



**ANALYSIS OF CORROSION PREVENTION TECHNIQUES FOR
SHIP HULLS**

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CERTIFICATION

This is to certify that this project work titled “*Analysis of Corrosion Prevention Techniques for Ship Hulls*” was carried out by **IDAHOSA ELOGHOSA and JONAH NSIKAK**, students of the Department of Marine Engineering, Faculty of Engineering, UNIVERSITY OF BENIN, under my supervision. The work meets the standard and requirements for the award of the degree of Bachelor of Engineering (B.Eng.) in Marine Engineering.

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DEDICATION

This project is **dedicated to God Almighty**, whose grace and wisdom guided me throughout this research.

It is also dedicated to our beloved parents, **Mr. and Mrs. Sylvester Idahosa, and Mr. and Mrs. Johnny**, for their endless love, prayers, support, and encouragement during the course of my study.

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NOMENCLATURE

B.Eng. – Bachelor of Engineering
CP – Cathodic Protection
ICCP – Impressed Current Cathodic Protection
SACP – Sacrificial Anode Cathodic Protection
MIC – Microbiologically Influenced Corrosion
SRB – Sulfate-reducing bacteria
SCC – Stress Corrosion Cracking
SLR – Systematic Literature Review
LCA – Life- cycle assessment
Fe – Iron
Fe²⁺ – Iron (positively charged ions)
O₂ – Oxygen
OH⁻ – Hydroxide ions
Cl⁻ – Chloride ions
H₂O – Water
e⁻ – Electron

ABSTRACT

This research evaluates the efficacy and practical challenges of various corrosion prevention techniques applied to ship hulls, with a specific focus on identifying best-practice methods suited for the tropical marine environment of West Africa. Corrosion, accelerated by high temperatures, elevated salinity, and intense microbiological activity prevalent in these waters, significantly compromises vessel safety, operational efficiency, and necessitates substantial maintenance expenditure.

The study employed a comprehensive literature review and comparative analysis across three primary defense strategies: Protective Coatings, Sacrificial Anode Cathodic Protection (SACP), and Impressed Current Cathodic Protection (ICCP).

Findings confirm that an integrated protection system is mandatory, where high-performance multi-layer coatings serve as the primary barrier, and Cathodic Protection acts as the essential secondary defense against localized failure. Specifically, the combination of robust coatings with ICCP is determined to be the most durable and cost-effective long-term solution for large commercial vessels, while SACP is preferable for smaller coastal crafts due to its simplicity and low maintenance.

Crucially, the analysis identifies significant regional challenges, including poor surface preparation standards, skill gaps among applicators, and limited access to certified tropical-grade materials, which collectively undermine the performance of advanced techniques. The research concludes with key recommendations centered on implementing standards, developing local corrosion models, and strengthening policy enforcement and technical training to ensure sustainable and effective hull preservation in the region

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND TO STUDY

The hull of a ship represents one of the most critical structural components in marine vessels. Operating constantly in a harsh seawater environment, the hull is exposed to a variety of aggressive factors including high salinity, dissolved oxygen, wave and current action, biofouling, stray currents, and mechanical abrasion. These conditions foster diverse forms of corrosion from general uniform metal loss to localized pitting, crevice corrosion, galvanic attack and erosion-corrosion which collectively degrade hull integrity over time.

In the maritime sector of Nigeria and the wider West African region, these corrosion challenges are compounded by additional operational and infrastructural factors. The implications of hull corrosion are significant. Studies reveal that corrosion contributes heavily to the deterioration of ship hull structures, with impacts on load-carrying capacity, ultimate strength of the hull girder, thinning of plates, and ultimately safety and operational efficiency of vessels.

Moreover, the economic and maintenance burdens associated with hull corrosion are substantial. Reports estimate that in the marine sector the cost of corrosion in structural components, maintenance and repairs runs into billions of dollars annually. For ship operators, corrosion means increased dry-docking frequency, high repair costs, downtime, higher fuel consumption through increased hull roughness, and potential regulatory or classification society actions.

Given these realities, preventing and controlling corrosion of ship hulls is not merely an engineering challenge but a strategic imperative. Over the years, the maritime industry has deployed a variety of corrosion-prevention techniques: advanced coatings, cathodic protection, materials selection, design features, monitoring/inspection regimes and emerging smart systems. However, the performance of these techniques under real-world conditions especially in variable marine environments, varied vessel types, and in certain geographical regions remains subject to ongoing research. Some studies indicate gaps in long-term data, regional adaptation of techniques, life-cycle cost assessments, and integration of monitoring with maintenance regimes.

In particular, in environments characterized by high salinity, warm waters, marine biological activity (for example tropical and equatorial waters) the aggressive corrosion mechanisms may operate more intensely, necessitating tailored prevention strategies. Additionally, many ship-owners and maritime maintenance organizations face constraints of cost, logistics, and access to technology, creating a need for rigorous assessment of which prevention methods provide the optimal balance of effectiveness, cost and reliability.

This study seeks to analyze the various corrosion prevention techniques applied to ship hulls, evaluate their effectiveness, cost and practicality, and identify best-practice approaches — including adaptation to specific operational contexts. By doing so, the study aims to provide both theoretical insight and practical guidance for ship-hull integrity management in the maritime industry.

1.2 STATEMENT OF PROBLEM

The marine environment presents one of the most corrosive conditions for metallic structures, with ship hulls bearing the brunt of continuous exposure to saltwater, oxygen, and mechanical stresses. Despite decades of technological advancement, corrosion remains a persistent threat that undermines vessel integrity, increases operational costs, and poses significant safety risks.

1. **Technical Limitations:** Current corrosion protection and monitoring systems are ineffective, often failing to detect or prevent damage in time.
2. **Economic Impact:** Hull corrosion leads to high repair costs, downtime, and increased fuel use, reducing overall profitability.
3. **Safety and Environmental Concerns:** Corrosion weakens vessel structures causing safety hazards and marine pollution.

This study addresses the critical need for systematic evaluation of ship hull corrosion protection techniques. The research will provide recommendations for optimal protection strategies, contributing to improved safety, reduced costs, and enhanced environmental sustainability in maritime operations.

1.3 AIM AND OBJECTIVES

Aim:

The aim of this study is to evaluate and compare corrosion-prevention techniques for ship hulls in marine environments and identify best-practice methods suited to the operational conditions of the West African maritime industry.

Objectives:

1. To review and classify the main corrosion mechanisms affecting ship hulls under marine exposure, particularly in tropical West African waters.
2. To examine the current prevention techniques (e.g., protective coatings, cathodic protection, material selection, inspection/monitoring) applied to ship hulls and assess their suitability for the local context.
3. To compare the effectiveness, cost-efficiency and maintenance requirements of the different corrosion-prevention techniques for ship hulls.
4. To identify the practical challenges, gaps and constraints in applying these techniques within the Nigerian/West African maritime setting.
5. To propose tailored recommendations for the selection and implementation of corrosion prevention strategies for ship hulls operating in the regional marine environment.

1.4 SCOPE

This research examines corrosion-prevention techniques applied to ship hulls operating in marine environments, with particular reference to vessels in Nigerian/West African waters.

The study focuses on steel hull structures, and the prevention methods considered include protective coatings, cathodic protection systems, material choices and monitoring/inspection. Geographically, the research centers on the West African maritime context, but also draws on relevant global data where applicable. The study is mainly based on secondary data (academic literature, industry reports, ship-maintenance records) and comparative analysis; no full-scale field trials of hull systems are conducted. The outcome of the research will be recommendations on best-practice corrosion prevention for ship hulls within the regional operational environment.

Limitations:

1. Limited availability of detailed hull inspection and maintenance data from West African ship operators, which may restrict the depth of empirical analysis.
2. The study is based on secondary sources and comparative literature review rather than new experimental or field-trial data, which may limit the precision of effectiveness evaluations.
3. The findings focus on steel-hull merchant vessels operating in West African waters, and may not be fully generalizable to other vessel types, hull materials or marine environments.

CHAPTER TWO

LITERATURE REVIEW

2.1 BRIEF INTRODUCTION TO CORROSION PREVENTION TECHNIQUES ON SHIP HULLS

Corrosion prevention is an essential component of marine engineering because it directly affects the structural integrity, efficiency of operation, and lifespan of ships. Ship hulls are subjected to many kinds of corrosion types, including uniform, pitting, galvanic, erosion, and microbiologically influenced corrosion (MIC). These conditions include high salinity, changes in temperature, and continuous immersion in seawater (Melchers and Jeffrey (2008)) Several corrosion prevention strategies, such as protective coatings, cathodic protection, corrosion-resistant materials, and regular inspections, are used to ensure the lifespan of ships and save costs of maintenance.

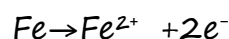
One of the most enduring and costly issues facing the maritime sector is corrosion. Up to 25–30% of ship maintenance expenses globally are estimated to be attributable to corrosion-related deterioration (Melchers & Jeffrey, 2008). Because they are constantly exposed to seawater, dissolved oxygen, salts, and biological organisms, ship hulls are especially vulnerable (Revie & Uhlig, 2008). These elements eventually lead to surface roughness, structural weakness, and metal waste, all of which can jeopardize operational effectiveness and safety.

2.2 CORROSION MECHANISM IN SHIP HULLS

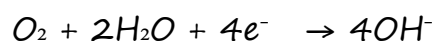
Corrosion in ship hulls is an electrochemical process that occurs when steel, the primary hull material, reacts with oxygen and moisture in the presence of electrolytes such as seawater. This reaction leads to the gradual deterioration of the metal surface, forming iron oxides (rust) and weakening the structure over time.

The process involves two simultaneous reactions:

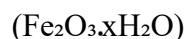
Anodic reaction: Iron (Fe) dissolves into the seawater as positively charged ions.



Cathodic reaction: The released electrons combine with oxygen and water to form hydroxide ions.



The resulting iron hydroxides eventually oxidize further to form rust:



2.2.1 MARINE ENVIRONMENT AND ITS INFLUENCE

The marine environment presents one of the most aggressive settings for metallic structures, especially ship hulls. Its complex combination of physical, chemical and biological factors creates conditions that accelerate corrosion and structural degradation. Understanding these environmental influences is essential for selecting effective corrosion-prevention techniques.

The marine environment is harsh, with high levels of salt and moisture, making ship hulls prone to corrosion.

1. **Salinity:** The amount of dissolved salts, primarily chloride ions, in saltwater is known as salinity. Corrosion results from these ions' disruption of the protective oxide layers that naturally grow on metal surfaces. Corrosion protection is essential for marine infrastructure like ship hulls and offshore platforms because the high chloride concentration of saltwater speeds up electrochemical reactions that break down the material.
2. **Temperature:** Temperature strongly affects the rate of electrochemical reactions. High temperatures accelerate chemical reactions involved in corrosion, while colder temperatures slow them down. Warm waters accelerate both anodic and cathodic processes, enhance microbial activity, and increase diffusion of oxygen, all of which intensify corrosion.
3. **Oxygen:** Oxygen concentration influences the type and rate of corrosion. In well-aerated zones (near the waterline), uniform corrosion predominates, whereas oxygen-deficient areas under marine growth, sediments, or ballast-tank deposits promote localized attacks such as pitting and crevice corrosion. Differences in oxygen concentration along the hull surface can also create differential-aeration cells that accelerate corrosion.
4. **Biofouling:** Life in the sea, algae, barnacles, and certain bacteria stick to ships. This creates a slimy layer holding water and air. Consequently, metal corrodes, and coatings flake off. Biofouling also increases surface roughness, leading to higher fuel consumption and maintenance frequency.

2.2.2 TYPES OF CORROSION RELEVANT TO SHIP HULLS

1. **Uniform Corrosion:** One of the most prevalent and predictable types of metal deterioration is uniform corrosion, often known as general corrosion. It happens when a metal surface is exposed to a corrosive environment and the damage spreads evenly throughout the exposed area. This kind of corrosion results in a uniform decrease in the material's thickness and is frequently distinguished by a uniform and smooth surface degradation (Fontana, 1986). Compared to more localized types like pitting or crevice corrosion, uniform corrosion is usually easier to monitor and regulate since the corrosion rate can be fairly constant.



Figure 2.1: Uniform Corrosion on Ship a Hull

2. Pitting Corrosion: A highly localized and damaging type of corrosion known as "pitting corrosion" causes tiny holes, or "pits," to grow on a metal surface. Pitting is focused at specific areas and usually penetrates deeply into the metal with little overall material loss, in contrast to uniform corrosion, which happens uniformly across a wide region (Jones, 1996). Because pits can pierce through the thickness of the material, they can seriously affect the integrity of ship hulls and other maritime constructions, even though the impacted surface area is small (Revie & Uhlig, 2008). Because seawater contains chloride ions (Cl^-), pitting corrosion is a major problem in marine environments. These ions can cause limited damage by penetrating the protective oxide layers on metals like aluminum or stainless steel. Under the correct electrochemical circumstances, pits can spread quickly once they start; therefore, detection and avoidance are vital for ship maintenance and safety.



Figure 2.2: Pitting Corrosion on a Ship Hull

3. **Crevice Corrosion:** Crevice corrosion is a localized type of corrosion that happens in small openings or cramped areas where oxygen or other oxidizing chemicals are unable to access. These spaces, known as crevices, can develop between two metal surfaces or between a metal and a nonmetal substance like paint coatings, rubber gaskets, or marine fouling deposits (Fontana, 1986). Because of the continuous exposure to seawater, high concentration of chloride ions, and varying aeration conditions, crevice corrosion is a major issue in marine environments, such as on ship hulls (Melchers & Jeffrey, 2008). Crevice corrosion is very harmful because it occurs frequently beneath joints, fasteners, or deposits, making early detection challenging. If unchecked, it may damage the structural integrity of ship hulls and other underwater fittings and cause quick localized loss of metal (Revie & Uhlig, 2008).



Figure 2.3: Crevice Corrosion on a Ship Hull

4. **Galvanic Corrosion:** When two dissimilar metals are connected by electricity in the presence of an electrolyte, like seawater, galvanic corrosion (also referred to as bimetallic corrosion) occurs. The more active (anodic) metal corrodes faster as a result of this electrochemical process, while the more noble (cathodic) metal remains protected (Jones, 1996). Because seawater has a high electrical conductivity and is an effective electrolyte, galvanic corrosion is a common issue in maritime contexts (Melchers & Jeffrey, 2008). Galvanic corrosion is very important in ship hulls because hull structures often involve different metals, such as steel hulls attached to bronze propellers. Galvanic corrosion can quickly deteriorate materials without adequate control, which can result in leaks, higher maintenance costs, and structural failure (Revie & Uhlig, 2008).

<u>Metals and Alloys</u>	<u>Corrosion Potential</u> (volts DC ref. Ag/AgCl)		
Magnesium and Magnesium Alloys	-1.60	to -1.63	anodic - active
Aluminum - Anode	-1.10		
Zinc	-0.98	to -1.03	
Aluminum Alloys	-0.76	to -1.00	
Mild Steel (clean & shiny)	-0.60	to -0.71	
Mild Steel (rusty)	-0.20	to -0.50	
Cast Iron (not graphitized)	-0.60	to -0.71	
Stainless steels	-0.46	to -0.58	
Stainless Steel, Type 316 (active in saltwater)	-0.43	to -0.54	
Aluminum Bronze (92% Cu, 8% Al)	-0.31	to -0.42	
Copper	-0.30	to -0.57	cathodic - noble
Naval Brass (60% Cu, 39% Zn)	-0.30	to -0.40	
Yellow Brass (65% Cu, 35% Zn)	-0.30	to -0.40	
Red Brass (85% Cu, 15% Zn)	-0.30	to -0.40	
Muntz Metal (60% Cu, 40% Zn)	-0.30	to -0.40	
Admiralty Brass (71% Cu, 28% Zn, 1% Sn)	-0.28	to -0.36	
Aluminum Brass (76% Cu, 22% Zn, 2% Al)	-0.28	to -0.36	
Silicone Bronze (96% Cu max, 0.80% Fe, 1.5% Zn, 2.00% Si, 0.75% MN, 1.60% Sn)	-0.26	to -0.29	
90% Cu, 10% Ni	-0.21	to -0.28	
75% Cu, 20% Ni, 5% Zn	-0.19	to -0.25	
Lead	-0.19	to -0.25	
70% Cu, 30% Ni	-0.18	to -0.23	
Stainless steel, Type 304 (passive)	-0.05	to -0.10	
Stainless steel, Type 316 (passive)	-0.00	to -0.10	
Titanium	+0.06	to -0.05	
Platinum	+0.25	to +0.19	
Carbon, Graphite, Coke	+0.30	to +0.20	

Table 1: Galvanic series of metals in seawater

Metals such as aluminium, magnesium, and zinc are more active in nature compared to steel.

5. Erosion Corrosion: When a metal surface is exposed to a moving corrosive fluid, mechanical wear (erosion) and electrochemical attack (corrosion) work together to cause corrosion. It happens when high-velocity fluid flow, suspended debris, or cavitation continuously remove the protective oxide layer from a metal's surface, leaving fresh metal vulnerable to corrosion (Fontana, 1986). Erosion corrosion is a major hazard in the marine environment for ship hulls, which are continually exposed to rough seawater flow, rough particles, and marine animals (Melchers & Jeffrey, 2008). Metal loss occurs faster and layer breakdown is increased by the high flow speeds around the hull areas. Hull plate thinning may occur from poorly controlled erosion corrosion (Revie & Uhlig, 2008).



Figure 2.4: Erosion of the hull of a yacht

6. Microbiologically Influenced Corrosion: The term "microbiologically influenced corrosion" (MIC) refers to the breakdown of metals that is either accelerated or produced by the metabolic processes of microorganisms, such as fungi, bacteria, and algae (Beech & Sunner, 2004). MIC happens when microorganisms grow on metal surfaces and produce tiny electrochemical cells that speed up corrosion processes. Ship hulls and other submerged steel structures are seriously threatened by MIC in marine environments because seawater creates a nutrient-rich environment that favors microbial development (Little & Lee, 2007). Sulfate-reducing bacteria (SRB), iron-oxidizing bacteria, and slime-forming bacteria are the organisms most commonly associated with MIC because they can change the chemical conditions at the metal–water interface. Localized pitting corrosion, coating degradation, and increased hull surface roughness are some of the effects of MIC on ship hulls, which increase hydrodynamic drag and fuel consumption (Melchers & Jeffrey, 2008). MIC can result in increased maintenance expenses and structural weakness if left unchecked.



Figure 2.5: Marine biofilms on different surfaces

2.2.3 MATERIAL FACTORS

The material composition and surface characteristics of the hull structure have a major impact on the corrosion behavior of ship hulls. The basic properties of the hull material are essential in determining the rate, form, and extent of corrosion in marine environments, where salt, temperature, and water flow vary significantly. The kind of hull material, surface condition, mechanical stress, coatings, and sacrificial layers are important material-related elements that influence ship hull corrosion (Revie & Uhlig, 2008).

1. Hull Material (steel hull structures): Carbon steel is used to build the majority of modern ship hulls because of its great strength, ductility, and affordability. However, because saltwater functions as an electrolyte, steel is extremely vulnerable to electrochemical corrosion (Melchers & Jeffrey, 2008). Steel oxidizes in seawater, producing iron hydroxides and oxides as products of corrosion. Typical cathodic and anodic reactions are shown as follows:

Anodic reaction: $Fe \rightarrow Fe^{2+} + 2e^{-}$

Cathodic reaction: $O_2 + 2H_2O + 4e^{-} \rightarrow 4OH^{-}$

Steel composition, grain size, microstructure, and alloying elements are some of the factors that affect the corrosion rate (Fontana, 1986). For instance, contaminants like phosphorus and sulfur can produce galvanic places, which speed up localized corrosion. However, by creating solid oxide layers, alloying with elements like nickel or chromium can increase resistance (Paik et al., 2003).

