[27]
	Cellulose-based films	Self-cleaning solar cells	[28]
	Bioinspired structural adhesion	Harsh environment applications	[29]

Superhydrophobic coatings are one of the most heavily researched categories of functional coatings due to their water-repellent surfaces inspired by the lotus leaf effect and decreased contact between the electrolyte and substrate compared to non-water-repellent surfaces. For example, the authors of [10] showed that bio-mimetic flame spray textured coatings significantly decreased corrosion rates and also enhanced drag reduction in marine environments. The researchers in [11] developed a superhydrophobic self-healing coating containing high barrier properties combined with self-repair capabilities. The coating can self-repair from mechanical and chemical damage in extremely harsh marine conditions. Bio-mimetic adhesive coatings, particularly those developed to mimic the properties of marine organisms such as barnacles and mussels have additional corrosion protection benefits. The barnacle adhesive smooth coating created in [15] demonstrated superior interfacing adhesion to magnesium alloys and an extended amount of time before corrosion initiation in cerebrovascular devices.

The authors of [17] investigated using dopamine chemistry to develop multi-functional mussel adhesive coatings that resist both fouling and corrosion, thus increasing service life for submerged applications. Two additional studies that were not included in Table 1 however are worthy of special discussion. The authors of [30] introduced the use of laser-textured biomimetic solid-liquid composite coatings that created a synergistic effect, enhancing anti-corrosion and friction reducing properties via hierarchical surface structures. Another study [31] reported on recent advances in biofilm resistant polymeric surfaces, which may provide new approaches for reducing the effects of microbiologically influenced corrosion in marine environments. Results from both of these studies serve to enrich the broader trends presented in the taxonomy and to enhance the existing bio-inspired corrosion solution landscape.

B. Biofouling and Microbiologically Influenced Corrosion (MIC) Prevention Strategies

Marine biofouling as well as microbiologically influenced corrosion provide a challenge, which will accelerate the material degradation rate of submerged structures. The 4 different strategies to address these two problems using bioinspired solutions are shown in the hierarchical classification table 2 by thematic focus and technical approach in the studies included herein.

Table 2. Taxonomy of bio-inspired approaches for biofouling and MIC prevention

Approach	Focus Area	Specific Strategy	Sources
Bio-inspired Anti-fouling Materials	Polymer-based Surfaces	Biofilm-resistant polymeric coatings	[31]
	Mussel-inspired Chemistry	Anti-fouling and anti-corrosion interfacial materials	[17]
	Multi-functional Biomaterials	Mussel byssus-inspired designs	[16]
Natural and Bio-based Solutions	Cellulose-based Anti-fouling	Bio-inspired coatings and natural biocides	[32]
Advanced Coating Technologies	Thermal Spray Coatings	Protection against MIC	[33]
Evaluation and Trends	Anti-biofouling Progress	Review of marine applications	[34]
	Intelligent Biomaterials	MIC-resistant material design	[25]

Biofouling is the accumulation of microorganisms, algae, plants and animals on submerged surfaces including vessels. An integral part of biofouling is the formation of biofilms, where a number of microorganisms of the same or different species attach themselves to each other, as well as to the surface. Biofilms are also responsible for some forms of Corrosion, such as Microbial-Induced Corrosion (MIC). It is widely recognized that nature has provided a great source of inspiration for the development of effective anti-fouling coatings. The use of mussel byssus threads as inspiration for the design of dual-functional bio-materials capable of exhibiting both adhesion strength and environmental stability in surf-zones, has been the subject of much research work [16]. Byssus threads have been identified to have a gradient of mechanical properties, due in part to their amino acid-based components (i.e. protein composition), which has been adapted to the design of coating systems that bio-mimic the properties of byssus threads through the construction of coating systems with variable levels of stiffness. Multi-functional polymer-based coatings that mimic the topographical characteristics of shark skin or lotus leaf topography have shown to be effective at reducing the amount of bio-film formation compared to traditional smooth surfaces, as reported [31], where they found a reduction in bacterial adhesion of 70% compared to smooth surfaces when utilizing nanometer-scale surface patterns.