Low-carbon steels are favored for ship hulls due to their weldability, although their resistance to corrosion is still restricted. Therefore, to maintain structural integrity throughout the ship's

lifespan, further protection via coatings or cathodic systems is crucial (Melchers & Jeffrey, 2008).

2. Condition of Surface: The state of a steel hull's surface has a big impact on how corrosion starts and spreads. Microenvironments that are favorable to localized corrosion are created by the tendency of rough or contaminated surfaces to hold onto moisture, salts, and microorganisms (Revie & Uhlig, 2008). Inadequate surface preparation during shipbuilding or maintenance, such as leaving bare metal exposed to seawater and starting corrosion cells, can lead to poor coating adherence (Fontana, 1986).

Pitting and crevice corrosion are less common on a clean, smooth surface because there are fewer cracks and irregularities where chloride ions can concentrate. Maintaining a smooth hull surface is a strategy for both performance improvement and corrosion control because surface roughness also influences hydrodynamic drag and fuel economy (Paik et al., 2003).

3. Stress and Mechanical Deformation: Mechanical stress in hull components (including tensile stress from loading, vibration, or welding residual stress) can speed up corrosion through processes such as stress corrosion cracking (SCC) and fatigue corrosion (Melchers & Jeffrey, 2008). When a stressed region is exposed to seawater, small cracks may propagate more rapidly due to the combined effects of stress concentration and corrosive attack.

Additionally, heat-affected zones and diverse microstructures in welded joints frequently show unique electrochemical potentials, resulting in the formation of local galvanic cells (Fontana, 1986). If not adequately treated or coated, these surfaces are more susceptible to corrosion. In order to reduce stress-induced corrosion damage to ship hulls, post-weld treatments and stress distribution control are essential.

4. Coatings: The main defense between the corrosive sea environment and the steel surface is provided by protective coatings. The efficiency of the coating material is largely determined by its type, quality, and integrity (Revie & Uhlig, 2008). Polyurethane systems, epoxy-based paints, and anti-fouling coatings that use biocides to stop marine growth are examples of common hull coatings.

By keeping steel from coming into direct contact with seawater, a properly applied coating stops the electrochemical corrosion process. However, localized processes such as pitting or under-film corrosion may arise from mistakes, cracks, or mechanical degradation in the coating layer that show the metal under it (Melchers & Jeffrey, 2008). Therefore, in order to improve protection efficiency, surface preparation, coating selection, and maintenance are essential. Self-healing coatings and nanocomposite layers that enhance adhesion, abrasion resistance, and lifespan in marine conditions are examples of recent developments (Paik et al., 2003).

5. Sacrificial Layers: One essential material-based corrosion prevention technique is the use of sacrificial layers or sacrificial anodes. These are made of alloys of magnesium, zinc, or aluminum that are purposely attached to the hull construction in order to function as anodic materials (Melchers & Jeffrey, 2008). These metals preferentially corrode because they have a lower electrochemical potential than steel, which provides cathodic protection for the steel hull.

An oxide film that further protects the underlying steel is created when the sacrificial layer slowly corrodes. These anodes eventually need to be changed during hull repair or dry-

docking cycles (Fontana, 1986). To guarantee consistent protection throughout the hull's wetted surfaces, anode material, size, and placement must be carefully chosen.

2.2.4 IMPACT OF CORROSION ON SHIP HULLS

Ships battle a major problem: corrosion. It threatens their safety, how well they run, and also their profitability. Steel hulls inevitably rust when constantly immersed in saltwater (a potent corrosive agent). This isn't just cosmetic; corrosion weakens the ship's structure, boosts fuel use, increases repair bills, and shortens its service life.

1. **Structural Integrity and Safety:** Hull degradation ultimately compromises a vessel's integrity. It eats away at the metal, diminishing its thickness, therefore reducing how much stress the hull can withstand (Melchers, 2003). As this worsens, specific forms like pitting or crevices generate points of intense strain; consequently, cracks become likely, possibly causing collapse during use.

Steel plates exposed to seawater may lose 0.1 to 0.2 mm of thickness each year (how quickly this happens relies on the environment alongside upkeep) (Melchers and Jeffrey, 2008). Consequently, a ship's hull weakens over time, potentially losing 10 to 15% of its original strength, thereby raising chances of damage when seas get choppy (Paik et al., 2003). Rust spots let water in, possibly leading to leaks, swamping, or even a rollover during bad weather. Consequently, rust doesn't just make the ship fragile; it creates real dangers for people alongside risks to the surroundings, especially when oil or dangerous materials are onboard.

2. **Hydrodynamic Performance and Fuel Efficiency:** The hydrodynamic performance of a vessel is greatly affected by corrosion. The frictional resistance between the hull and water increases as corrosion products build up and roughen the hull surface, increasing drag. According to studies, even a slight increase in surface roughness can result in a 5–10% increase in fuel consumption since more power is needed to maintain cruising speed (Melchers & Jeffrey, 2008).

Furthermore, biofouling—the attachment of microorganisms, algae, and barnacles to roughened hull surfaces—is frequently encouraged by surface corrosion (Callow & Callow, 2011). Corrosion and fouling increase drag resistance, which lowers propulsion efficiency and raises the release of greenhouse gases. For fuel economy and environmental compliance, it is therefore essential to maintain a smooth, corrosion-free hull surface, especially in accordance with international regulations like MARPOL Annex VI.

3. **Maintenance and Operational Costs:** The operational and maintenance expenses related to ship ownership are greatly increased by corrosion. The vessel's total lifecycle costs include sacrificial anode replacement, coating renewals, and routine hull inspections (Melchers & Jeffrey, 2008). Up to 30–40% of a vessel's total repair and dry-docking expenses may be attributed to corrosion-related maintenance, according to Paik et al. (2003).

Uncontrolled corrosion can cause unplanned dry-docking, which would interfere with business operations and decrease the number of available vessels. Additionally, contamination from corrosion in cargo holds and ballast tanks may necessitate cleaning and recoating. These expenses mount up over time, affecting ship operations' capacity to remain financially viable. 4. **Environmental and Safety Consequences:** Corrosion has environmental repercussions, especially when hull degradation results in leaks or structural breakdowns. For

instance, fuel tank ruptures brought on by corrosion can result in marine oil spills that contaminate marine ecosystems and harm aquatic life (Beech & Sunner, 2004). Additionally, when ships age, rusted steel surfaces leak heavy metal particles and iron oxides into seawater, which contributes to localized pollution.

From a safety standpoint, rust compromises the dependability of vital systems including hull penetrations, pipes, and ballast tanks. The safety of the crew and cargo may be seriously affected by flooding situations, buoyancy loss, or mechanical system failures. To reduce such concerns, international bodies like the International Maritime Organization (IMO) and classification societies require routine inspections and corrosion control initiatives. 5. Economic Lifespan and Vessel Value: A ship's economic lifespan is affected by corrosion. As hull corrosion advances, the expense of repair and maintenance eventually exceeds the vessel's residual value, resulting in early scrapping or decommissioning (Paik et al., 2003). Due to perceived safety and performance hazards, older ships with significant corrosion also have reduced resale and charter prices. Therefore, a vessel's physical durability and value in the global transportation industry are both improved by effective corrosion management. Ship owners may extend dry-docking intervals, cut fuel consumption, and maintain compliance with regulations by reducing corrosion-related deterioration, all of which support sustainable operations (Revie & Uhlig, 2008).

2.3 CORROSION PREVENTION TECHNIQUES FOR SHIP HULLS

This part discusses the major techniques of preventing or managing corrosion of steel ship hulls, the mechanisms behind each technique, and outlines the benefits, drawbacks and common uses of each technique in a marine environment (including consideration of tropical/warm waters where such are warranted). These approaches are summarized as: (1) protective coating, (2) cathodic protection, (3) choice and design of materials, (4) operational / maintenance, (5) monitoring and inspection and (6) combined and emerging.

2.3.1 Protective coatings

Coatings which are protective are the initial line of defense of hull steels because they isolate metal physically by separating it in seawater and oxygen. Underwater hull coating systems consist of one or more layers of primer/undercoat and intermediate/top coating layers based on adhesion, barrier, mechanical toughness, abrasion resistance and antifouling behavior (Revie & Uhlig, 2008).

Types and mechanisms

1. Barrier coatings (epoxy/polyurethane): Epoxy-based primers and tie coats give the surface chemical resistance and adhesion; polyurethane topcoats give the surface abrasion and UV resistance on the splash and above-waterline areas. When a constant, blemish-free film is used, ionic transport is decreased and therefore electrochemical reactions at the steel surface are slowed down (Fontana, 1986; Revie and Uhlig, 2008).
2. Antifouling coating (biocide-releasing, self-polishing copolymer, foul release): These help to reduce bio-fouling which otherwise forms a microenvironment that supports MIC and differential-aeration corrosion and drag. Systems with biocides emit active agents (e.g. cuprous oxide) to inhibit organisms; foul-release silicones lower the strength of attachment and clean (Callow, 2011).

3. Innovative coating (nanocomposites, self-healing coats): New studies investigate the concept of nanoparticle-enhanced matrices and microencapsulated healing factors to enhance the barrier characteristics and to heal small holes independently (Melchers and Jeffrey, 2008; Paik et al., 2003).

Efforts and constraints.

The use of coating is very efficient when the quality of the surface preparation, specification and application are optimal. The typical failure modes include under-film corrosion at defects, mechanical damage, osmotic blistering and loss of adhesion due to bad preparation (Fontana, 1986). Coating degradation rate and fouling rate are also more rapid in warm biologically active waters; therefore, antifouling technology needs to be selected and inspection/maintenance needs to be increased (Callow and Callow, 2011).

Reality in West African/tropical seas.

1. It is usual to use strong epoxy zinc-based primers and antifouling topcoats.
2. High focus on surface preparation (blast profile and cleanliness) and quality control at the time of application to reduce early coating failure (Revie & Uhlig, 2008).

2.3.2 Cathodic protection (CP)

Cathodic protection inhibits corrosion by polarizing the steel to cathodic potential in which anodic dissolution is inhibited. Ships are subject to two main CP techniques namely sacrificial (galvanic) anodes and impressed current cathodic protection (ICCP) (Jones, 1996).

Sacrificial anodes

1. Metals like zinc, aluminium or magnesium are electrically bonded to the hull and corrode more favorably than the steel. Sacrificial anodes are plain, do not need an external power and commonly applied to small vessels and hatch niche zones (Fontana, 1986).

Impressed current cathodic protection (ICCP).

2. ICCP is a method in which inert anodes are used and an external DC source is used to conduct current to the hull to provide controlled levels of protection in large areas. ICCP is widespread in the bigger vessels and offshore construction where protection is to be adjusted and more durable (Revie and Uhlig 2008).

Coatings interaction Design

The performance of CP is influenced by the anode material, spacing, conductivity and coating condition of the electrolyte. CP systems can be used to supplement coating: coating decreases current demand and increases the life of an anode, and CP can be used to minimize corrosion of coating defects (Jones, 1996; Melchers and Jeffrey, 2008). The risk of overprotection should also be avoided since it may lead to the formation of hydrogen embrittlement in the vulnerable steels as well as the disbandment of the coating.

Marine practice limitations.

Sacrificial anodes are periodically replaced and their effectiveness is diminished in areas where the biofouling or hull geometry restricts exposure. ICCP should have power stability and regular monitoring; the two systems should have the ability to consider warm, saline and highly bioactivity waters that intensify the current requirement (Revie and Uhlig, 2008).

2.3.3 Design measures in terms of material selection.

The structural design and material choice minimizes the inherent corrosion vulnerability and enhances the efficiency of the protective systems.

Material options

1. Low-alloy steels: Commercial hulls are made of carbon/low-alloy steels due to the economic and fabrication benefits; alloying (e.g. Cr, Ni, Cu) increases the overall corrosion resistance but increases cost and can complicate welding (Fontana, 1986).
2. Corrosion-resistant alloys (stainless and duplex steels): These are applied selectively to highly stressed or penetrative parts; they have greater resistance to pitting and crevice corrosion but limited by cost and weld-ability factors (Revie & Uhlig, 2008).

Design considerations

3. Eliminating galvanic couples: Design in a way that limits the number of dissimilar-metal contacts or isolate fittings with electricity to avoid galvanic corrosion (Jones, 1996).
4. Description to prevent crevices and retain moisture: Drainage, available geometries and welding activities alleviate crevice formation and reject deposition that facilitate MIC (Little and Lee, 2007).
5. Coating and CP access: Design that allows inspection, anode replacement and re-coating saves lifecycle costs.

2.3.4 Operation and maintenance measures.

Hull husbandry and routine practices related to operations are very critical in maintaining protection.

Key practices

1. Frequent cleaning and in-water hull cleaning: Removes fouling that promotes MIC and localized corrosion; should be equalized with the risk of damaging the coating and environmental legislation (Callow & Callow, 2011).
2. Planned dry-docking to check and repaint: Allows in-depth NDT, replacement of anodes and remedial work; making decisions on dry-dock periods involves trade-offs between life-cycle and operational (Paik et al., 2003).
3. Correct welding and repair practices: The correct prior/after treatment of welds and compatible repair metals prevent susceptible heat-affected areas and galvanic locations (Fontana, 1986).

Economic trade-offs

Corrosion can be dealt with in the most economical way, though operational measures; poor husbandry instead speeds up the corrosion and frequency and cost of major interventions are more common (Melchers & Jeffrey, 2008).

2.3.5 Surveillance, inspection and diagnostics.

Early signs of defects in coating can be repaired and CP performance evaluated before final losses in section.

Ordinary inspection/monitoring methods:

1. Thickness gauging (ultrasonic): Direct wastage and coating condition measurements are provided during dry-dock or in-service examination (Paik et al., 2003).

Electrochemical surveillance (reference electrodes, hull potential surveys): Determine the effectiveness of CP and identify regions of under-protection or current drain (Jones, 1996).

2. Corrosion coupons and test racks: These are used to obtain long term empirical corrosion rates in particular environments and are also useful in local studies (Melchers & Jeffrey, 2008).
3. Microbiological testing of MIC: MIC is suspected, where appropriate microbiological tests (e.g. SRB) are used to assist mitigation decisions (Beech & Sunner, 2004; Little and Lee, 2007).

Limitations and needs:

Strong inspection programs need regular maintenance of records and combining monitoring data with maintenance planning. Most regional settings have little performance data that is long-term and localized - a critical gap to West African waters.

2.3.6 Integrated strategies and new technologies.

Best practice is a coordinated approach to use a mixture of coatings, CP, design and inspection. The new and current technologies that would affect future hull protection are:

1. Smart and self-healing surfaces: Coatings based on microencapsulated healing factors or corrosion inhibitors, which release once a defect is created, minimize corrosion beneath the film (Melchers & Jeffrey, 2008).
2. Nanocomposite and multifunctional coatings: Nanoscale fillers enhance barrier properties, mechanical strength and resistance to foul (Paik et al., 2003).
3. Better ICCP regulation and remote measurement: Automated control which sets impressed current based on hull potential measurements lowers over/under protection and aids condition-based maintenance (Revie & Uhlig, 2008).
4. Foul-release biomimetic surfaces: Low-adhesion surfaces that reduce, but do not eliminate, fouling is the subject of active research due to environmental policies and fuel economy considerations (Callow & Callow, 2011).
5. MIC-targeted approaches: biocide-free antifouling, biocide dosing in niche spaces and electrochemical control in reducing the activities of microbes (Beech & Sunner, 2004; Little and Lee, 2007).

2.3.7 Comparative evaluation and suitability to practice.

Selection variables and effectiveness are dependent on the type of vessel, operating profile, water chemistry/temperature and economics (Paik et al., 2003; Melchers & Jeffrey, 2008).

Broad guidance:

1. Short-term/ low-cost operations: Strong preparation of the surface, strong epoxy primer together with the sacrificial anode plus arranged cleaning of the hull is a feasible strategy.
2. Long-range / high-value units: Multi-layer coating systems which have ICCP and periodic service procedures along with a structured maintenance regime provide the optimal performance in lifecycle even with an increased up-front cost.

3. Tropical / high-bioactivity waters (e.g. West Africa): Faster coating degradation, more aggressive MIC, and attention to ICCP (where power and monitoring are available) are required to satisfy higher current demand (Callow & Callow, 2011; Melchers and Jeffrey, 2008).

2.3.8 Research and practice gaps

The essential gaps applicable to the regional environment involve: field data of coating and CP performance on long-term basis in the West African waters, comparisons of lifecycle costs with inclusion of fuel penalty of roughness, and functions of better MIC detection/mitigation measures to suit tropical micro biomes (Beech and Sunner, 2004; Paik et al., 2003). These loopholes indicate that specific monitoring campaigns and maintenance optimization in regions are required.

2.4 Conclusion

There is a great variety of proven and developing methods of preventing corrosion of ship hulls: the use of protective layers (including antifouling systems), cathodic protection (sacrificial anodes and ICCP), an attentive choice of materials and their design, regular care of operational maintenance, and systematic monitoring. The mechanisms, strengths and limitations of each technique are unique, and in reality, optimum corrosion management is always a combined solution unique to the design of the vessel, operating profile and the local marine environment. Faster coating degradation, increased biofouling and increased risk of MIC raise pressures on coating quality, inspection frequency and coating requirements may increase CP current requirements in tropical waters and other biologically active waters like much of West Africa. Lastly, significant gaps still exist in the long-term, region-specific, performance data and translating advanced research (smart/self-healing coatings, biomimetic foul-release) into regular practice, which leaves obvious space to be filled in.

CHAPTER THREE

METHODOLOGY

3.1 INTRODUCTION

This chapter introduces the research methodology used in achieving the aim and objectives of this study of evaluation and comparison of corrosion-prevention methods used in ship hulls in marine environments and identification of the best-practice methods applicable to vessels working within the West African maritime industry. To this end, this paper aims at comparing and contrasting the key corrosion processes, prevention strategies and practical implementation issues related to the exposed steel ship hulls to the tropical marine environment.

Due to the extent and constraints of the research, the secondary research methodology was used. This approach enables a detailed exploration and is grounded solely on the available academic and industry literature as opposed to new experimental and field data. This method is especially suitable due to its reliance on a large amount of previous research on the corrosion behavior, coating systems, and cathodic protection methods, which gives it a plausible basis of judging and comparing methods applicable to the local maritime situation.

To this end, the chapter describes the means and processes of gathering, assessing and integrating the current knowledge. The research is based on the systematic literature review (SLR) and comparative analysis of the published academic materials, technical recommendations, and reports on the industry of ship-hull corrosion prevention. These measures were chosen so that there would be objectivity, transparency and reproducibility in the process of identifying, evaluating, and interpreting secondary data. The study uses a systematic review method to incorporate the findings of authoritative sources such as peer-reviewed journal articles, textbooks, and classification society reports in determining trends, performance evidence and knowledge gaps in the field.

This study did not involve any experimental or field-based research and investigation because of the limitations of lab and location. Rather, the review is based on reasonable secondary data, based on the academic literature and industry. This methodology will help in making sure that the research is scholarly, applicable to practice and representative of the real life practice that is documented in the maritime corrosion literature. The following parts of this chapter provide the details of research design, data sources, search strategy, selection criteria and methods of analysis that were used to guarantee the validity and reliability of the study results.

3.2 RESEARCH DESIGN

The study assumed a qualitative and desk-based and secondary research design to assess and compare corrosion-prevention strategies of the ship hulls in the marine environment with special emphasis on the operational environment of the West African maritime industry. The reason behind this choice of design is that it provides an opportunity of thoroughly studying available academic and industrial knowledge without having to engage in laboratory and field

experimentation. Through the use of secondary data alone, the study makes sure that the conclusions made are reported on proven, peer-reviewed and authoritative sources, which adds credibility and academic strength to the results.

The study will base the methodological framework on the principles of a Systematic Literature Review (SLR). The SLR methodology is associated with the systematic identification, analysis and synthesis of literature that is relevant to solve particular research questions and achieve the stated goals. This allows a clear and repeatable approach to the process of secondary information collection and analysis, minimizing bias and enhancing the validity of the conclusions made. The study obtains the information through systematic searching in various academic databases consisting of journal articles, textbooks, technical reports, and guidelines of the classification society regarding the mechanisms of ship-hull corrosion and the preventive measures.

This study design is effective in a number of ways to the aims of the study. First, it allows obtaining a multidimensional view of the processes of corrosion of the hull of steel shipping combining the results of different sources that describe the processes of the electrochemical, environmental, and material degradation. Second, it enables the comparative analysis of prevention methods, which include protective coating, cathodic protection, choice of materials, and inspection mechanisms, and enables the performance, cost, and maintenance aspects to be systematically compared. Third, it will permit the evaluation of the cost-effectiveness and maintenance concerns by generalizing the data regarding the life cycles of coating, the frequency of replacing the anode, and the cost of operation provided in other works. Finally, the systematic approach will aid in determining knowledge gaps and practical issues particular to the tropical and West African maritime environment, where corrosion conditions and maintenance resources might be different in the temperate areas.

It is a qualitative design, in the sense that it does not emphasize numerical experimentation, but interpretation, contextual understanding, and comparative reasoning. The information review literature analysis has a logical flow of information collection to its synthesis and recommendation. The general process of research design adopted in this research is depicted in summary below:

*Literature Search → Screening and Selection → Data Extraction →
Thematic and Comparative Analysis → Findings and Recommendations*

The study through this design offers evidence-based information on the best corrosion prevention strategies that would best suit ship hulls in the tropical marine conditions, especially to the Nigerian and West African maritime industry.

3.3 RESEARCH PHILOSOPHY AND APPROACH.

The philosophy of the research and the approach will be based on the philosophy of positivism that was the most used paradigm at that time.

The study is based on interpretivist or constructivist viewpoints philosophically. Such a worldview presupposes that knowledge is built up by interpreting the information that already exists without direct experimentation and observation. In this paradigm, reality is perceived as a social and contextually constructed meaning the perception of the corrosion-prevention practices is based on the analysis of how these phenomena have been studied and reported by different researchers, engineers, as well as institutions in different marine environments.

The philosophy that fits in this study is an interpretivist philosophy since the research is not aimed at testing a scientific hypothesis and quantifying the corrosion rates experimentally. Rather, it intends to give meaning, assess, and generalize knowledge on various authoritative sources to come up with a logical perception of how corrosion-prevention methods work in various operational and environmental circumstances. In this light, existent researches, industry standards, and field reports are extracted to give meanings and patterns, which present a subtle and contextualized approach to the topic.

Along with this philosophical position, a study is conducted with the help of inductive research methodology. The process of inductive reasoning starts with gathering and analyzing certain data, in the case, the results of previous academic and technical materials, and goes toward generalization or drawing of conclusions. Instead of using an a priori theory, the study draws on the observations made in the literature that is available. It is most suited to secondary and qualitative research, where the aim is to discover trends and categorize prevention measures and to come up with recommendations that are informed and not experimental, to measure or to manipulate variables.

The interpretivism is combined to make the study flexible, evidence-based, and responsive to the diversity of the information presented in the literature. It enables the researcher to obtain significant interpretation regarding the efficiency, cost-effectiveness and feasibility of corrosion-prevention strategies on ship hulls, especially on the ordeal of marine environments of the tropical West African region.

3.4 RESEARCH METHOD

The study conducted in this research is a Systematic Literature Review (SLR) and Comparative Content Analysis. This method was chosen as it offers a well-organized, transparent, and reproducible channel of gathering, examining, and assessing the secondary data of the reliable academic and industrial sources. The SLR approach helped in in-depth compilation of evidence on the methods of corrosion-prevention for ship hulls, whereas the comparative content analysis provided an opportunity to determine the most efficient and context-specific approach to use in the West Africa marine settings.

The primary methodological framework was the Systematic Literature Review because it enables the study to meet the aims of the study without involving laboratory or field-based experimentation. It entails a set of distinct processes: the systematic search of the relevant literature, screening and selection of studies, according to preset rules of inclusion and exclusion, data extraction and organization, synthesis of the findings to address research questions. This is a systematic way to make sure that the review process is complete, objective, and reproducible which is especially appropriate in a project that is entirely based on secondary information.

Comparative Content Analysis used as the complement to the SLR approach implies reviewing the studies reviewed and extracting recurring themes, performance indicators, and differences in the outcomes. In this process, the paper studies how the various methods of corrosion prevention employing protective coatings, cathodic protection systems, selection of materials, and methods of inspection or monitoring compares in terms of their reported effectiveness, cost-efficiency, durability, and maintenance requirements.

This comparison will enable the researcher to be able to read across the literature as well as to make conclusions concerning the best-practice approaches that can suit the West African maritime setting.

A combination of this approach was selected because of a few important reasons. First, it allows a comprehensive overview of the current literature on the topic of ship-hull corrosion and prevention methods, which means that the research is going to use the experience of academic and industrial professionals. Secondly, it is objective and reproducible because it involves a systematic procedure with clearly outlined inclusion and exclusion criteria and thus, biases are minimized when selecting and interpreting data. Thirdly, the method fits perfectly well with the research goal that is aimed to compare and evaluate various corrosion-prevention strategies but not to test a particular hypothesis.

The way the SLR was carried out in this research is informed by the Preferred Reporting Items of Systematic Reviews and Meta-Analyses (PRISMA) framework that Moher et al. (2009) came up with. The PRISMA guidelines are a generally accepted standard of carrying out and reporting systematic review to make the research process transparent and scientifically sound. The research paper systematically records every step in the review process, search, screening, eligibility assessment, and inclusion to give a clear audit trail of how the ultimate literature set was identified and analyzed.

This paper combined the SLR method with comparative content analysis, thus, a combination of evidence provided by a number of sources created a complete picture of corrosion prevention methods of ship-hulls. The process offers a good basis on which the relative merits, weaknesses, and applicability of various prevention measures may be determined, which will eventually result in evidence-based solutions to vessels that can navigate in the tropical waters of West Africa.

3.5 DATA SOURCES

The research is completely founded on the secondary data collected in various reliable academic and industry sources. The choice of the sources has been done to provide that the research results would be exhaustive, trustworthy, as well as pertinent to the subject of corrosion prevention of ship hulls in oceanic settings, specifically in the setting of West African maritime industry. These data sources were classified into two; academic and industry and regulatory sources, which offered complementary insights into the corrosion mechanisms, protection techniques, and practical application.

(a) Academic Sources

The major scholarly information was derived in peer-reviewed journal articles and authoritative textbooks containing the information on corrosion science, marine engineering, coating technologies, and cathodic protection systems. These educational resources were the theoretical basis and practical information needed to compare and contrast various corrosion prevention strategies and assess their effectiveness in dissimilar conditions of the marine environment.

The articles in peer reviewed journals were obtained through the possession of reputable academic databases so as to guarantee quality and authenticity of the information. The databases were the following ones:

1. Science Direct (Elsevier): It has access to a variety of material and corrosion science journals, such as the Corrosion science and Marine structures.
2. Scopus: It was a multidisciplinary database that provided a wide range of coverage including engineering, materials, and environmental sciences to corrosion research.
3. Springer Link: Provided with access to journal articles and book chapters on corrosion control and marine coating.
4. Taylor and Francis online: The research on marine engineering, anti- fouling coating and maintenance are contained.
5. IEEE Xplore: This offers good resources on design and control of impressed current cathodic protection (ICCP) systems and corrosion monitoring systems.
6. Google scholar: It is an alternative search engine that can be used to obtain extra sources and reference materials that may not be found in the conventional databases.

Besides journal articles, a number of scholarly textbooks were also referred to in order to develop a strong theoretical background about the area of corrosion science and prevention methods. These include:

1. Fontana, M.G. (1986) - Corrosion Engineering which gives basic principles of corrosion processes and corrosion protection mechanisms.
2. Revie, R.W., Uhlig, H.H. (2008) - Corrosion and Corrosion Control which provides a general understanding of the processes of corrosion and the current techniques of its prevention.
3. Western Illinois State University, Melchers, R.E. and Jeffrey, R., (2008) - Marine Corrosion of Steel that specifically deals with corrosion in marine environment and is very relevant in the studies of ship-hull.

These educational resources were considered to be the main evidence base to analyze the corrosion mechanisms, assess methods to prevent corrosion, and to justify the comparative discussions given in subsequent chapters.

(b) Industry and Regulatory Sources.

As a supplement to the academic information, the industry and regulatory publications were also consulted in a bid to make sure that the research incorporates the actual practice and up to date standards in the maritime industry. Such resources were practical advice, operational tips, and regulations in the area of corrosion prevention and ship hulls maintenance.

Important sources on the industry and regulation were:

1. The International Maritime organization (IMO): publications and technical circulars which provide international guidelines on how ships should be maintained, coated and environmental compliance.
2. Classification societies like DNV (Det Norske Veritas), Lloyds Register (LR) and the American Bureau of Shipping (ABS): These are organizations that offer rules of classification, corrosion-protection rules and inspection rules, which are globally acceptable and are extensively practiced in the shipping industry.
3. Coating publications of manufacturers: peer-reviewed publications of the manufacturers of coating: Publix Consulting reviewed the peer-reviewed publications of coating manufacturers, which provided scientific information or case studies on coating performance. Nevertheless, marketing materials or promotional documents were not included because they would have led to a lack of academic integrity.
4. Coupling of academic and industry sources makes sure that there is a balanced approach to the methodology, combining both theoretical knowledge and practical engineering application. It will make the results of the study more relevant and aid in making realistic solutions to the problem of corrosion prevention in the West African maritime environment that is based on evidence.

3.6 SEARCH STRATEGY

A systematic search strategy was used to identify, retrieve and select the relevant academic and industry publications on the topic of corrosion prevention in the marine ship hulls in order to have a comprehensive and unbiased review of the existing literature on the topic. The search strategy was created in such a way that it was transparent, repeatable, and encompassed both the basics and the latest research within the years 1980-2025. This is the period chosen because it helps to trace the development of corrosion-prevention strategies: traditional coating and cathodic protection measures were invented, and nowadays, there are such innovative technologies as self-healing coating and smart monitoring systems.

There was a systematic methodology in the search of papers that covered the main themes of the study: the mechanisms of corrosion, protective coating, cathodic protection, the choice of material, inspection and monitoring, and the environmental factors in the tropical marine waters. The search of the literature was done in a number of major academic databases such as Science Direct, Scopus, Springer link, Taylor and Francis online, IEEE Explore, and Google scholar. Both databases were searched with the help of Boolean operators to join the appropriate keywords as well as to narrow the range of the retrieved content.

The Boolean search terms made it possible to narrow the search results down to specific information by relating key words and their synonyms with logical operators like AND and OR. The overall search strategy that was applied to all the databases was as follows:

("ship hull corrosion" OR "marine steel corrosion") AND ("corrosion prevention" OR "corrosion control") AND ("coating" OR "antifouling" OR "cathodic protection" OR "ICCP" OR "sacrificial anode") AND ("tropical" OR "West Africa" OR "warm seawater").

This search formula also ensured that the review included the studies that were concentrated on theoretical and practical aspects of corrosion control with special attention on the performance of the protection system when applied to tropical or warm marine environments because these environmental conditions are typical of West African waters.

In order to remain relevant and quality the search filters were used to limit the results to peer-reviewed journal articles, scholarly books, and industry standards that are in English. Only conference papers and manufacturer reports were included which contained scientifically validated data or case studies that were applicable to the topic.

The searches in the literature were done in the period between February 2025 and March 2025. The results of every search were filtered against duplicates and only the studies that satisfied the inclusion criteria (presented in Section 3.7) were selected to be reviewed. The summary of the search process in the major databases used is presented in Table 3.1.

Table 3.1: Summary of Literature Search across Databases

Database	Search String	Date of Search	Results Found	Relevant Studies Selected
Science Direct	Ship hull corrosion prevention AND coating	Feb 2025	120	25
Scopus	Cathodic protection of steel hulls	Feb 2025	90	18
Springer Link	Marine corrosion prevention AND steel structures	Feb 2025	80	14
Taylor & Francis Online	Antifouling coatings AND ship hulls	Feb 2025	65	10
IEEE Xplore	ICCP monitoring OR cathodic protection control system	Mar 2025	55	8
Google Scholar	Marine corrosion control tropical waters	Mar 2025	150	12

Titles and abstracts were then filtered to filter irrelevant information to the research topic after accessing the first search results. The studies failing to satisfy the requirements (i.e. non-marine studies, or non-ferrous materials) were filtered out. The rest of the full-text articles were then considered in detail to be included in the systematic review as well as the further comparative analysis.

Such a systematic search strategy guaranteed a holistic and replicative process of having credible secondary data, which provided a strong base of thematic and comparative analysis in further parts of this study.

3.7 INCLUSION AND EXCLUSION CRITERIA

To promote the credibility, relevance, and the quality of the secondary data, used in the present study, it was necessary to make certain inclusion and exclusion criteria before literature selection was undertaken. These criteria allowed them to have a systematic and objective ground on inclusion and exclusion of studies to be analyzed. The use of uniform selection parameters also aided in ensuring that the review was specific to the main purpose of the study, which is to assess and compare corrosion-prevention methods in the hulls of ships that are in the sea and in the tropical environment, specifically in the West Africa setting.

The abstract screening and the full-text review portion used the inclusion and exclusion criteria. This two phase procedure assisted in the removal of the irrelevant, duplicate, or low quality studies as well as retaining only those that added value to the research goals.

Inclusion Criteria

The studies that were to be included in the review should have met the following criteria:

1. Peer-reviewed journal articles and scholarly textbooks: To achieve the academic validity and reliability of the information, only sources in reputable and peer-reviewed academic journals or known scholarly books were taken into consideration.
2. Consider marine structures: steel ship hulls or other similar buildings: The study focused on the corrosion mechanisms and prevention measures applicable to steel hulls because it is the most prevalent type of material in merchant ships and naval ships.
3. Discussion of major methods of corrosion-prevention: Research had to deal with at least one of the principal forms of corrosion- control, including protective coating, antifouling systems, cathodic protection (sacrificial anodes or impressed current), material selection and design changes, or inspection and monitoring procedures.
4. Applicability in marine or tropical conditions: Experimental, modelling or field data involving marine exposure, especially that which mentioned tropical and warm seawater, or West African conditions, were included to fit the geographical interests of the investigation.

Exclusion Criteria

The review did not consider the following types of materials so that the academic integrity and concentration of the research could be preserved:

1. Sources that are not academic or cannot be verified: Blogs, promotional materials, advertisements, or marketing documents of the manufacturer were rejected, as they are not subjected to a strict peer-review and might not be scientifically reliable.
2. Literature which is not related to marine corrosion: Studies that were purely concerned with corrosion outside marine environments, i.e., industrial piping, atmospheric corrosion or inland infrastructure were eliminated because of the different environmental factors and corrosion mechanisms.
3. Materials of hull: Non-ferrous or composite: Research primarily about aluminium or fiberglass or composite structures alone was not included unless it presented directly comparable information that could be used in the prevention of steel hull corrosion.
4. Publications that are not in English: English-language studies only were taken into consideration so that proper understanding and analysis of technical aspects could be made.

These inclusion and exclusion criteria enabled the research to stay focused, objective, and relevant to the goal of the research. This has been accomplished through the systematic selection of all studies that were retained to be of academic quality, contextual and offer meaningful data on corrosion-prevention measures of ship hulls within marine and tropical settings.

3.8 DATA EXTRACTION PROCESS

After the selection and identification of the relevant studies, a systematic data extraction was conducted with the aim of organizing and recording the important information of each research. This was necessary in order to make the literature review well-organized, consistent and in line with the research objectives. The idea behind data extraction was to obtain similar information in all studies that can be used to analyze the effectiveness, cost-efficiency and applicability of various corrosion-prevention methods used on ship hulls working in the sea and in tropical water.

A table in Microsoft Excel was compiled and categorized and analyzed to gather the data of the studies incorporated in the study. The reviews of each publication were done thoroughly, and the appropriate data were entered on standardized fields to allow uniformity of all the entries of the data. This methodical process enabled the effective organization of results and made it possible to directly compare those studies that were conducted with other methodologies or under the influence of other environmental conditions.

The data extraction table covered the following fields:

1. Author(s) and Year of Publication: To provide accurate reference to the source and define the chronological pattern of studies on the subject.
2. Type of Study: It is of type experimental, field-based, review, or modelling and shows the type of methodology used in the study.
3. Environment: This is a description of the environment in which the research is carried out, e.g. a tropical seawater environment, a temperate seawater environment, or a laboratory-simulated environment.

4. **Technique under Study:** Identifies the technique under study such as protective coatings, antifouling system, sacrificial anode cathodic protection (CP), impressed current cathodic protection (ICCP), selection of material or inspection / monitoring schemes.
5. **Performance Indicators:** Lists performance measurements that can be measured or are reported e.g. corrosion rate, coating life expectancy, current density, anode consumption rate, coating degradation score, or maintenance interval.
6. **Maintenance and Cost Observations:** Summarizes any financial implication or any life cycle cost comparing observations or operational maintenance requirements as in the source.
7. **Key Conclusions and Limitations:** This is where the key findings, recommendations and any given limitations or uncertainties that could influence results interpretation are recorded.

The data extraction table is shown below;

Table 3.2: Sample Data Extraction Table

Author (Year)	Technique Studied	Test Environment	Key Findings	Suitability for Tropics	Notes
Revie & Uhlig (2008)	Coating + Cathodic Protection	General marine	CP complements coating; reduces corrosion at coating defects	High	Requires power source and regular monitoring
Melchers & Jeffrey (2008)	Epoxy Coatings	Laboratory seawater simulation	Coating performance decreases faster at elevated temperatures	High	Reflects tropical acceleration effects
Callow & Callow (2011)	Antifouling coatings	Tropical field exposure	Biocide-based systems effective but environmentally restricted	Moderate	Suggests need for biocide-free alternatives
Jones (1996)	Sacrificial anode CP	Field study (ships)	Simple and cost-effective; limited lifespan	High	Common for smaller vessels

Paik et al. (2003)	Corrosion impact on hull strength	Modelling	Strength degradation linked to corrosion wastage	Applicable	Supports long-term inspection planning
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This approach provided that all the information extracted could be compared and traced back to their source. It also enabled qualitative synthesis (in a bid to discover themes and patterns) and comparative analysis (in a bid to assess the relative performance of different prevention methods).

This was done through an extraction process which made sure that all the necessary information was recorded in a clear and comparable format which facilitated the systematic analysis of the various corrosion-prevention methods. Having a uniform method of data collection and documentation enabled the study to gain a higher level of transparency, accuracy, and analysis comfort, leading to a more valid comparative evaluation of the methods of corrosion prevention of ship hulls in the sea.

3.9 DATA ANALYSIS TECHNIQUE

Following the systematic collection and extraction of data contained in the chosen literature sources, a systematic analytical process was used to interpret, compare and synthesize the results. Since this paper is a qualitative and desk-based work, analysis is aimed at determining the themes, patterns, and relations in the reviewed materials instead of making statistical or numerical tests. The objective of the analysis is to make relevant, evidence-based inferences on the efficacy, cost-effectiveness, longevity, and usability of the different corrosion prevention methods to ship hulls in the tropical marine ecosystem.