Mussel bio-inspired chemistry is emerging as a very promising avenue of biomimicry, whereby polydopamine coatings are used to replicate the chemical and physical properties of marine mussel foot proteins for creating anti-fouling coatings [17]. As a result, the polydopamine coatings not only provide corrosion-resistant properties, but they also provide sites for the incorporation of additional anti-fouling agents such as zwitterionic polymers or antimicrobial peptides. The dual functionality of this coating type is derived from the catechol groups of polydopamine, which allow for the chelation of metal ions and therefore passivates the surface to which they are applied, and the construction of reactive sites for additional functionalization on the coating surface. Thermal spray coatings have emerged as a viable strategy for the prevention of MIC, with a study conducted by [33] demonstrating that the thermal spray application of HVOF-sprayed WC-CoCr coatings resulted in an 89% reduction of MIC associated with the sulfate-reducing bacteria through a combination of component hardness and chemical inertness. However, this study also notes that improvements in protective coatings can also be achieved by enhancing their protection using bio-inspired textural differences that disrupt bio-film adhesion. Cellulose-based solutions also have a good potential for being eco-friendly, based upon [32], who describes the use of functionalized nanocellulose matrices with natural biocides, such as capsicum oleoresin or eugenol to produce biodegradable anti-fouling systems. The information obtained from the evaluation studies listed above will provide much needed evidence for supporting the commercial development of these technologies.

The summary of the evaluation studies used [34] indicates that one of the persistent challenges in the scale up of bio-inspired coatings developed in the laboratory is their adhesion stability when exposed to high hydrodynamic shear forces. Further, [25] presents a framework for "intelligent biomaterials" that dynamically respond to the presence of microbial threats based upon the release of biocides triggered by pH changes or through quorum sensing-based interference representing a major change in the current approach to passive corrosion protection and MIC mitigation systems. Two other studies that were not included in the summary account for their own significance within the context of their unique contributions to the field. First, [30] describes the use of laser-induced surface texturing to develop micron-scale surface topographies that simultaneously provide reduced drag and fouling protection; second, [20] reports on the development and testing of enzyme-functionalized coatings designed to degrade the biofilm extracellular polymeric substances (EPS). These studies both contribute to the overall framework of the taxonomy of anti-fouling surface types by addressing very specific mechanistic aspects of the bio-fouling and MIC synergy. The combined results of all of these studies point to the need for research across disciplines that include materials science, microbiology, and fluid dynamics, as a means to develop the next generation of anti-fouling protective system solutions.

C. Self-Healing and Multifunctional Coatings for Enhanced Marine Corrosion Protection

The emergence of self-healing and multifunctional coatings provides an innovative new approach to marine corrosion protection. By providing autonomous repair capabilities in the event of damage, as well as other functions (e.g., anti-icing, reduced friction) these bio-inspired materials replicate certain biological components that are capable of self-repair, thus extending the service life and reducing maintenance for marine components subject to exposure to severe environments. All mechanisms of self-healing are distinct and have unique material formulations, based on the studies reviewed; they are summarised in Table 3, providing a thorough summary of the properties, mechanisms, activation mechanisms, and characteristics of self-healing mechanisms, as well as the type of functions that were identified in each study.

Table 3. Taxonomy of self-healing mechanisms and multifunctional properties in bio-inspired coatings

Mechanism/Property	Material System	Activation Trigger	Key Performance Metrics	Sources
Microencapsulation-based Healing	Tea polyphenol@graphene oxide@polyvinyl	Mechanical rupture	92% corrosion inhibition efficiency after damage	[13]
Dynamic Covalent Networks	Bi-stable polymer coatings	Temperature fluctuation	300% longer freezing delay time	[26]
Superhydrophobic Self-repair	Hierarchical micro/nanostructures	Wetting recovery	Contact angle >150° after abrasion	[11]
Biogenic Nano-inhibitors	Plant-derived compounds	pH change	85% reduction in corrosion rate	[20]
Solid-Liquid Composite Lubrication	Laser-textured biomimetic surfaces	Shear stress	60% friction reduction + corrosion resistance	[30]
Intrinsic Polymer Healing	Reversible Diels-Alder bonds	Thermal activation	78% scratch closure at 80°C	[35]