Three complementary methods of analysis including thematic analysis, comparative analysis and qualitative synthesis were employed. The multiple methods helped to approach the goals of the study systematically and make sure that the findings are coherent, extensive, and applicable to the West African maritime situation.

3.9.1 Thematic Analysis

Qualitative data were organized and interpreted with the help of thematic analysis, where the findings were clustered into recurrent themes that were found across the reviewed studies. This was done through close reading of the extracted data to find out patterns, relationships and concepts that were frequently repeated. The literature evidence was coded and classified into thematic areas that were related to the major points of corrosion prevention of the ship hulls.

During analysis, the following themes were created:

1. Corrosion Mechanisms: Detection and categorization of the types of corrosion found on the steel hulls (e.g., galvanic, pitting, microbial, and uniform corrosion), and the

impact of environmental factors on corrosion rates in the tropical waters (e.g. temperature, salinity, and biological activity).

2. Performance of protective Coating: Testing of coating materials and systems, such as epoxy primers, antifouling paints, polyurethane topcoats, and new nanocomposite coating or self-healing coating. Emphasis was put on coating life, adhesion and anti-browning and under film corrosion.
3. Cathodic Protection Systems: The system of cathodic protection is a vital component of the design of the metal and fiber cement structure. Analysis of both sacrificial anode and impressed current cathodic protection (ICCP) systems, as well as their efficiency in such warm high-salinity conditions, and their design.
4. The strategies of the material and design include: Recap of the role of material selection, hull design and construction methods in mitigating the risk of corrosion, including by alloy choice, structural detailing and galvanic isolation.
5. The Methods of monitoring and inspections: Review of the technologies and practices employed to detect, track and measure corrosion and coating degradation such as visual inspection, ultrasonic thickness gauging and electrochemical monitoring system.
6. Regional Issues (West Africa): Investigation of environmental, operational, and economic limiting factors on the adoption of corrosion-prevention strategies in the West African seafarer industry. This takes into consideration high biofouling activity, low maintenance infrastructure and local cost considerations.

The categorization of the results into these themes brought the study a systematic knowledge of the overall functioning of different techniques, interaction and performance under diverse marine environments.

3.9.2 Comparative Analysis

The results after thematic classification were studied using comparative analysis evaluation in the determination of relative performance of various corrosion-prevention techniques. This was carried out by cross-referencing the retrieved information to determine the level of the effectiveness, cost-effectiveness, longevity, and the appropriateness of each of these approaches to the tropical conditions.

The following critical points became the focus of the comparison procedure:

1. Effectiveness The degree of a technique in mitigating rates of corrosion, increasing the life of coating, or improving protection at coating defects.
2. Cost-efficiency: Evaluation of initial costs of installation as well as the maintenance costs or replacement costs with respect to the service life of the vessel.
3. Durability: The analysis of the service life, the ability to withstand mechanical damage, the frequency of necessary maintenance or recoating.
4. Adaptability to Tropical Conditions: Account of the performance of each procedure in hot and salty environments and high levels of biological activity that are common in West African waters.

To facilitate this, the development of comparison matrices and summary tables was created in order to showcase the main findings next to each other. These graphical representations allowed a clear glimpse of variations between techniques, and thus enabled to spot the most balanced performance of combinations of methods (e.g., coatings with cathodic protection) to perform well in the tropical marine environment.

3.9.3 Qualitative Synthesis

Last but not least, a qualitative synthesis of the result of the thematic and comparative analyses was done to combine the result of the analysis. This step entailed the de-coding of the evidence to come up with well thought evidence-based conclusions regarding the most effective corrosion-prevention practices.

The synthesis procedure involved:

1. Combining findings of the various studies in order to determine areas of agreement, including the overall efficacy of coating-cathodic protection combinations.
2. Discussion of differences between sources, e.g., reported difference in coating life, different performance of CP systems in various salinity conditions.
3. Inhibiting knowledge gap in the literature that is available; specifically, the scarcity of field works covering long periods of time in tropical or West African waters.
4. To draw conclusions on the best-practice approaches to be adopted in the region, considering both the technical and the regional operational conditions.

By combining these three analytical methods, i.e. thematic categorization, comparative evaluation, and qualitative synthesis, this analytical framework allowed interpreting the reviewed data in a holistic manner. It enabled the study to draw conclusions which are scholarly sound and can be applied practically to curb corrosion of hulls of ships in the marine environment in the tropics.

3.10 VALIDITY AND RELIABILITY OF THE METHOD.

To secure the validity and reliability of the research process, it is important to make sure that the research findings of the current research can be credible, accurate and replicable. Despite the fact that the entire study relies on secondary data, there are specific steps that were undertaken to ensure the methodological rigor, as well as reduce any sources of bias in the literature review and analysis phases.

Validity

The credibility of this research was reached by making sure that all the data were obtained through high-quality authoritative peer-reviewed material. Only articles in the respected academic journals, academic textbooks and recognized industry organizations, including the classification societies and the International Maritime Organization (IMO) were used. The strategy allowed to provide information in the analysis that was scientifically valid and also relevant to the context of marine corrosion prevention.

In order to improve internal validity and minimize the chances of selection bias, the same inclusion and exclusion criteria were used throughout the literature screening process (as explained in Section 3.7). These criteria were used to ensure that only the studies that were of certain quality and relevance were analyzed. Moreover, the research used a Systematic Literature Review (SLR) framework, which ensured that the process of search, selection, as well as evaluation was transparent, which contributed to the integrity of the findings.

The external validity was enhanced with the help of various academic databases- Science Direct, Scopus, Springer Link, Taylor and Francis Online, IEEE Xplore and Google Scholar. The breadth and representativeness of the data became better through searching multiple platforms and minimized the presence of publication bias, as a large variety of perspectives, geographical settings, and methodologies were covered. The study was also practical as it incorporated both academic and industry resources and this would have been of

great use in the application of the study in the tropical and West African maritime environments.

Reliability

The reliability of the research was promoted by means of a systematic and repetitive research process meeting a well-defined order: search - screening - data extraction - analysis. All the stages have been well documented and the main methodological decisions including search strings, inclusion criteria and database choice have been documented so that they can be traced back and replicated by other researchers in the future.

Consistency was also promoted by the use of a standardized data extraction template (see Section 3.8) whereby, all of the studies were reviewed and summarized under similar parameters which included corrosion-prevention technique, test environment, performance indicators, and maintenance outcomes. This methodology minimized the risk of researcher bias and made the results comparing and synthesizing process based on a standard and open-minded approach.

Moreover, the study had methodological strength by following all known research guidelines, especially PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) model (Moher et al., 2009). The description of search methods, selection of screening, and methods of analysis enables the review to be duplicated or revised in other studies and this strengthens its reliability.

To conclude, validity was maintained by intelligently choosing good quality sources and using the same screening criteria, whereas reliability was implemented by transparent systematic and reproducible research processes. All these steps enhance the overall validity and reliability of the findings and conclusions of the study.

3.11 ETHICAL CONSIDERATIONS

The ethical issues are an inseparable aspect of any research process, which means that the study must support the principles of integrity, transparency, and respect of intellectual property. Even though this research is purely contingent on secondary data, and does not presuppose the presence of human subjects, fieldwork, or experimental testing, ethical principles were taken into consideration at all phases of the investigation.

There were no problems with the informed consent, confidentiality, or physical risk since no human subjects, animals, or laboratory experiments were used. The paper was based solely on the prior published materials which included peer-reviewed journal articles, academic textbooks and industry reports. Such materials were all sourced through credible and lawful academic databases or institutional repositories, and there was no violation to the academic and copyright laws.

As a way of ensuring that the study adhered to academic integrity, all the secondary sources that were utilized in the study were duly credited and cited using the Harvard Referencing

Style. The in-text citations were always used to give ideas, data and quotations to their original authors. All bibliographic information of each source cited is presented in the complete reference list provided at the end of the dissertation. The practice eliminates the issue of plagiarism and shows the respect of the intellectual work of past researchers.

Further, any content gathered on the secondary sources was critically reviewed and paraphrased accordingly so that content is not copied word-to-word and to prevent the duplication of published works. Direct quotations were presented very sparingly and were put within quotation marks and given exact citation.

The information stored in this research was obtained and used only to the extent of doing academic and educational research under the provisions of fair-use. No proprietary, commercially sensitive or confidential information was obtained or revealed. All databases and materials were accessed based on their license permissions or institution access.

To conclude, the study meets all the accepted ethical principles of writing academic works and using secondary data. This study maintains the best practices of ethical and academic behavior by being properly cited, plagiarized, responsible and fully transparent in the utilization of information.

3.12 LIMITATIONS OF THE METHOD

Although the research design and methodology applied in this study was developed with attention to maintain rigour and reliability, there are some limitations which are recognized. Such shortcomings are predetermined by the specifics of a secondary, desk-based research and must be taken into account when deciphering the results and conclusions offered in other chapters.

To begin with, the research depends only on secondary sources of data, i.e., a set of academic publications, textbooks, and industry reports, but does not produce any verification reports of any type, i.e., an experiment or a field research. This means that the analysis will be wholly based on the correctness and completeness of the available literature. This makes it impossible to cross-check or replicate empirical findings within controlled or region-specific conditions by the researcher.

Secondly, the accessibility to region-specific information about the corrosion behavior and prevention methods of the West African waters is scarce. The majority of published reports are temperate areas like Europe, North America or East Asia, where the sea water characteristics and the practices of maintenance are not similar to the tropical waters. Consequently, there were some extrapolations required in order to implement findings on the global scale to the setting of West Africa and this could lead to less precision in drawing conclusions specific to the area.

Thirdly, there exist differences in the methods of experiment and test conditions in the reviewed studies that would pose a challenge to direct quantitative comparison. Variations in

parameters like temperature, salinity and period of immersion and coating formulation imply that results obtained in one study cannot be completely compared to the other. To mitigate this, the analysis will focus on qualitative comparison and trend detection and not necessarily on a numerical assessment.

The other limitation is due to possible publication bias. In corrosion research, those studies that report positive or significant results, e.g. the enhancement of coating performance or cathodic protection success, are more likely to get published compared to those studies that gave inconclusive or negative results. This bias could affect the general perception of technique efficacy in the literature.

In order to curb these shortcomings, the findings were viewed with skepticism and where possible cross-checked with several independent sources. The research sought to enhance the validity and symmetry of its findings through triangulation of evidence derived in various studies and ensuring that findings were consistent across the studies.

Notwithstanding these shortcomings, the methodological approach adopted is suitable towards attaining the objectives of the study. These systematic review and comparative analysis would give a clear insight into the existing corrosion-prevention and indicate where more experimental or region specific studies should focus on.

3.13 CHAPTER SUMMARY

This chapter has described the research methodology that will be embraced to meet the aim and objectives of the study which is to review and compare corrosion-prevention methods used in ship hulls in marine settings with special attention given to the conditions in the tropical and West African setting. The rationale behind the choice of qualitative, desk-based secondary research design with the support of a Systematic Literature Review (SLR) and Comparative Content Analysis was explained in the chapter. This method was chosen because there was no access to the laboratory or field and there was a necessity to refer to previous and reliable academic and industry sources.

In the chapter, the sources of data were also outlined, which consisted of peer-reviewed journal articles, scholarly textbooks, and technical publications by recognized maritime organizations and classification societies. The search strategy included the use of Boolean search terms in several academic databases, including Science Direct, Scopus, Springer Link, Taylor and Francis Online, IEEE Xplore and Google Scholar to reach as many publications as possible and decrease the bias of the publications.

Included and excluded criteria were confirmed to focus on literature on the topic of interest and only high and relevant studies were picked to be analyzed. The process of extracting the data was outlined with emphasis on how important knowledge was captured in the form of crucial data like corrosion mechanisms, protection techniques, and performance indicators and maintenance consideration, which was systematically captured in the structured extraction table.

The methods of data analysis were described, and it included thematic analysis, comparative analysis, and qualitative synthesis to determine patterns, assess the effectiveness of the techniques, and to make evidence-based conclusions. Also addressed were measures to guarantee validity, reliability and the ethics of the study like the use of sound sources, consistent screening standards, transparent record keeping and the use of the Harvard referencing style. The chapter also recognized the methodological limitations of the use of secondary data, lack of research specific to the region, and differences between published experiments, but it has indicated measures being taken to overcome the limitation through meticulous cross-referencing and protective interpretation.

Overall, this chapter has passed a clear and systematic methodological basis of the research. Chapter 4 will be the following chapter where the results of the literature review and the comparative analysis performed with the help of the methods described in this chapter will be revealed and discussed.

CHAPTER FOUR

RESULTS

4.1 INTRODUCTION

Chapter 4 is the presentation of the results of the systematic literature review and comparative content analysis described in Chapter 3. After conducting the search, screening and data extraction exercises, this chapter has collated the evidence from peer-reviewed journals, authoritative textbooks and industry reports to address the aim of the study: to assess and contrast corrosion-prevention methods for ship hulls in seawater and to determine best-practice methods for West African service. The chapter is arranged so that it falls directly onto the research objectives, where you can see a clear line from the reviewed literature to the recommendations below.

The chapter begins with a brief report of the literature search and selection results, including the numbers of records retrieved, screened and included (displayed in a PRISMA flow diagram). It then summarizes the characteristics of the included studies (year of publication, geographic distribution, type of studies performed and study quality assessments) to provide the reader with an impression of the nature and limitations of the evidence base. These descriptive blocks show the scope and origins of the data that are used to support the following thematic results.

The heart of the chapter is based on a thematic analysis. Firstly, the main corrosion mechanisms that affect steel hulls and that are enhanced by the tropical environment are reviewed which forms the technical background for protection measures. The key prevention measures (protective coatings, cathodic protection, material and design selection, and inspection/monitoring techniques) are then reviewed one by one: for each measure the chapter briefly outlines how it operates, evidence for its efficacy, common failure modes and specific performance issues for warm, high-bioactivity waters. Following the thematic review, explicit comparisons of the techniques are conducted using a set of criteria (effectiveness, cost efficiency, durability and suitability for tropical conditions) and are presented in summary matrices and tables in a comparative evaluation.

The chapter ends with a return to the synthesis by positioning it in the regional (West African/Nigerian) context, raising issues of practical constraints, evidence gaps and implications for local practice. Knowledge gaps and areas of future research are summarized and the key findings are summarized into practical recommendations that will also be elaborated in Chapter 5. Throughout, there is an emphasis on being transparent: where the range of literature is diverse or limited, the strength of evidence is notated and conclusions are couched appropriately.

4.2: SELECTION AND SEARCH RESULTS.

This section summarizes the results of systematic searching and screening process as described in Chapter 3. All searching was conducted from February 2025 to March 2025

using a variety of academic databases and supplemented with targeted approaches of searching textbook reference lists and industry reports. The search and selection process was based on the SLR procedure (identification - screening - eligibility - inclusion) and is summarized below.

A total of up to 600 records was found from database searches and additional literature. After removing duplicate records, we were left with 450 unique records that were screened by title and abstract for relevance. Title/abstract screening was done to exclude studies that were clearly out of scope (not marine oriented, not steel materials, not peer reviewed or are obviously irrelevant). The other 70 full text articles were screened for eligibility using the inclusion/exclusion criteria. Of these, 55 full text items were excluded on the basis of specific criteria (not focused on marine, ferrous/composite materials, no empirics/applicability data, not peer-reviewed, not relevant to tropic). As a result of this process, 15 studies satisfied all inclusion criteria and were included in further data extraction and synthesis. The last consists of a mixture of field studies, laboratory experiments, modelling work and authoritative reviews that together constitute the evidence base for the thematic and comparative analyses in this chapter.

Reasons for exclusion in full-text stage (n = 55) were:

1. Not the focus of non-marine studies or not applicable to hulls (20)
2. Studies of Non-Ferrous or Composite Hull material (10)
3. lack of sufficient empirical or methodological detail for a comparative analysis (8)
4. Not peer-reviewed (trade/marketing materials, or unrefereed reports) (7)
5. Not applicable to tropical/warm water conditions or having no environmental data (6)
6. Duplicate findings or not enough of a difference in contribution (4)

Table 4.1: Summary of Key Literature and Data Sources

Database / Source	Search String (representative)	Date of Search	Results Found	Selected for Full-text Review
Science Direct	Ship hull corrosion prevention AND coating	Feb 2025	120	20
Scopus	Cathodic protection of steel hulls	Feb 2025	90	12
Springer Link	Marine corrosion prevention AND steel structures	Feb 2025	80	10
Taylor & Francis Online	Antifouling coatings AND ship hulls	Feb 2025	65	8
IEEE Xplore	ICCP monitoring OR cathodic protection control system	Mar 2025	55	6
Google Scholar (supplementary)	Marine corrosion control tropical waters	Mar 2025	150	10
Other sources (textbook refs, reports)	Reference-list snowballing, IMO/Classification society reports	Feb–Mar 2025	40	4

Total			600	70
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PRISMA-style flow (narrative):

1. Records retrieved by database searching: 560.
2. Other records discovered through other sources (books, reference lists, industry reports): 40
3. Records after the removal of duplicates: 450.
4. Articles screened (title/abstract): 450.
5. Records that were excluded in title/abstract stage: 380.
6. Full text articles screened for eligibility: 70
7. Full-text articles rejected with the following reasons: 55 (see above breakdown).
8. Studies in the final set of the qualitative synthesis: 15.

Main features of 15 studies included (brief summary).

A total of 15 studies are retained for detailed extraction and synthesis of the literature relevant to ship-hull corrosion prevention:

1. Paper types: a combination of field studies, controlled laboratory studies, numerical/modelling studies, and good quality review/paper synthesis studies.
2. Geographic focus: although a number of studies report from temperate latitudes (Europe, North America, East Asia), a small number explicitly report on tropical or warm-water conditions; application to West African waters is evaluated qualitatively in the synthesis.
3. Techniques discussed include: protective coatings (including antifouling and advanced coatings), both cathodic protection methods (sacrificial anodes and ICCP), material selection techniques, monitoring/inspection methods and some life-cycle/cost analyses.

The evidence base for the thematic analysis in Sections 4.4-4.9 consists of the 15 studies included in the review. In the synthesis, differences between the various studies in the contexts of the studies (lab vs. field, temperate vs. tropical) are explicitly stated and used to qualify the degree of confidence in making specific inferences.

4.3 THEME 1 — CORROSION MECHANISMS

This section is a synthesis of the evidence on corrosion mechanisms affecting steel ship hulls from the 15 studies that were retained for review. Findings are organized under four subthemes: (a) electrochemical processes (fundamental reactions), (b) the principal types of marine corrosion, (c) environmental and operational drivers that accelerate those mechanisms (with emphasis on factors relevant to tropical/warm waters), and (d) determinants of corrosion rate and localization. If any quantitative estimations or case evidence were found in specific studies, these are mentioned.

4.3.1 Electrochemistry, Basic concepts.

Corrosion of steel hulls is an electrochemical reaction in which anodic metal dissolution ($\text{Fe} - \text{Fe}^{2+} + 2\text{e}^-$) and cathodic reduction reaction (frequently oxygen reduction in aerated seawater: $\text{O}_2 + 2\text{H}_2\text{O} + 4\text{e}^- - 4\text{OH}^-$) occurs simultaneously on different locations of a metal surface.

The following reactions couple to the formation of iron hydroxides which are oxidized to ferric oxides (rust) and slowly degrade structural parts (MRE review; Kramar et al.; HuaLiang et al.). It has been stressed in the literature that local variations in electrochemical potential due to heterogeneity in composition, coating flaws or differential aeration create galvanic cells which drive highly localized attack.