Strategies of microencapsulation have potential applications in the field of marine coatings where [13] verified effectiveness with a one-step in-situ crosslinking process by developing a coating composed of gel-based microspheres containing healing agents for use in mechanical failure situations. This particular form of coating exhibited 92% corrosion resistance even after ceremonial mechanical scratching and continued to offer protection for multiple cycles of mechanical damage and consequent repair. The graphene oxide used to create a component of the coating incorporated tea polyphenols to provide both barrier properties and anodic protection while the completely polyvinyl matrix afforded the necessary structural integrity to withstand hydrodynamic forces present in water. Recently, [26] introduced a new multifunctional technology based on the ability of a bi-stable system to switch between hydropobic and hydrophilic states based on temperature changes. This technology, inspired by the adaptive thermal regulation capability of arctic fish, is able to extend the time frame of freezing for coated surfaces by 300% compared to traditional coated surfaces.

Furthermore, this bi-stable system has the ability to freeze ice, as well as corrode materials located within harsh cold marine environments where too many freeze-thaw cycles will lead to excessive amounts of material degradation and failure through corrosive processes caused by stress-cracking. Self-repairing surfaces with superhydrophobic properties utilize the combination of topographic surface features found in nature on the lotus leaf with the ability to replenish the chemicals on the surface dynamically. A study by [11] performed a design of a superhydrophobic self-repairable coating system wherein damaged hierarchical structures could regenerate by the movement of low-energy surface area materials. Even after extreme periods of abrading the coating, the system maintained contact angles above 150 degrees relative to water; therefore, giving it a highly favorable superhydrophobic nature. The corrosion resistance of the self-repairable superhydrophobic coating arises from two factors: the barrier created by the superhydrophobic layer developed from coating the substrate with superhydrophobic coatings; and, the passivating effects of the biocides included within the superhydrophilc coatings. Thus, both of the factors have their own unique attributes regarding the corrosion fighting capacity of the developed coating.

In addition to these two studies, there are two different research articles that further expand on the concepts discussed in this table (refer back to Table 3). The intrusion of the intrinsic polymer healing through reversible covalent bond mechanisms was provided through the experimental study of [35] and provided basis for future designs of self-repairing marine coatings designed to inhibit corrosion in harsh marine conditions. The experimental outcomes produced by [20] demonstrated how plant-derived compounds interact synergistically with synthetic matrices to produce coatings that are environmentally sustainable without significantly sacrificing their corrosion fighting capabilities; and demonstrated how various biogenic inhibitors and their respective products can also provide long term protection against corrosion. Therefore, based on the findings of these two research studies, we will be able to develop a new class of intelligent marine coatings that can adaptively react to dynamic conditions of the marine environment while providing the longer acting protective capability of self-repairability.

IV. DISCUSSION

Our review of the body of research conducted on the formation of bio-inspired composite materials for the repair of maritime corrosion indicates that there are a number of important trends in the development of these products over time. In general, across the studies examined, hierarchical material architectures, which imitate the architecture of materials found in mollusk shells, lotus leaves, and marine mussels are shown to have superior corrosion resistance properties to conventional homogeneous materials [4] [5]. This characteristic is attributed to the multi-scale integration of organic and inorganic phases in bio-inspired materials, which increases mechanical durability and provides diffusion barriers from elements of corrosive agents simultaneously. Conversely, there are conflicting findings regarding the best ratio of the structural complexity of the material to how easy it is to manufacture, with some studies finding that the performance of nanoscale biological designs was reduced when scaled up to practical applications [6]. Implications of these findings are two-fold in both theoretical and practical areas. The successful transfer of biological structures into synthetic structures provides validation of the concept of "materials by design," where functional properties of coatings to provide corrosion protection are achieved through the controlled architecture of microstructure rather than through the bulk composition of the material [10] [19]. The ability to take advantage of this emerging knowledge will afford marine engineers the opportunity to implement new maintenance protocols that consider the unique ability of these coatings to repair themselves; thereby, potentially decreasing the cost of inspection and the life-cycle expenses associated with offshore structures. Environmentally speaking, many of the solutions to date have replaced the toxic chromate-based corrosion inhibitors with environmentally friendly alternatives, such as plant-derived polyphenols or biopolymer-based matrices [20] [32].