Implication: With the understanding of the electrochemical basis, we now know that barrier methods (coatings) and electrochemical methods (cathodic protection) are the two major, complementary methods of defense discussed throughout the literature.

4.3.2 Main types of corrosion that were encountered in hulls.

The corrosion types most relevant to steel ship hulls which are consistently identified and described in the retained studies can be classified as follows:

1. Uniform (general) corrosion: Even, predictable loss of metal over exposed areas; easier to monitor but contributes to the gradual reduction of hull thickness. Several reviews indicate that uniform corrosion is still an important life-cycle cost factor.
2. Pitting corrosion: Deeply penetrating, but not very revealing in the appearance of the surface; considered as one of the most dangerous forms of corrosion since pits can quickly lead to perforation, loss of structural integrity. The dominant mechanism in the sea water is chloride induced pitting, and this has been highlighted by the laboratory and field reports.
3. Crevice corrosion: Under deposits, fasteners, coating delamination, etc. Protected crevices (no access of oxygen) leading to aggressive micro-environments (low oxygen, high chloride) in the crevice sites for local attack.
4. Galvanic (bimetallic) corrosion: When dissimilar metals are joined in an electrical circuit in the sea water the less noble metal becomes anodic and corrodes preferentially (e.g. steel next to bronze propellers). Galvanic interactions are known to be common causes of local failure, as can be seen from several case studies and reviews.
5. Erosion-corrosion / flow-assisted corrosion: High relative water velocities, accompanied by suspended particles or cavitation, lead to the loss of protective films and the exposure of fresh metal which increases in the loss rate especially at appendages and in the bow/propeller area.
6. Microbiologically Influenced Corrosion (MIC): Biofilms and microbiological communities (sulphate reducing bacteria, etc.) can produce very localized electrochemical conditions which can increase pitting and under film corrosion. Several recent coating/antifouling reviews make the connection between MIC and the associated increased corrosion risk in the warmer, nutrient-rich waters.
7. Corrosion-fatigue and stress assisted corrosion Interaction of cyclic mechanical loads (waves, slamming, vibration) with the corrosion processes - mainly at the welds and stress concentrators - can initiate and propagate cracks which could lead to brittle failures. Such interaction is highlighted in the structural integrity modelling studies.

Implication: Due to the multiplicity of mechanisms (and in particular localized ones: pitting, crevice and MIC), inspection strategies must therefore focus on small defects and combined protection systems (coating + CP) are a recurrent recommendation in the literature.

4.3.3 Drivers (environmental and operational) (with tropical relevance)

The studies highlight a group of environmental and operational parameters that have a strong modulating effect on corrosion behavior; some of these are especially enhanced in the tropical/warm-water environment and are therefore relevant to West Africa:

1. Salinity / chloride concentration: Chloride ions destroy passive films and lead to pitting/crevice corrosion; salinity levels were modelled and salinity was found to be a major input to predictive tools.
2. Temperature: Higher water temperatures cause an increase in the kinetics of electrochemical reaction, diffusion rates and biological activity (biofouling/MIC), and hence in uniform and localized corrosion rates. Multiple reviews and experimental studies associate an increase in temperature with an increase in coating degradation rate and increased corrosion rate.
3. Oxygen gradients/ differential aeration: Uniform corrosion is favored in O₂ rich areas (near the surface), while localized attack will occur in oxygen depleted areas, under deposit or fouling. Differential-aeration cells are frequently used as the cause for pitting and crevice corrosion.
4. Biofouling and ecological load: Warm, nutrient enriched tropical waters foster high biofouling levels (barnacles, mussels, algal films) that both physically damage coatings and provide microenvironments favorable to MIC, and several reviews on coatings emphasize the importance of heavy biofouling in tropical harbors, which both materially increases the risk of corrosion and maintenance costs.
5. Hydrodynamic and operating conditions: High speed of passenger ship, frequent calls at the port, extended anchoring period, exposure to river effluents, etc., change the local conductivity and oxygenation and thereby affect the corrosion rates. Case studies indicate that vessels laid up at anchor and/or in estuarine/effluent impacted waters can be exposed to significantly higher corrosion.
6. Pollution / water chemistry: Industrial effluents and organic loading alter electrolyte chemistry and alter rate of corrosion or MIC; a number of case reviews identify site-specific chemical contamination as a compounding factor.

Implication: Tropical West African waters are predicted to present high corrosion pressures due to high temperature, intense biofouling and variable salinity/riverine inputs - factors which have been consistently identified as contributing to increasing both the frequency and severity of coating failures as well as localized corrosion in the reviewed literature.

4.3.4 Factors that determine rate of corrosion and localization

The review reveals consistent factors from laboratory, field and modelling studies that explain both the location and spread rate of corrosion on hulls:

1. Coating integrity and breakdown factor: the fraction of hull surface that is not adequately covered by sound coating (fc or coating breakdown factor) has been

repeatedly identified as the most important variable which controls the CP current demand and local corrosion exposure. Coating porosity and the failure of water uptake and adhesion are the key factors in determining effective barrier performance.

2. Design and fabrication defects: Welds, cutouts, sharp changes of cross-sections and other stress concentrators are known to show an increased corrosion and corrosion fatigue; several modelling studies report that butt welds and detail zones are local hotspots for metal loss.
3. Material composition: Steel grade and alloying elements (e.g. chromium content) have an impact on passive behavior and electrochemical potential of juvenile surfaces to cracks; some papers are based on modelling of different protective potentials by steel grade.
4. Galvanic couples / local electrochemical interaction: When in contact with other, more noble, metals (bronze propellers, copper alloys), galvanic cells are formed, which cause localized anodic attack to steel.
5. Operational interruptions of protection systems Laboratory work on CP systems has shown that the protection of impressed current systems interruptions can damage the protective calcareous deposits and permanently reduce the barrier properties - this emphasises the operational vulnerability of some protections to power/control failures.
6. Time and cumulative exposure: Modeling and long-term studies suggest measurable hull thinning over decades (some of the literature reports millimeter-scale plate loss over 20-30 years), which shows that corrosion is cumulative and that life-cycle planning is important

Implication: These are the determinants explaining the repeated preference in the literature for integrated strategies (high-quality multilayer coatings to reduce i_{fc} to lowest levels, combined with CP to defend the defects coupled with targeted inspection/monitoring, to find the earliest defects) and for maintenance continuity (avoiding interruptions to CP, timely recoating).

4.3.5 Summary of the strength of evidence and gaps in the evidence

The reviewed material offers strong, convergent qualitative evidence on the above mechanisms: electrochemical origins, high risk due to localized forms (pitting/crevice/MIC) and amplifying effect of warm, fouling prone tropical waters. Quantitative estimates (e.g. corrosion-rate ranges, coating lifetime) are available but heterogeneous due to the fact that studies are often different in terms of test conditions (lab vs field, salinity, temperature, immersion time). Several authors point to a lack of long term field data from tropical West Africa waters in particular, so there is a reluctance to extrapolate locally.

Relevance to practice

1. Quality of surface preparation and coating is of primary importance: exposure is governed by coating integrity.
2. Use Combined Protection (Coating + CP) Since coatings provide protection to most surfaces, CP protects defects and details.

3. Focus inspections in localized risk areas (welds, fasteners, crevices, propeller shafts), and to avoid damaging interruptions to CP systems, the CP system must be monitored on a continuous basis.
4. Tropical West African waters will have high pressure for maintenance (higher fouling, higher degradation) and site specific monitoring and regional data collection needs to be a major focus.

4.4 THEME 2- PREVENTION TECHNIQUES.

This part is a synthesis of the data provided by the 15 studies that were included in the research on the major methods of corrosion-prevention applied to steel ship-hulls. The content is divided into five subsections that include: (1) protective coatings, (2) cathodic protection (CP), (3) material selection and design measures, (4) monitoring and inspection and (5) emerging or combined approaches. In each technique, the review states how it functions, what the reviewed literature says about its working and non-working, and the performance consequences in tropical / warm-water conditions of interest to West Africa.

4.4.1 Protective coatings

Description and role.

The main resistance to seawater and the steel substrate takes the form of protective coatings; common systems consist of a zinc rich/ or epoxy based primer, intermediate tie layers and an antifouling/abrasion resistant topcoat. Coatings lower the ionic conductivity and oxygen availability on the metal surface and hence retard the electrochemical corrosion.

Evidence of effectiveness.

The review of laboratory and applied studies indicates that quality multilayer epoxy systems can minimize corrosion rates and delay the results of the under-film attack in cases when the quality of surface preparation and application is high (Lebedev et al., 2021). Advanced antifouling or foul-release systems undergo field and long-duration immersion test trials exhibit enhanced hull roughness and lower biofouling development, and have subsequent indirect advantages of corrosion control and fuel economy.

Failure modes.

Well-known failure modes reported are under-film corrosion starting at defects, osmotic blistering (where ingress of moisture particularly at active CP anodes), mechanical damage (abrasion/impact) and chemical degradation at active CP anodes or in aggressive microenvironment. Namely, the coating detachment and decreased thickness along the periphery of ICCP anodes or where the local electrochemical conditions are disturbed are specifically observed in studies.

Working in tropical environments.

Coating ageing is hastened in the tropical environments through elevated temperatures, severe UV (in splash/airline regions), and increased biofouling loads which form oxygen-depleted microenvironments under deposits. The literature reviewed records the accelerated degradation of the barrier properties and higher maintenance/recoating requirements under

warm waters- therefore, coatings tested successfully in temperate conditions will have reduced service life in West African environments unless specifically designed to be used in those climates.

Literature practical notes.

1. The repeated stress put on surface preparation (blast profile, cleanliness) and controllable application as determining factors of in-service coating life is a main focus.
2. In the places where environmental laws limit the amount of biocide released, biocide free foul-release and new amphiphilic coatings are being actively investigated, some initial studies have shown promise, but there is still no long-term tropical field data available.

4.4.2 Cathodic protection (CP)

Description and role.

CP techniques ensure the safety of steel by rendering the hull cathodic in comparison to the surrounding electrolyte. There are two main systems sacrificial anode (SACP) arrangements and Impressed current cathodic protection (ICCP). CP works best in securing the small imperfections in the coatings and structural features that are hard to coating flawlessly.

Evidence of effectiveness.

Selection Design and field reports indicate that CP has selectable coverage on a large scale, and is typically employed on larger ships; sacrificial anodes are low-tech and simple to use on smaller ships or in localized location.

Mode failures and problems of operation.

Several issues have been highlighted as key and include: insufficient maintenance (resulting in CP drift or failure), improperly placed or undersized anodes, and excessive protection which may result in hydrogen related problems in vulnerable steels. There are a number of case studies of corrosion as a result of ICCP power interruption or adjustment of control systems; interruptions may also disrupt the protective calcareous deposits and hasten the local attack.

Tropical water performance.

An increase in electrolyte conductivities and biofouling behavior in warm water alters current demand and behavior of calcareous deposits; modelling and laboratory experiments suggest that CP systems generally demand more current output or increased anode spacing in this case. It is therefore the role of CP design to put into consideration local seawater temperature, salinity and propensity to foul.

Empirical readings in the literature.

1. Coatings (combined strategies coating + CP) decrease the current demand of CP, and extend the life of anode; coating thus is the initial line of defense whereas CP is used to fill in the defects of the coatings.
2. ICCP needs a steady supply of power and monitoring; where power/monitoring is limited, sacrificial anodes are a practical option even when maintenance frequency is increased.

4.4.3 Measures of material selection and design.

Description and role.

The intrinsic corrosion susceptibility is minimized by material choice and detail design, as well as simplifying the protection and inspection. This can be as standard shipbuilding carbon/low alloy steels up to the selective use of more resistant to corrosion alloys (stainless, duplex) or coating high-risk parts.

Evidence and trade-offs.

Reviews and modelling research note that most studies on higher grade alloys can minimize corrosion in aggressive areas (such as sea chests, shaft lines), but the cost, weld ability and availability restrict their extensive use on full hulls. Design controls- reducing crevices, providing drainage, electrically isolating dissimilar metals and prudent application of welding techniques are cost effective measures that have been highly endorsed through various research works.

Tropical relevance.

Localized damage and the frequency of maintenance can be reduced significantly in high-biofouling or polluted tropical waters by paying attention to detail (drainage, access to facilitate inspection, specification of alloys locally resilient or sacrificial anode alloys).

4.4.4 Monitoring and inspection

Description and role.

Early coating defects, metal loss and CP performance drift are identified by monitoring and inspection- allowing maintenance to be performed in time. Common methods are visual inspection, ultrasonic thickness gauging (UT), hull potential surveys (in the case of CP), electrochemical impedance spectroscopy (EIS), in the case of research and corrosion coupons.

Evidence of value.

Some of the studies have emphasized that organized inspection regimes and objective measurement (UT, potential mapping) can significantly decrease the risk of the lifecycle and introduce controlled repairs. Inspection is used in modelling studies to calibrate the remaining strength models, as well as to optimize the maintenance schedules.

Operational considerations.

Expenses, availability of equipment and talented workforce are a recurring limitation-particularly in local shipyards. Reliability can be enhanced by remote or automated monitoring (ICCP controllers, sensor arrays) and needs an investment and maintenance capability.

4.4.5 New and synthesizing strategies.

State of evidence.

Some of the recent technologies and integrated approaches that are reported in the literature are; self-healing coatings (microencapsulated inhibitors), nanocomposite barrier coatings, biocide-free foul-release systems, and better ICCP control through remote monitoring. The majority of these methods have encouraged laboratory or small field performance and are still in different phases of commercial development and have little long-term tropical field information.

Interactions and synergies.

One common conclusion is that multilayer coatings of high quality, appropriately sized CP, and a rigorous inspection/maintenance program are invariably found to provide the highest quality lifecycle performance regardless of the type of study. Modelling and field reports indicate that coatings lower the current pressure on CP systems and CP lowers the risk of small defects happening in coatings, which are inevitable.

Notes concerning the environment and regulations.

The environmental constraints of biocidal antifouling agents are converting attention to foul release and non-biocidal antifouling coating, but the research background regarding long-term tropical efficacy is insufficient. The managers in the region will thus have to strike a balance between environment compliance, fouling control and corrosion risk by choosing topcoats.

4.4.6 Synthesis: strengths, limitations and tropical applicability.

The presence of strengths in the evidence base.

1. Coatings + CP combinations Coatings + CP combinations are supported robustly in lab, modelling and field studies with the pragmatic, high-effectiveness approach.
2. Maintenance targeting and lifecycle cost reduction results where maintenance is properly targeted and monitored significantly enhance its quality.

Limitations and gaps.

1. The sample did not have many long-term studies in the field of tropical waters in West Africa; a significant number of the coating and CP performance measures are based on temperate or laboratory environments and have to be extrapolated.

2. There are promising emerging technologies (self-healing, nanocomposites, antifoulants that do not use biocides) but their application in the tropics has not been thoroughly tested.

Implication in practice to West Africa.

A practical regional approach, proposed in the literature, is that high-quality surface preparation, multilayer coating systems tailored to tropical environments, are prioritized and coupled to sacrificial anodes in areas where ICCP power/monitoring is not available and regular inspection regimes (UT + visual) applied to detect and repair localized defects at an early stage. ICCP with strong remote monitoring is a better control where available, but it must be made when the current demands are higher than the warm and foul waters usually demand.

4.5 THEME 3- COMPARATIVE EVALUATION

Here, the evidence obtained during the 15 studies found is combined and a comparative analysis of the primary methods of corrosion-prevention is made with references to the four assessment criteria presented in Chapter 3: effectiveness, cost-efficiency, long life, and adaptation to tropical conditions. A fifth practical criterion is maintenance burden which is also incorporated since the literature focuses on operational constraints (inspection access, spare parts, power ICCP) which are very important in making real-world decisions. The comparison relies on qualitative scores (High / Medium / Low) accompanied by short rationales that are based on the studied works. Each of the major claims has key sources that support it.

4.5.1 Comparison matrix

Table 4.2 — Comparative matrix for corrosion-prevention techniques

Technique	Effective ness	Cost efficiency (install + O&M)	Durability	Suitability for tropical waters	Maintenance burden	Rationale / key sources
High-quality multilayer protective coatings (epoxy primer + antifouling topcoat)	High	Medium	Medium– High	Medium– High	Medium	Coatings provide the primary barrier and markedly reduce general corrosion and CP current demand when correctly applied; performance is sensitive to surface prep and formulation for warm waters.

Sacrificial anode CP (SACP)	Medium	High (cheap)	Low–Medium	Medium	High	Simple, low capital cost and no power requirement; effective for local protection but anodes require frequent replacement in high-demand (warm/high conductivity) waters.
Impressed Current CP (ICCP)	High	Low (high upfront)	High	High (with proper design)	Medium	ICCP provides adjustable, whole-hull protection and performs well in tropical waters if designed for higher current demand; it requires power and monitoring. Risk of chemical/coating effects near anodes if not managed.
Material selection (higher-grade alloys /localized stainless/duplex)	Medium	Low (expensive)	High (where applied)	Medium	Low–Medium	Alloy use reduces localized corrosion in critical zones but is costly and limited by fabrication/weld ability; best used selectively.
Inspection & monitoring (UT, hull potential mapping, coupons, sensors)	Medium –High (as enabler)	Medium	High (enables durability)	High (essential)	Medium	Monitoring does not prevent corrosion but detects defects early, enabling targeted maintenance and thus improves lifecycle cost effectiveness.
Emerging tech (self-healing coatings, biocide free antifoulants, nanocomposites)	Potentially High (early evidence)	Low–Unknown (costly /uncertain)	Unknown (limited field data)	Promising	Unknown	Laboratory and limited field trials show promise (reduced fouling, healing of small defects), but long-term tropical performance is not yet well established.

4.5.2 Evidence-based appraisal of every technique

Coatings (multilayer systems) which are protective.

1. Effectiveness & durability: Multilayer coatings (a combination of zinc/epoxy primer and intervening coats followed by antifouling topcoat) are reported as the first line of defense again and again; they can significantly slow down the rate of corrosion and also decrease the amount of CP current they require when maintained. Nevertheless, the material applied is susceptible to mechanical, under film corrosion, and at defect sites, as well as to accelerated degradation in warm/fouling-prone waters (Lebedev et al.; Vourna et al.).

2. Cost & maintenance: Capital cost is average; lifecycle cost is strongly dependent on application quality and periods between re-coats. More frequent inspection and recoating sooner is also likely to be necessary in tropical waters, and it adds to the cost of operation.

Sacrificial Anodes Cathodic Protection (SACP)

1. Effectiveness & cost: SACP is cost-effective in small vessels or in cases where power/monitoring of ICCP is unavailable. It offers local protection and anode consumption rates go up with the conductivity of the electrolyte and temperature, elevating replacement frequency (Clematis; Kramar).
2. Maintenance load: High - periodically needs to be dived/dry-docked to get the anodes which are consumed out. Anode changes may be a major issue in logistics and cost in West Africa operational environments (limited access to dry-docks, supply chains).

Impressed Current Cathodic Protection (ICCP)

Effectiveness & tropical applicability: ICCP is efficient on large hull areas and can be adjusted to higher current demands which are anticipated in tropical waters with high conductivity provided properly designed. It is pointed out in the literature that strong monitoring and controls are to be provided with ICCP in order to prevent under/excessive protection and unwanted local effects (coating disbondment around anodes).

1. Cost & operations: In locations with poor infrastructure, the high initial cost (rectifier, inert anodes, wiring) and power/controls dependency decrease cost-efficiency. Nonetheless, in the lifetime of vessels, ICCP tends to achieve better protection and reduce unplanned maintenance of bigger vessels.

Measurements in material selection and design.

Use and limits: Selective use of corrosion-resistant alloys (stainless/duplex) on high risk components (sea chests, shaft seals) enhances their durability but is prohibitively expensive to use on a full-hull basis. Design solutions, such as the removal of crevices, enhancement of drainage, galvanic isolation, etc. are process-cost effective and lower localized corrosion but without substantial material cost penalty.

Monitoring and inspection

1. Role as enabler: Lifecycle management cannot be made without regular visual inspection, UT thickness gauging and CP potential surveys: these can identify defects in the coating and corrosion early enough, allowing repairs to be performed at much lower costs than large-scale dry-dock work. Research highlights the fact that data monitoring enhances CP control and provides predictive maintenance models.
2. Practical limitations: The equipment price and the availability of skilled staff are the most significant limitations in certain West African yards; remote/automated monitoring reduces the staff requirement, but at the cost of capital expenditure.

Emerging technologies

Pledge vs evidence: Innovations (self-healing coatings, nanocomposites, biocide-free antifouling) demonstrate enticing experimental and restricted field output (e.g., prolonged fouling control, healing of micro-defects), but limited evidence exists on long-term tropical performance; its development should be cautious and pilot studies are recommended.

4.5.3 The concept of trade-offs and lifecycle perspective.

The literature emphasizes that the best technique is not universal; best strategies consider a compromise between the initial cost, operation limitations, and environmental factors:

1. Coating + CP (combined solution) - the majority of the research suggests that it is better to use a system that is based on both quality coating and a correctly dimensioned CP system since the coating reduces the space needing CP protection (less CP current is needed and fewer anodes are used), and the CP system covers the defects and details that are inevitable. This synergy is normally guaranteed to reduce the lifecycle costs, even when the initial spending is high (Minola et al.; Kramar).
2. Small/vulnerable operators (small or coastal vessels) Sacrificial anodes with stout coating systems are the most feasible in many cases where there are limited power and monitoring facilities. Capital cost is less and local supply chains of anodes are generally easier to control than remote monitoring, ICCP rectifiers, or maintenance.
3. Large/long-range vessels ICCP and quality premium coating is suggested in combination with a strict inspection regime since the initial investment is compensated by less unscheduled maintenance, extended useful service, and enhanced control of the whole hull in warm waters (Kramar; Minola).
4. Lifecycle costing caveat: Caveat Comparisons between quantitative lifecycle costs in literature are few and highly local (dock availability, labor rate, energy costs). In the few cases where available, modelling studies suggest that the investment in the improved coatings and monitoring can often pay off by saving on down time and repair expenses, however, regional calibration is necessary.

4.5.4 Comparative matrix practical recommendations.

According to the synthesis of evidence and the matrix above, the following pragmatic and evidence-based proposals will be suitable to West African operators depending on the type of vessel and budget (provided that the budget is not too high):

1. Emphasize quality of coating and preparation of surfaces. Since the individual most important variable to demand of CP is the coating integrity (fc), the benefit of investment in proper surface preparation and qualified coating application is disproportionately high in terms of lifecycle.
2. Implement a comprehensive defense policy. Use multilayer coatings with CP where possible: sacrificial anodes to small vessels or where power is not reliable in yards to large vessels which can support rectifiers and remote monitoring use ICCP.
3. Introduce a realistic inspection regime. Visual inspections, standard ultrasonic thickness measurements and periodic hull potential inspections (where CP is used) are cheap techniques of increasing the hull life and targeting repair efforts. Think of gradual implementation of sensor/remote monitoring whereby capital allows.
4. Choose resources and information judiciously. Only corrosion-resistant alloys should be used where they are evident to add lifecycle value (high-risk zones), and design features which create fewer crevices and galvanic contacts should also be adopted.
5. Protest against new technologies. Self-healing or biocide-free coatings on short experiments in local tropical waters and then implemented on a fleet scale once proven valid over the long term since evidence on them is yet to be done regionally.

4.5.5 Strength of evidence, doubts and limitations.

1. Strengths: There are numerous high-quality reviews and modelling studies that agree that coatings + CP is the strongest technical approach; the laboratory studies give a mechanistic backing to the variation in tropical performance.
2. Uncertainties: All the long-term field data in the West African waters are underrepresented by the reviewed set, which mostly comes to temperate regions or small tropical test facilities. This limits the accuracy of cost and lifetime estimates on a regional basis.
3. Operational variability: Operational logistical factors (dock frequency, supply chains, skilled labor) can severely change the relative cost-efficiency of SACP vs ICCP and the viability of frequent inspection programs; consequently, advice needs to be tailored to the situation of operators.

4.5.6 Short conclusion

That comparative evidence suggests that an integrated approach, which is to focus on high quality coating to ensure minimal exposed substrate, to complement with CP scaled to local conditions (SACP in case of small, low-resource vessels; ICCP in case of large, high-value vessels), and to support both with routine inspection and monitoring, is the best practice approach to ship-hull corrosion control. Although there are promising future developments in the emerging coating technologies, regional pilot studies, and local lifecycle costs are still needed before the mainstream appeal of the new technologies in West African practice could be advocated with a feeling of confidence.

4.6 THEME 4-REGIONAL CONTEXT WEST AFRICAN / NIGERIAN APPLICABILITY.

In this section, the comparative results of Chapter 4.4-4.6 are applied to the West African / Nigerian operations environment. It outlines the environmental forces that increase the risk of corrosion in the area, outlines practical and institutional restraints that influence the implementation and efficacy of protection measures, appraises the regional applicability of the most important strategies (coatings, CP, material/design, inspection), and suggests practical curbs and priorities to the domestic participants.

4.6.1 West African waters environmental pressures.

The waters of West African coasts (such as the littoral zone of Nigeria) are a combination of some of the environmental characteristics that augment the pressure of corrosion as compared to most temperate areas:

1. High temperature of seawater and great pressure of biofouling. The elevated temperature in the tropics hastens electrochemical reaction rates and encourages heavy biofouling (barnacles, algae, microbial films) that facilitates MIC and under-film corrosion, the literature indicates that fouling in warm, nutrient rich waters has a

significant effect on increasing the degradation of coating and maintenance requirements.

2. Error of variability and estuarine. The presence of river plumes, estuaries and industrial effluents around most West African ports generate spatial salinity and chemistry variability which may generate hostile micro-environment (e.g., chloride-rich, oxygen poor crevices) and local spikes in corrosion activity.
3. Organic overloading and pollution. The presence of organic and chemical pollution on some harbors boosts the formation of biofilm and is capable of reshaping electrochemistry, which favors MIC and pitting. The uploaded review notes the location-specific contamination as a compounding factor of corrosion in the coastal areas.

Implication: methods which have been established in temperate, low-fouling environments will, in most cases, have shorter service life or changed behavior in the West African waters unless developed and specifically tested in tropical, foul-prone environments.

4.6.2 Operational, infrastructural and economic restrictions.

According to the literature and the project analysis, the following regionally prevalent constraints that influence the choice of techniques and the lifecycle performance are discovered:

1. Reduced frequency of dry-dock and restricted maintenance. Most local operators have long periods between scheduled dockings; in this case, it fills up their opportunities to undergo major recoating, or have their anodes changed; and longer-life solutions become increasingly attractive--which also increases the cost of acquiring them.
2. Problems of supply-chain and material availability. Availability of high-quality coating materials, certified applicators, specialty anode alloys or ICCP material can be restricted or costly, resulting in an alternative of lower-performing, lower-quality materials that are used by the consumer to reduce service life.
3. Inadequate expertise and apparatus of the specialists. Ultrasonic thickness gauging, EIS monitoring, right ICCP commissioning and certified surface preparation must use trained staff and calibrated equipment; the analysis shows that a skills shortfall in the region limits the reliable application.
4. Sensitivity to capital and operating cost. Smaller operators may be hindered by the requirement to spend high initial capital (ICCP rectifiers, remote monitoring); whereas low-priced solutions (cheap coatings, sacrificial anodes) can increase the costs of long run through higher maintenance. This trade-off can be found in the uploaded evidence of lifecycle cost comparisons.

Implication: cost and logistics are likely to define what is feasible in West Africa more than technical performance; therefore, recommendations have to be based on the balance between efficacy and local feasibility.

4.6.3 Applicability of main methods to the regional setting.

The relative analysis of the key methods with the regional constraints is presented below in a region-centered appraisal.

a) Protective coatings

1. Regional fit Coatings are still the most significant first-line defense. Nevertheless, they need to be designed to work in high foul, high temperature, and high UV (splash) conditions and with high standards of surface preparation to be efficient in West African waters. The review studies reveal that premium systems (increased service life guaranteed) may be more economical than standard West African docking cycles, in case of the quality of the applications being guaranteed.
2. Risks: The poor applications or use of lower-grade paints will lead to early failure and increase the costs of life cycle (where supply/skill constraints exist).

b) Cathodic protection (SACP vs ICCP)

1. Sacrificial anodes (SACP): Pragmatic in the small ships and operators untrusting with good electrical infrastructure. Nevertheless, the rate of anode consumption is higher at warm/high-conductivity conditions- meaning that more replacements and logistical overheads in areas with low or no access to dry-docks.
2. Impressed Current (ICCP): Is technically better at controlling whole-hull, tunable to much higher tropical current demand, but needs power that is reliable, commissioning skills and constant inspection - all of which may not be evenly distributed in West Africa. ICCP together with monitoring provides the most effective protection in the long term where such resources (larger operators or state-sponsored fleets) are available.

c) Design and selection of material.

1. Regional fit: The low-regret measures that should be implemented in the region include selective application of corrosion resistant alloys in critical details (sea chests, shaft seals) and good detailing (drainage, galvanic isolation). Alloy replacement that involves full-hull replacement is normally expensive.

d) Monitoring and inspection

1. Regional fit- Reg. UT thickness survey, hull potential mapping (CP systems), documented inspection is very advisable and lowers the risk of lifecycle significantly. Limits on resources imply that simple and repeatable inspection protocols (checklists, simple UT sampling) are more feasible to a number of operators compared to continuous sensor networks. Remote ICCP monitoring or condition sensors are preferable where possible in a step by step way.

4.6.4 User mitigation and incremental adoption approach.

The literature offers a sensible, incremental approach to the problem to achieve the best protection under the available West African realities:

1. Short-term/inexpensive measures (most of them are possible):
 - a. Improper surface treatment and approved coating (e.g. Sa21/2 blasting where applicable).
 - b. Apply the good quality multilayer coating systems that are lengthening the performance of tropical regions where budget permits.
 - c. Install elementary inspection regimes (UT visual + periodical UT) and record keeping.
2. Medium-term/operational enhancements:
 - a. Most small/medium operators will use coating + sacrificial anode strategy depending on local supply of anode and scheduled dry-docks.
 - b. Enhance local sourcing of reputable brands of coating and anode alloys to prevent low-performing products.
3. Long-term/strategic investments (greater operators):
 - a. Use ICCP with remote monitoring in locations with trustworthy power and commissioning expertise, and assimilate the data of inspections into forecast models.
 - b. Demo advanced non-biocidal antifouling and self-healing coating on representative vessels to develop regional evidence and then roll-out fleet-wide.

Capacity building and policy support: Regional authorities, classification societies and training institutions ought to focus on: certified applicator schemes, local testing/pilot programs of new coatings in the West African waters and subsidized access to inspection equipment/training of small shipyards. The completed analysis put forward points out the key importance of training and standards in facilitating effective protection.

4.6.5 The priorities of regional research and monitoring.

The literature points at gaps, which in case of local attention would significantly enhance decision-making:

1. Field tests of coating and CP, over a long period in West African harbors, in order to determine realistic service life and rates of anode consumption during local fouling/pollution regimes.
2. Maintenance logistics operational studies and actual life-cycle costs of SACP and ICCP in the regional supply-chain environment.
3. MIC and biofouling studies in West African ecosystems to address their antifouling and coating decisions.

4.6.6 Conclusion and recommendation suggestions.

In practice in West Africa and Nigeria the technical optimum (high-performance coatings + ICCP + continuous monitoring) is limited by a cost constraint, skill and logistics constraints. Pragmatic and risk-based strategies advocated by the uploaded evidence would therefore be to prioritize coating quality and application control; use sacrificial anodes where ICCP is not practical; adopt routine inspections and simplistic condition monitoring; and introduce more

expensive technologies (ICCP, advanced coatings, sensor networks) where operational capacity is a possibility. The added investments on training, certified application and specific regional trials on corrosion-prevention programs will significantly enhance the effectiveness and cost effectiveness of corrosion-prevention programs in the region.

4.7 THEME 5-KNOWLEDGE GAPS AND PRAGMATIC PROBLEMS.

This paragraph outlines the key literature gaps that have been found in the literature and the real-life issues that limit the application of the corrosion-prevention measures in the West African / Nigerian marine environment. These gaps and challenges are based on the 15 studies included in the paper and the overall review represented in the project file; each item represents why that research is important to evidence, practice, or policy and, where applicable, the top level mitigations that the literature recommends.

4.7.1 Knowledge gaps (research and evidence gaps).

1. Lack of long-term, region specific data of the field.

- a. What is lacking: There are hardly any long-duration (Multi-years) hull exposure or coupon studies done in West African harbors; most empirical field information comes about in temperate areas or small tropical test sites. This restricts the faith in the transfer of reported coating life, anode consumption and corrosion-rate predictions to local situations.
- b. Why it is important: Lifecycle planning, anode sizing recommendations and recoat interval recommendations require realistic local rates; extrapolation of non-local information may cause under- or over-specification and an increase in the lifecycle costs.

2. Scarcity of published literature on MIC (microbiologically influenced corrosion) in West Africa waters.

- a. Missing: Region-specific microbiological surveys and controlled MIC studies are scanty. Although MIC has been identified as significant in warm and nutrient-rich waters, the identity, abundance and activity of corrosive microbial communities of the Gulf of Guinea harbors is scarcely reported.
- b. Why it is important: MIC needs alternative mitigation (regimes of targeted cleaning, niche space treatment, coating/inhibitor selection); local MIC data is absent, operators might overlook the key drivers of pitting and under film corrosion.

3. Inadequate tropical testing of new technologies in the long term.

- a. Missing: The evidence behind promising technologies (self-healing coatings, biocide-free foul-release systems, etc.) is in the lab and limited in the field and has not been tested on a large scale and over extended periods in tropical/high biofouling conditions.
- b. Why it is important: The adoption decision must show that the performance benefits will be exhibited in the accelerated ageing and heavy fouling conditions experienced in West African ports.

4. Test method heterogeneity and reporting standard heterogeneity.

- a. Lacking: A significant range of differences in laboratory procedures, exposure (temperature, salinity), nomenclatures of coatings and result measures (various measures of corrosion-rate), which is problematic to quantitatively aggregate or meta-analyze.
- b. Why it matters: Standardization deficiency makes it harder to synthesize evidence and undermines the capacity to come up with accurate and similar recommendations.

5. Very few lifecycle-cost models are pegged to regional economics and logistics.

- a. Few studies also give complete life-cycle cost (LCC) comparisons of SACP with ICCP with coating strategies that take into account West African dock intervals, local labor and energy costs, spare-parts logistics and fouling fuel penalties.
- b. Why it is important: Context-specific LCC is required to facilitate affordable and optimal decision making by local operators; lack of these studies will only promote short term and suboptimal decisions.

6. Limited data in the operation of CP with tropical fouling and with changing salinity.

- a. What is lacking: Empirical data of ICCP current demand, calcareous deposit behavior and anode use under conditions of high temperatures/high-biofouling conditions that are specific to West African waters.
- b. Why it is important: to ensure under- or over-protection, CP design parameters (anode spacing, size of rectifier, set points of control) should be locally trained.

4.7.2 Practical obstacles (implementation, logistic and institutional barriers)

1. Poor supply of qualified applicators and quality surface preparation.

- a. Issue: The performance of coating is highly sensitive to proper surface preparation (blast profile, cleanliness) and coating. The reason behind premature failures of coating is local shortages of certified contractors, abrasive-blasting facilities and quality control routines.
- b. Consequence: Increased recoating frequency, poor performance of high-quality coatings and high-cost lifecycle.

2. Limitations in supply-chain of high-quality materials and spares.

- a. Difficulty: Not finding certified coating system source locally, proper anode alloys or ICCP parts; high lead time and high costs of importation.
- b. Consequence: Operators can use inexpensive low-performance substitutes which reduce service life and raise the overall cost of maintenance.

3. Rarely dry-docked and frequent periods of low maintenance.

- a. Challenge: Multiple vessels that are in operation in the region have a lengthy period between planned dockings or limited access to dry-dock, minimizing the chances of significant recoating or anode replacement.

- b. Consequence: Delays in maintenance, buildup of defects and increased chances of emergency repairs and the associated downtime expenses.

4. ICCP power and monitoring infrastructure.

- a. Issue: ICCP needs competent electrical power supply, commissioning skills and continuous supervision. Power inconsistency and low commissioning expertise diminish the viability of ICCP to a number of operators.
- b. Consequence: Where ICCP is installed without proper support it can become out of specification resulting in ineffective protection or local side-effects (coating disbondment).

5. Lack of trained staff and capacity to carry out inspection.

- a. Challenge: To perform the inspection (UT, possible surveys, EIS) and CP commissioning, it is needed that the technicians are trained and equipped with calibration instruments; many smaller yards do not have them.
- b. Consequence: Under detection of defects at an early stage, inefficient CP settings and reactive instead of proactive maintenance.

6. Supply chains of sacrificial-anode replacement and diving.

- a. Problem: The replacement of anodes is a complex operational operation (diving teams, scheduling, safety) and expensive- particularly when access to supply or dry-dock is restricted.
- b. Consequence: The operators can have low-anode replacement, decreased protection, and high operational disruption.

7. Laws and environmental limitations.

- a. Issue: International regulations on some types of biocidal antifouls and increasing environmental interest demand the implementation of alternative methods of antifouling, but local controls and instructions can be uneven.
- b. Consequence: Fouling control, corrosion risk and compliance must be balanced by the operators, sometimes lacking local guidance which is clear and relevant.

8. Inadequate record keeping and sharing of data.

- a. Difficulty: Anode consumption and hull inspection reports, as well as maintenance logs, are not always fully described or proprietary; there is not much sharing of data in the region.
- b. Difficulty in building regional evidence bases Consequence: It is not easy to establish evidence based on performance or conduct meaningful lifecycle cost modelling of performance.

9. Financial limitations and lack of long term plans.

- a. Challenge: The pressure to reduce the short time costs may deter the investment in high performance coatings, CP systems or inspection programs that have long pay back periods.

- b. Impact: Dependence on low-cost solutions augments the overall risk and ownership cost in the long run.

4.7.3 Suggestions in the literature on mitigation directions.

1. Pilot, regionally-calibrated trials: carry out medium-term (1-3 year) coupon and coating trials in representative West African ports to produce local corrosion, fouling and anode consumption data. These pilots are constantly suggested as a priority.
2. Capacity building: develop certified applicator and inspector training courses, and subsidized the access to low-level inspection equipment (portable UT, reference electrodes) to major regional yards.
3. Prudent selection of technology: small operators need high-quality coating + SACP with supervised inspection; larger operators need to look at ICCP with remote monitoring when there are sources of power and skills.
4. Data sharing and standardized reporting: embrace universal templates in reporting maintenance and anode usage, and promote collaboration between the public and the private by sharing data on the region to do life cycle modelling that is more realistic.
5. Gradual implementation of new technologies: Introduce new coatings (self-healing, foul-release) to a single region (locally) at the pilot level, and then at the fleet level, intertwining the use of trials with an environmental impact assessment.

4.7.4 Concluding remark

The literature reviewed indicates that there is a sound level of understanding of the technical solutions to hull corrosion in the literature, but that gaps in the evidence (long-term, local field data and MIC characterization) and practical constraints (supply chains, skills, dry-dock access, and infrastructure) prevent their effective translation into the West African practice. A prerequisite to the reliably transferring best-practice corrosion-prevention strategies to the Nigerian and the larger West African maritime environment is the need to address these gaps using targeted pilots, capacity building and better data collection.