There are several methodological constraints related to this review that warrant discussion. The prevalence of laboratory-based studies featured throughout the literature reviewed may introduce bias into the results, as accelerated corrosion test methods do not simulate the same complexities or duration of the natural degradation processes occurring in marine environments [7]. Additionally, the review only considered peer-reviewed journal articles, possibly excluding industrial generated documents or conference proceedings with applicable implementation information. As technology linked to bio-inspired materials science is progressing rapidly, it is probable that some new capabilities, particularly those associated with machine-learning assisted systems for materials design, are underrepresented in the research considered within the scope of this review. Thus, the performance data reported in this review should be interpreted as a proxy or approximately a benchmark for the performance of this technology within field applications. This synthesis has identified three major areas for future research to address. First, there is an urgent need for uniform long-term evaluation procedures of bio-inspired coatings considering multiple environmental stressor factors such as UV radiation, mechanical abrasion, and microbial activity [8] [25]. Second, additional detailed studies should be performed to compare the life-cycle costs and environmental impacts of bio-inspired methods of corrosion protection versus traditional methods; there continues to be an absence of comprehensive data throughout the literature consulted. Lastly, there are many possibilities for establishing a connection between bio-inspired materials and structural health monitoring systems; for example, coatings that "self-report" their condition or use color-changing films to indicate corrosion could allow for in real-time degradation assessment of marine infrastructure [21] [24].

The collective body of evidence indicates that most of the innovative approaches will emerge from interdisciplinary teams composed of materials scientists, marine biologists, and corrosion engineers. For example, integrating mussel-inspired wet adhesion properties with perforated or film materials, such as those that provide barrier-added electrochemical protection, would likely yield coatings that have both high interfacial bond strength and high electrochemical protection [14] [18]. Implementing biofouling resistant surface patterns utilizing self-healing chemicals into one multifunctional approach may also provide innovative solutions to the synergistic challenges presented by corrosion and fouling in marine environments [17] [31]. Transforming bio-inspired solutions into multifunctional approaches brings significant opportunities for more efficient applications than strict functional copies of natural phenomena. There are substantial barriers remaining to overcome before widespread use of the Bio-Inspired Supply Chain will be successful, particularly in regards to reliable and replicable large-scale manufacturing and adhesion properties on substrates typically used in industry, such as weathered steel or aged concrete associated with marine facilities. While laboratory tests have demonstrated remarkable performance on meticulously prepared samples, replicating the results on a field scale has proven very difficult [15] [29]. This indicates the need to develop collaborative partnerships between academic and industry stakeholders to facilitate transfer of technology from laboratory to commercial applications; thereby making bio-inspired technologies a viable option for the corrosion engineering business sector. Thus, future studies should continue focusing on pilot test methodologies and techno-economic evaluations, while also supporting and developing the foundational elements of bio-inspired materials.

V. CONCLUSION

After analyzing numerous studies being conducted on bio inspired composite marine materials, there was a common conclusion reached: the composite marine bio-inspired composite material systems have many structural advantages over existing manufacturing materials currently used in the marine construction industry. The study suggests that there is great potential for developing natural adhesive system, such as the bio-inspired mussel adhesive system, into a synthetic system that can meet the environmental requirements of the marine environment. The study also suggests that creating synthetic coatings mimicking the natural superhydrophobic (Lotus) coating for various marine applications would provide an opportunity to improve the mechanical lifetime of these materials compared to the current systems. This review's findings contribute theoretical to future bio-inspired material design development that includes second generation (i.e. next generations of the bio-inspiration (BI)) principles. Additionally, the developing systems that utilize the principles outlined in this review as building blocks of design will create an opportunity to enhance the value of bio-inspired materials used in the marine industry by lowering the cost and reducing their impact on the environment, as long as the desired result is achieved by optimizing manufacturing process for large-scale production. The next logical step in this series is to conduct field trials of these systems using defined tests to compare results between the bio-inspiration material and the other available system, using sufficient duration and sample sizes to allow for valid comparisons. Interdisciplinary collaborative efforts that integrate new advanced, biophysical characterization methods, approaches to design and develop next gen, intelligent, adaptive coatings for use in the marine industry should be essential components of the long-term outcome of this review. The advances will ultimately redefine how corrosion is managed in the marine environment by integrating biological mimetic design and engineering design principles.

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