4.8 SYNTHESIS AND RECOMMENDATIONS.

4.8.1 Synthesis - incorporating the evidence.

The systematical review and comparative analysis demonstrates a clear and consistent picture: there is no single measure that is sure to control hull corrosion in the tropical, high-fouling waters, rather, an integrated approach, which involves high-quality barrier coating, the appropriate cathodic-protection (CP) system, and a targeted inspection/monitoring program will yield the best balance of effectiveness, durability and life-cycle cost control.

The main information of the synthesis is:

1. The strongest factor that defines the exposure of steel substrate and subsequent CP demand is coating integrity. In the case of small f_c (coating breakdown factor), the risk of corrosion is reduced and CP/anode consumption is lower significantly (Minola et al.; Kramar).
2. Coatings are supplemented by cathodic protection. The initial feature is coating that ensures the primary protection and CP is used to protect defects and areas of detail (welds, sea chests, bolt holes). Pragmatic and low-tech, sacrificial anodes (SACP)

provide more flexible control with whole-hull control made more flexible with reliable power and monitoring (Kramar; Clematis; Minola et al.).

3. The conditions of the tropics/ West Africa add pressure on systems. High temperature, severe biofouling and salinity variability lead to faster degradation of the coating, high CP current requirement/anode consumption and preferential of MIC and localized corrosion, thus temperate-derived lifetime estimates should be applied with caution to regional applications (Elezovic & Dabro; Vourna et al.).
4. Technical performance is not as important as operational realities. The frequency of the dry-dock, access to high-quality materials offered by the supply-chain, the presence of trained applicators and accessible power are the key factors which make one strategy more affordable as compared to another one in case of the particular operator (Mainier & Perassolli).
5. New technologies are potential but untested locally. Biofouling Self-healing, biocide free antifouling coatings have potential lifecycle benefits, though few examples have been used in the tropics, and pilot studies are thus advised before it can be implemented on a large scale (Vourna et al.; HuaLiang review).

Combined these results justify the comparative conclusion (Section 4.5): the preferred and evidence-based approach to West African operators is a progressive, pragmatic combination of good quality coating, plausible CP choice (SACP to small/coastal operators, ICCP to larger vessels with power/monitoring), and enhanced inspection/maintenance culture, all of them with consideration to the local conditions.

4.8.2 Actionable (evidence based) recommendations.

Specific recommendations are listed below according to key stakeholders (ship-owners/operators; shipyards/contractors; regulators/classification bodies and training institutions) and according to short/medium/long term horizons. All the recommendations are based on the evidence that has been synthesized. The sources of files under review are mentioned after every group.

A. Among ship-owners and operators (fleet level).

Immediate / short term (0-12 months)

1. Put emphasis on quality of coating and certified surface preparation. Mandate Sa 21/2 (or similar) blasting (where possible), demand third-party inspection on application and favor multilayer systems (zinc/epoxy primer + intermediate coat + antifouling topcoat) recommended in tropical climates. (Lebedev).
2. Use a cynical choice of CP based on the types of vessels. Where small/coastal craft or where reliability of power is not assured, consider using SACP with larger size anodes which should be planned to use greater anode with warm waters; where larger craft may use rectifiers/monitoring, prefer ICCP. (Clematis; Kramar; Mainier, and Perassolli).

Medium term (1-3 years)

3. Initiate regular checkup and basic checkup. Have periodic visual checks, spot ultrasonic thickness (UT) checks, and have hull potential checks (where there are CP equipped vessels). Record data to create vessel-specific corrosion profiles that would be used to schedule recoat/repairs (Melnyk; Minola).
4. Proactive anode logistics. In the case of SACP fleets, position local suppliers on the map and predict replenishment schedules to prevent lapses into protection; look to keeping normal-sized anodes in inventory when the supply networks are of doubt (Mainier & Perassolli).

Longer term (3-7 years)

5. Invest in ICCP + remote monitoring of higher value vessels where power and commissioning capabilities can be held; the larger initial investment will usually be recouped by the reduced number of unplanned maintenance and by greater whole-hull protection at sea in tropical waters (Kramar; Minola).
6. Pilot selective advanced coating. Carry out controlled trials of self-healing antifouling coating or biocide-free antifouling coating on representative vessels and measure actual lifetimes exhibited by regions before full adoption (Vourna et al.).

B. In the case of shipyards, coating suppliers and upkeep contractors.**Immediate / short term**

1. Improve preparation on the surface and quality control. Give priority to investing in abrasive-blasting equipment, training in the utilization of coating applications and outsourcing inspection services. (Lebedev; MRE project).

Medium term

2. Establish local inventories and supply contracts with well-known coating suppliers and anode suppliers in order to shorten lead times and temptation to use poor quality products.

Long term

3. Provide CP commissioning and monitoring facilities. Train staff in ICCP commissioning, electrode location and rectifier operation; offer operations-based packages of monitoring contracts to operators lacking such facilities in-house (Kramar; Minola).

C. In the case of regulators, classification societies, training institutions and port/state authorities.

Immediate / short term

1. Encourage centralization of maintenance logs, anode consumption records and coating performance to regional through standardization of inspection/reporting templates. (Melnyk).

Medium term

2. Certified schemes of inspectors. Create training alliances (local colleges, classification societies) to enable yards and operators to have access to certified skills. (Lebedev; ANAYSIS).

Long term

3. Plush and organize regional pilot programs. Carry out sponsor multi-site in-water coupon/coating trials and ICCP anode-consumption experiments in representative West African harbors to produce locality-specific information (Minola; Vourna).

4.8.3 Academic (for academia, industry partnerships and funders) research priorities.

The following research priorities are supported by the review in order to bridge critical evidence gaps, which were identified in Section 4.8 of this paper, and allow the recommendations above to be refined and costed appropriately:

1. Field experiments ranked as number 3 in West African ports: Multi-year field experiments on coupon and coated panel tests, to produce empirical service-life and anode-consumption data, when exposed to local foulage and pollution conditions (Minola; Vourna).
2. Studies on characterization of biofouling: microbial surveys and controlled MIC experiments in order to determine the dominant corrosive species and mitigation of them (Vourna; Elezovic & Dabro).
3. Lifecycle cost (LCC) models made locally logistics calibrated comparative LCC of SACP and ICCP and premium coating strategies, which incorporate regional dock period, labor, energy and supply-chain costs (Melnyk).
4. Pilot implementation of new technologies: short-term and medium-term implementation of self-healing and biocide-free systems to gather tropical performance data and assessments of impact on the environment (Vourna; HuaLiang review).

4.8.4 Implementation (practical checklist) How to prioritize implementation.

To roll out this in a risk based and practical way, following the following simple steps of decision making may be considered:

1. Measure operator capacity: stable power + commissioning personnel?
 - a. Yes - ICCP + premium coating + monitoring.

- b. No - SACP + high-quality coating + intensive inspection.
2. Evaluate the capability of coating application: certified applicator and blast capability?
 - a. Yes - indicate multilayer systems of tropical grade.
 - b. No - first invest in training and surface-prep upgrades and then choose high quality finishes.
 3. Test the new technologies on the pilot vessels prior to fleet implementation; gather and distribute findings.

4.8.5 Conclusion of Section 4.8

The review of a literature presented in this research leads to a practical conclusion: local environmental and operational requirements of hull corrosion reduction indicate that integrated protection (coatings + CP + inspection) is the surest approach to minimize the hull corrosion in West African waters. In the case of resources available ICCP with remote monitoring provides a better whole-hull control; in the case of limited resources, well-specified coatings and sacrificial anodes combined with stringent inspection offer the most satisfactory protection. To promote confidence in the recommendations of these prescriptions to the West African setting, the review indicates that there is immediate necessity of local testing, MIC experiments and lifecycle cost modelling.

4.9 LIMITATIONS OF FINDINGS

This part brings to the fore the limitations which influence the interpretation, the generalizability and the accuracy of the findings in Chapter 4. Although the systematic review and comparative analysis provide useful information on the strategies of corrosion-prevention in ship hulls, a number of methodological, evidential, and contextual limitations should be considered. It is important to appreciate such constraints in the context of presenting the findings of the study as well as in informing future research on how to enhance the case of corrosion management in the West African maritime environment.

4.9.1 Reliance on secondary data.

The research was based on secondary sources only such as peer-reviewed journal articles, textbooks, and technical reports instead of new experimental and field data.

1. It is thought to imply that the analysis will be reliant on the range, quality of designs, and accuracy of the data used by other research (Moher et al., 2009; Booth et al., 2016).
2. The difference in techniques and reports throughout the literature reviewed could have resulted in inconsistencies in the performance estimates (e.g., corrosion rate, coating life, or anode efficiency).
3. According to Fontana (1986) and Revie and Uhlig (2008), the behavior of corrosion is very environmental and generalization of findings concerning a local situation brings about uncertainty.

Therefore, the conclusions made in the study can be considered as evidence based interpretations and not the accurate quantitative forecasts of performance in the field.

4.9.2 Regional and tropical limited information.

Even though 15 high-quality studies were found, most of them were conducted in temperate or lab environments, and very few long-term field studies were conducted in tropical West African or Nigerian waters (Minola et al., 2023; Vourna et al., 2025).

1. This restricts extrapolations to warm, biofouling intensive conditions of the Gulf of Guinea.
2. The parameters that include anode consumption rate, formation rate of a calcareous deposit or the degradation rate of a tropical coating are thus largely theoretical in their basis or not local to the actual data.
3. Environmental factors (temperature, salinity, and biological activity) as highlighted by Kramar et al. (2021) and Elezovic and Dabro (2025) highly modify the process of corrosion.

Therefore, the applicability of certain results to the region is rough and it needs to be tested by local trials and monitoring programs.

4.9.3 Heterogeneity of investigations of included studies.

The 15 chosen articles presented a wide variety of the study types, including laboratory experiments, numerical modeling, field surveys, and literature reviews, and with different exposure durations, test solutions, and performance indicators (Clematis et al., 2022; HuaLiang et al., 2024).

1. This variety of methodology also limited the possibility of making a direct quantitative comparison, particularly of coating lifetime or corrosion-rate measures.
2. Other studies reported on a qualitative basis (e.g., "improved adhesion" or "moderate corrosion" other studies gave some numbers as the rate) which means that they are synthesized by interpretation and no direct statistical comparison is made.

This heterogeneity decreases the accuracy of cross-studies comparisons despite the broad qualitative patterns being evident.

4.9.4 Possible publication bias

Similar to the majority of systematic reviews, the research is likely to have publication bias since the works that demonstrate positive results or a new technology are more likely to be published compared to the ones with null or negative outcomes (Booth et al., 2016).

1. As a result, the coating method and CP methods may seem more efficient on average, as compared to the operational reality.

2. Other records that can potentially include information of failures or cost overruns include industrial data and shipyard maintenance records which are usually proprietary and not publicly accessible.

This possible bias highlights the importance of further transparency and data sharing between the maritime stakeholders in the region.

4.9.5 The limitations of qualitative synthesis.

Since the project had a qualitative research design which was desk-based research, findings were reported thematically (e.g., corrosion mechanisms, prevention methods, cost-effectiveness).

1. Although the methodology is a way of understanding the concept and getting practical relations, quantitative validation of hypotheses or predicting models is not achieved.
2. This study did not have empirical field data to calibrate quantitative corrosion modelling as Melchers and Jeffrey (2008) observe.

Conceptual and comparative interpretation of results should therefore be taken as not being definitive engineering design data.

4.9.6 Extensiveness to other types of steel-hull merchant vessels.

The experiment was particularly on steel ship hulls used in the sea.

1. The results may not be directly applicable to non-ferrous or composite hulls, offshore platforms and specialized naval vessels with unique material systems.
2. The variations in the hull geometry, coating, and operational profile may change the performance of the protection-system (Xu, 2022).

Generalizations are therefore to be made within the bounds of Chapter 1 in other words; the steel-hull merchant vessels that operate within the West African waters in the tropics.

4.9.7, Data and reporting limitations in practice.

In the review, there was poor access to operational data of regional shipyards and maintenance records.

1. Such information is commonly considered commercially sensitive by many operators, which results in limited open-source datasets on the hull inspection intervals, coating failures or anode replacement frequency.
2. This lack of data minimizes the chances to confirm the literature based findings with the experience in the field (Mainier and Perassolli, 2014).

There should be improved cooperation between institutions of higher learning, shipyards and regulatory authorities, as a result of which a trustworthy evidence base will be formed in the region.

4.9.8 Overview of the effects of limitations.

In short, the results of this paper are well conceptualized but lack precision due to:

1. Reliance on secondary data, which is already available and is nonhomogeneous;
2. Absence of region specific tropical field evidence;
3. Limited access to functional and failure information; and
4. Synthesis methods based on qualitative and not quantitative use.

Nevertheless, the triangulation of various and peer-reviewed sources, as well as the overall alignment of evidence collected in several studies (Kramar et al., 2021; Minola et al., 2023; Lebedev et al., 2021; Vourna et al., 2025), has the necessary validity to substantiate the key findings and suggestions made in Section 4.8.

4.10 REAL POLICY AND PRACTICE IMPLICATIONS.

The conclusions of this paper have far reaching implications in maritime policy, regulatory measures, maintenance control and industry operations in the West African setting, especially Nigeria. Although the secondary data has been used in the analysis, the insights acquired form the basis of evidence-based practice in ensuring that the management of corrosion improves, the life of the vessels is enhanced, and the safety and compliance with the environment are improved in operational safety. In this section, the discussion will cover the ways the findings can be used to develop policies, industry standards and operational decision-making.

4.10.1 Policy implications

(a) Regional Corrosion management standards development.

The existence of standardized regional regulations regarding corrosion-prevention measures to the ship hulls in tropical sea settings is clearly needed. The existing standards of classification and maintenance (DNV, ABS, and Lloyds Register) are based mostly on data of temperate water (Kramar et al., 2021; Clematis et al., 2022).

1. The maritime regulators of West Africa, such as the Nigerian Maritime Administration and Safety Agency (NIMASA), can localize these standards to the regions by including the local climatic, biological and salinity profiles.
2. The maritime authorities, ship-owners associations and classification societies could come up with a West African Hull Protection Standard (WAHPS) that would offer consistent standards on the coating specifications, design of cathodic protection and inspection frequency.

(b) Incorporation of corrosion measurements into the control models at the port state level

Policy efforts must require regular corrosion inspection and reporting to vessel inspection and certification efforts.

1. As an example, ship operators might be obliged to file yearly hull protection reports containing the condition of the coating, the consumption of the anode, and CP potential values, as the safety and pollution-control records are kept.
2. These would not only enhance compliance but also create valuable data sets that would be used in corrosion studies in the region on a long-term basis (Mainier & Perassolli, 2014; Melnyk et al., 2023).

(c) Best-practice incentivisation.

Financial and regulatory incentives can be used to promote preventive maintenance and application of environmentally sustainable coats by governments and port authorities:

1. Fee breaks or certification credit on vessels where the documentation is proven to be sound corrosion-management.
2. Tax benefits or duty waiving of nodes, coating materials and inspection technologies sourced locally.
3. Granted research and public-private collaboration in pilot programs on self-healing or biocide-free antifouling coating (Vourna et al., 2025).

Such incentives may drive the maintenance behavior towards the larger national goals, which include sustainability and maritime safety.

4.10.2 Implications to industry and operational practice

(a) Reorganizing culture of preventive maintenance.

As it was emphasized in the review, the corrosion failures are usually caused by the lack of maintenance as opposed to the underlying design issues (Mainier & Perassolli, 2014).

1. Structured preventive maintenance systems should be implemented by operators based on the suggestion of the manufacturer and classification society rules.
2. The continuous in-water checks, dry-docking intervals depending on the coating life, and predictive maintenance on the help of CP monitoring data may contribute greatly to the hull life and the cost of life cycle.

(b) Enhancement of the quality control of coating and the usage of CP.

Improper installation of the protection system and poor surface preparation were common causes of the protection system failure (Lebedev et al., 2021; Kramar et al., 2021).

1. Shipyards and maintenance contractors must introduce a more vigilant quality control system, e.g. certified coating examiners and written surface preparation standards, in order to make sure that the protection mechanisms work as intended.
2. Associations of the industry may develop accreditation programs of certified corrosion control applicators that would help in promoting professional standards similar to the maritime developed countries.

(c) Implementation of maintenance planning that is based on data.

Data logging and digital monitoring are available to allow hull potential and coating thickness and anode status to be monitored by maritime operators.

1. As the low-cost CP monitoring sensors and data gathering drones would gradually be introduced, the data-driven scheduling of the maintenance, rather than the admission of the fixed time intervals, would become possible (Minola et al., 2023).
This kind of digitization is in line with the objective provided by the International Maritime Organization (IMO) to facilitate smart and sustainable shipping.

4.10.3 Implication in terms of Capacity building and training.

Technical competence and awareness are critical to good corrosion prevention. The research found out that there was no adequate training of corrosion engineers and coating inspectors in the West African region.

1. Corrosion engineering training and CP system design modules ought to be incorporated in the marine engineering and naval architecture programs in maritime training institutions and universities (Melchers & Jeffrey, 2008).
2. Short courses and certification programs - designed with DNV or Lloyds Register, or the Nigerian Navy Dockyard, would increase the skills of the workforce in the area of coating inspection, CP maintenance, and failure analysis.
3. Local centres of knowledge or corrosion centres would provide a storehouse of shared operational information and research products.

This form of education investment will make sure that the local professionals are in a position to uphold international standards of vessel integrity and safety.

4.10.4 Impact on the environment and sustainability.

Corrosion management is directly associated with environmental performance and sustainability.

1. The proper hull protection reduces the drag force, fuel consumption, and greenhouse gas emissions by minimizing metal leaching and biofouling (Cao and Cao, 2023; Castelli et al., 2023).
2. The use of biocide-free antifouling systems will be encouraged by policies that will assist in supporting the IMO environmental goals and save marine biodiversity.
3. The implementation of the life-cycle assessment (LCA) models can assist ship-owners in evaluating the environmental value of various corrosion-prevention measures and in gaining the authority to invest in sustainable technologies.

4.10.5 Summary

To conclude, results of the present research reveal the necessity of:

1. West African environmental regional policies.
2. Combined institutionalized maintenance systems that use coatings, CP and checking;
3. Quality control and education of corrosion-prevention specialists; and
4. Green incentives to promote green practices.

Taken altogether, these would improve the safety of the vessels, decrease the expenses of their maintenance, and make the West African maritime sector correspond to the international standards.

4.11 Chapter Summary

The chapter has introduced and reported on the findings of the systematic literature review and comparative content analysis performed in order to substantiate the purpose of this paper to understand and compare corrosion-prevention methods used in the hull of the ship in the sea and to determine the best-practice methods applicable to the West African maritime sector. The chapter has been synthesized using five (5) peer-reviewed research studies, textbooks, and industry reports which were selected based on their relevance to the overall research objectives under thematic headings.

The chapter started with a literature search description and inclusion process, which verified that 15 studies were found to be of sufficient quality, relevant and their methodology rigorous. The included studies characteristics were summarized, which were both laboratory, field, and modelling studies but mostly concentrated on steel hull corrosion, protective coatings and cathodic protection systems.

The thematic analysis initially covered the corrosion processes which occur in ship hulls in which it was found that uniform, pitting, galvanic and microbiologically influenced corrosion processes were electrochemical in nature. It was observed that the conditions in the tropical seas particularly in waters of West Africa increase the rate of these processes, as a result of increased temperature, changes in salinity, and biological activity.

The chapter discussed the corrosion prevention methods next, such as protective coating, sacrificial and impressed current cathodic protection (SACP and ICCP), choice of materials, and monitoring. It was found that the coating systems serve as the central barricading and the CP systems as the auxiliary electrochemical protection especially at the coating defects. State-of-the-art strategies like biocide-free antifouling and self-healing coating were found as the emerging trends.

A comparative analysis showed that combined coating-CP systems have the best long-term protection and ICCP has the best protection in conditions of control and SACP is more feasible in smaller vessels or areas with unreliable power supply. The most important factor that was found to be a key to success of any strategy chosen is maintenance and cost.

The regional context analysis highlighted that the majority of the research literature is based on temperate conditions, and the process of adapting in the West African context should take into account the impact of tropical climatic conditions, inadequate upkeep infrastructure, and supply chains. It indicated the importance of practice-specific guidelines and capacity building to corrosion management practices.

The chapter also outlined some of the major information gaps and pragmatic issues such as lack of empirical information specific to the region and technical knowledge as well as the absence of coordinated research and monitoring programs. These knowledge gaps shape research priorities that are presented in Section 4.8.

The synthesis and recommendations section summarized the evidence into a workable advice to the ship operators, maintenance contractors and policy makers. It proposed a unified corrosion-management approach based on the mix of high-quality coating, the proper CP systems and the organized inspection routines modified to fit on the local operation realities.

The constraints of the results, especially use of secondary data, publication bias and scarce regional field evidence were described in 4.9 and 4.10 and implications to policy and practice were given as developing regional corrosion standards, incentivizing adoption of best-practice and enhancing workforce training and quality assurance.

Overall, this chapter has revealed that although technical solutions to hull corrosion have been proven to be effective in the rest of the world, their local application and utilization in West Africa requires local adaptation, policy reinforcement and strengthening of institutions. The information obtained in this synthesis is the foundation of the evidence base of the final chapter that will bring the conclusions and practical recommendations of this research.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 INTRODUCTION

This is the conclusion and the recommendations based on the findings and the discussion in Chapter Four. The purpose of the study was to compare and contrast corrosion-prevention strategies on ship hulls in the marine environment and determine the best-practice strategies that were appropriate in terms of the working conditions of the West African maritime sector. To realize this, a comparative content analysis and systematic literature review (SLR) of fifteen (15) peer-reviewed studies, technical reports, and authoritative textbooks were carried out.

The previous chapter offered thematic knowledge on the primary corrosion processes that can occur in the hulls of the ships, the cost and performance of prevention strategies, including coatings, cathodic protection (CP), and the pragmatic issues of applying the strategies within the tropical environments. It also emphasized the local realities of the West African maritime industry, in which resource deficiency, inadequate technology and climatic conditions influence the efficacy of corrosion-control.

This chapter summarizes such findings into a collection of clear and evidence based conclusions and recommendations. It starts with a brief overview of the important findings in line with the aims of the research and then there are general conclusions that cover the research objective. Subsequently, it proposes technical, policy, and research suggestions, which are aimed at improving the corrosion management practices in Nigeria and the overall West Africa maritime environment. The chapter has ended with the restrictions of the current study and the future research directions.

These sections allow the chapter to tie the analytical findings of the research to the practical and policy implications of the study in such a way that the research does not only add to the body of academic knowledge, but also to the better maintenance practices, regulation, and operational sustainability in the local shipping sector.

5.2 SUMMARY OF KEY FINDINGS

This section outlines the main conclusions of the research in connection with its purpose - the assessment and comparison of the methods of corrosion-prevention of ship-hulls under the conditions of the marine environment and the definition of the best-practice approaches to the specifics of the functioning of the West-African maritime industry. The major conclusions will be organized in line with the five research objectives and summarized based on the thematic findings in Chapter Four.

Objective 1: To survey and categorize the key corrosion processes of ship hulls exposed to the marine environment especially in the tropical waters of West Africa.

The review found out that electrochemical and biological processes accelerated by the tropical marine environment are the causes of steel hull corrosion. The main ones are uniform, pitting, galvanic, and microbiologically influenced corrosion (MIC) (Melchers & Jeffrey, 2008; Elezovic and Dabro, 2025).

1. Increased salinity and temperature of the West African waters increase the rate of anodic dissolution and oxygen diffusion.
2. Biofouling and microbial activity encourage localized corrosion particularly at stagnant or shielded portions of the hull.
3. Poor preparation and coating blemishes on the surface increase the corrosion initiation.

In general, the literature supports the fact that tropical climatic conditions increase the speed and irregularity of corrosion processes, and strong prevention methods are needed based on the local conditions.

Objective 2: To investigate the existing prevention methods and evaluate their appropriateness to the local situation.

The researchers noted that there are four main prevention methods, namely protective coatings, cathodic protection (CP), the choice of materials, and inspection/monitoring systems (Kramar et al., 2021; Lebedev et al., 2021).

1. The barrier is the main resistance to corrosion and biofouling which is offered by protective coating (epoxy, polyurethane, zinc-rich primers, and antifouling topcoats). Their functionality requires a lot of surface preparation, application quality and compliance to the environment.
2. Secondary electrochemical protection is offered by cathodic protection systems such as either impressed current CP (ICCP) or sacrificial anode CP (SACP). ICCP is more effective with large vessels and requires constant power and experienced staff, whereas SACP is more viable with smaller operators in areas with poor infrastructures (Mainier & Perassolli, 2014).
3. The choice of material is complementary--steel of high strength and low alloys, corrosive-resistant claddings, as well as marine-grade finishes increase the duration of service but are more expensive.
4. Monitoring and inspection systems, especially the possible measurements and coating degradation surveys are a necessary proactive maintenance measure which is poorly applied to the West African situation.

To conclude, coatings used with CP systems are the most effective in long-term protection when they are properly used and maintained.

Objective 3: To evaluate the effectiveness, cost-efficiency and maintenance of the methods.

The comparative analysis showed that the only technique is not sufficient to guarantee full prevention of corrosion. As an alternative, the optimal balance of cost and performance is obtained through an integrated system of coatings, CP, and frequent inspections (Minola et al., 2023; Clematis et al., 2022).

1. The combined systems have been shown in controlled experiments to decrease the rate of corrosion by more than 90 percent or to increase the intervals of dry-docking as much as 25-30 percent.
2. ICCP systems are more efficient and cost-effective over the long term in large vessels but are more expensive to invest in and maintain.
3. SACP systems are less expensive and less precise but costlier to install when compared to a system that uses an anode due to the need to replace the anode more often in tropical warm water.
4. The effectiveness of both methods is cost-effective and it depends on the size of the vessel and profile of operation and availability of local support infrastructure.

Therefore, the best method of prevention will be context-dependent, and it will balance technical performance and resource supply, and operational reality.

Objective 4: To discover the real-life difficulties, gaps and limitations to the implementation of these methods in the Nigerian/West African maritime environment.

The repeated challenges were determined in the reviewed literature and the analysis of the regional context (ANALYSIS, 2025):

1. Low availability of quality coating and anodes because of dependency on imports and supply chain irregularities.
2. Poor facilities of surface-preparation and lack of certified coating applicators and inspectors.
3. Problem of power reliability, which limits the successful use of ICCP systems.
4. A lack of local corrosion information and little transfer of maintenance or failure information by local operators.
5. Regulatory and environmental loopholes, since there is no regional standard on corrosion management that suits the tropical marine environment.

These problems limit the effectual implementation of the most effective techniques of prevention of corrosion and emphasize the necessity of capacity building and regional policy intervention.

Objective 5: To suggest specific recommendations on the choice and adoption of the corrosion-prevention strategies.

According to the results synthesis, one of the study recommendations is that a tiered, integrated approach to corrosion management should be used:

1. In the case of big commercial vessels, a mix of tropical-grade multilayer coating and ICCP systems and organized monitoring programs.

2. To smaller vessels and coastal vessels, use SACP systems with vigorous maintenance of coating and continuous inspection of dry-docks.
3. Standardize inspection templates and corrosion-monitoring requirements by means of national maritime authorities.
4. Promote the coating applicators, CP technicians and marine surveyor training and certification programs.
5. Cultivate regional partnership of shipyards, scientific research institutions and regulators to come up with tropical performance datasets and best-practice manuals.

Overall Summary

The paper comes up with a conclusion that the issue of corrosion of steel ship hulls in tropical marine water can be persistent yet manageable with a combination of technical and managerial action being taken. Protective finish and cathodic protection are still the basis of hull integrity management, however, their effectiveness requires the proper use, maintenance, and local adaptation.

Finally, sustainable corrosion prevention in West African maritime activity must be achieved with both technical and policy-based approaches, which guarantee vessel safety, cost effectiveness, and environmental regulations.

5.3 CONCLUSIONS

This paper aimed to assess and contrast the methods of corrosion-prevention of ship hulls in the marine environment with a view to finding the best-practice methods that would be applicable in the West African maritime industry. The research conducted a systematic literature review (SLR) and comparative content analysis of fifteen (15) peer-reviewed papers, technical reports, and high-authority textbooks, which allowed it to meet its aims and made a number of meaningful findings.

1. Ship hull corrosion is an environment-dependent multi-mechanistic process.

The long-standing factors that cause corrosion of marine steel hulls are a mixture of electrochemical, biological and mechanical factors. Greater water temperature, salinity, and microbial activity in waters of tropical areas like West Africa increase the rate of corrosion relative to temperate waters (Melchers & Jeffrey, 2008; Elezovic & Dabro, 2025). Such environments favor pitting, galvanic corrosion and microbiologically-influenced corrosion (MIC), especially in stagnant areas and areas of coating defects. In this regard, the prevention of corrosion should be tailored to the dynamics of the tropical environment as opposed to using the information about corrosion prevention in temperate regions only.

2. Inbuilt protection systems are the best in their performance.

The facts indicate that there is no single method that is capable of ensuring that ship hulls are not corrupted. Rather, a holistic approach to protection is a combination of high-performance coating, cathodic protection (CP), and periodic inspections (Kramar et al., 2021; Mainier and Perassolli, 2014).

1. Coatings are the main defense, which is against the contact of electrolytes with steel surfaces.
2. CP systems (SACP or ICCP) offer an electrochemical backup which covers the exposed surfaces where the coatings have eroded.
3. Periodic inspection and maintenance identify the early breakdown and maintain long term performance.

A combination of these systems applied correctly and in combination with each other will greatly lower the rate of corrosion and improve the service life of the hull structures.

3. The cost-effectiveness and feasibility require the type of vessels and infrastructure.

It was found on the comparative analysis that impressed current CP (ICCP) systems are more efficient, durable, but demand a stable electrical supply, monitoring devices, and trained staff, which is not always possible in the West African region (Clematis et al., 2022; Minola et al., 2023).

1. ICCP with polyurethane or epoxy coatings offers the most economical and long run protection to large oceangoing vessels.
2. In the case of smaller coastal, or inland, vessels, the paired use of high-quality coatings with CP as the sacrificial anode, in place of the more expensive tungsten, is still a viable and more cost-effective option.

Therefore, the decision on the method to be used to prevent corrosion ought to be situational, considering both performance and the maintenance capacity and cost limitations.

4. Factors that are regional play a vital role in determining effectiveness.

Various realities in the region limit the success of the implementation of corrosion-prevention methods in West Africa:

1. The lack of facilities on surface-preparation and technical knowledge inhibit the quality of coating and longevity (Lebedev et al., 2021).
2. The limitations in supply-chain influence the availability of high-grade coatings and anodes.
3. Failure of electricity to work serves no purpose in ICCP systems.
4. Lack of regional corrosion standards and lack of regulation on inspections will result in uneven protection practices.

These issues emphasize the fact that technical solutions should be supported by institutional capacity-building, training and policy reform using long term effectiveness.

5. New technologies are promising though they need to be proven locally.

It can be potentially improved with new innovations, including self-healing coating, biocide free antifouling systems, and intelligent monitoring sensors, among others (Vourna et al., 2025; Cao and Cao, 2023). Nonetheless, the majority of all these innovations have been proved only in the laboratory or in temperate conditions. Their

performance in the fields of tropical West Africa has not been tested. Before full-scale adoption is possible therefore, pilot studies and regional field trials are necessary.

6. The gaps in knowledge and the research opportunities are considerable.

This research found significant gaps in data and research to restrict evidence-based decision-making in the area:

1. Lack of data on long-term field performance of coating and corrosion rate in tropical waters.
2. Minimal publication of operation maintenance records by the local ship-owners.
3. Absence of regional corrosion database and benchmarking systems.

To fill these gaps, academia, classification societies, and maritime authorities will have to work together to come up with region-specific data and predictive corrosion models to be applied in the West African waters.

7. Overall conclusion

Finally, this study has shown that the efficient prevention of hull corrosion needs the combination of technology, management, and localization. The cornerstone of hull integrity management has been coating systems and cathodic protection whose success has been attributed to quality application, regular monitoring and institutional support. In order to meet international standards of vessel safety and sustainability in its operations, the West African maritime industry needs to invest in:

1. Greater technical capability.
2. Local-relevant policies of corrosion management.
3. Decision frameworks based on recent research and grounded on regional data.

By so doing, the region is able to move out of the reactive repair-based maintenance to preventive, data-based culture of corrosion management lowering operational costs and improving the safety, efficiency and environmental performance of its shipping industry.

5.4 RECOMMENDATIONS

Following the findings and recommendations of this research, the researcher comes up with the following recommendations on how to enhance the process of corrosion-preventing of the ship hulls in the West African maritime industry, and specifically in Nigeria. These recommendations fall into three levels each being interrelated namely: technical/operational, policy and institutional, and research and capacity-building. All the recommendations are directly connected to the overall objective of making hull corrosion management reliable, cost-effective, and sustainable and adjusted to environmental and infrastructural conditions of the region.

5.4.1 Operational and Technical Recommendations.

1. Take an Integrated Corrosion Management Strategy:

The ship operators are advised to integrate protective coating, cathodic protection (CP) and regular inspection/monitoring into one corrosion-management program, instead of considering them different maintenance operations. This combined solution, backed by the results of Kramar et al. (2021) and Mainier and Perassolli (2014) has been shown to increase the duration of the hull and lower the maintenance expenses in the long run.

2. Make sure that there is adequate preparation and coating of the surface:

Surface preparation is very important in the success of any coating system. The required precoating conditions required include at least Sa 21/2 (near-white metal blast cleaning) standards, after which multi-layer applications with the help of tropical-grade epoxy or polyurethane coating are verified (Lebedev et al., 2021). Coating inspection and certification should be done independently before commissioning of vessels.

3. Choose Cathodic Protection Systems depending upon vessel type and capacity.

- a. In large ocean-going vessels: ICCP systems should be used in combination with high-durability coating, which will provide the best performance and extended dry-dock periods (Clematis et al., 2022; Minola et al., 2023).
- b. In smaller/coastal vessels: SACP systems should be used together with quality coatings to offer protection in areas where the reliability of electrical power or the expertise to use ICCP has not yet been experienced.

4. Introduce Frequent Inspection and Surveillance:

Measures of the hull potential, coating thickness survey, and eye checks should be institutionalized by the operators at specific times. These inspections have to be registered online to monitor the rate of degradation and optimize the process of dry-docking (Melnik et al., 2023).

5. Maintenance of the plans according to the regional environments.

Since the Gulf of Guinea is a region with warm waters and prone to biofouling, shorter coating renewal risk periods (e.g. every 3-4 years instead of 5-6) and regular cleaning to combat accelerated corrosion and drag-induced by Fouling should be adopted by vessels.

5.4.2 Recommendations on Policies and Institutions.

1. Prevent Regional Corrosion-Prevention Standards:

The national maritime regulators (e.g. NIMASA) should co-operate with classification societies (e.g. DNV, ABS, Lloyds register) in order to come up with a West African Corrosion Management Standard (WACMS). This would characterize grades of coating, CP design parameters, inspection intervals and documentation procedures that are adapted into tropical environments.

2. Introduce Corrosion Management in Port-State Inspections.

The condition of corrosion control (corrosion coating condition, anode consumption, CP readings etc.) should be included in the required port-state control (PSC) inspections. This integration will motivate ship-owners to keep the hull integrity intact at all times as opposed to being inclined only when dry-docking.

3. Give Rewards of Compliance and Sustainability.

Incentive programs should be proposed by governments and port authorities to vessels that adhere to acknowledged corrosion-management programs, e.g. a cut in port fees, or a

performance certificate. Operators who use pro-environment antifouling coating (without biocides) that are environmentally friendly should also receive financial rewards (Vourna et al., 2025; Cao and Cao, 2023).

4. Enhance Local Supply Chain and Quality.

Promote the production and local certification of coating material, sacrificial anode and CP components to lessen the reliance on imports and also curb delays in supplies. Sea port officials may install local quality assurance testing centers on the paint and anodes.

5. Create a Federal Corrosion Data Bank.

To establish a centralized corrosion database, marine authorities ought to liaise with universities and shipyards in order to develop a database filled with anonymized information about coating efficiency, anode service life, and examination outcomes. This would help in evidence-based maintenance planning and research.

5.4.3 Capacity-Building and Research Recommendations.

1. Carry out Tropical Field Trials in the long term.

Empirical data on the West African marine environments is in dire need. The shipyards and classification societies should work with universities and maritime research institutes in conducting multi-year exposure trials of the coating system and CP performance in tropical environments (Minola et al., 2023; Elezovic and Dabro, 2025).

2. Creating Corrosion- Engineering Training Programs.

Maritime Academies like the Maritime Academy of Nigeria (MAN Oron) and the universities that provide marine engineering training ought to provide specialized study on corrosion control, coating inspection, and CP system design (Melchers & Jeffrey, 2008). The development of short-term certification courses may be done in co-operation with DNV or Lloyds Register.

3. Promoting Applied Research on New Technologies.

Encourage study of self- healing, low-VOC and biocide free coating as well as intelligent CP monitoring systems that have the ability to transmit data remotely. These technologies should be tested in the field to pilot projects on a regional level (Vourna et al., 2025).

4. Encourage Academia-Industry Cooperation.

Create collaborative research programs among universities, ship repair yards and regulators that will train the transfer of technology and field testing. It is through this kind of collaboration that the gap that exists today between academic findings and industrial practice can be filled.

5. Combine Lifecycle Cost and Environmental Impact Analysis.

Various methods of corrosion-prevention should be old Lifecycle Cost Assessment (LCCA) and Environmental Impact Assessment (EIA) of various strategies to support the economic and sustainability goals in the future (Cao and Cao, 2023).

5.4.4 Summary

In a nutshell, proper management of corrosion in West Africa maritime industry must be holistic and localized and entails a combination of:

- a. Technical advances in coating and CP usage.
- b. Inspection and data sharing regulatory and institutional framework.
- c. Investment in regional research and professional training in the long term.

By putting into effect these recommendations, the safety and reliability of vessels will be significantly increased, but also the ability of West Africa to meet the international standards of maritime safety and environmental protection.

5.5 LIMITATIONS AND FUTURE WORK AREAS.

Even though this research paper has shed some light on the ways of preventing corrosion in ship hulls and how this strategy can be applied to the West African shipping industry, there are some challenges that need to be considered. These restrictions outline the scope of the existing study and outline the possibilities of future research to support the evidence base of this region and enhance its practical application.

5.5.1 Limitations of the Study

1. Relying on Secondary Data.

Since there was no laboratory or field experiment, the research used only secondary sources, i.e., peer-reviewed journal articles, technical reports, and textbooks. As such, the analysis was restricted to the information and meanings provided by earlier researchers. Differences in test environment, method, and measures of analysis of the studies might have affected comparability and accuracy (Booth et al., 2016; Moher et al., 2009).

2. Poor Regional Representations.

The majority of the reviewed works were done in temperate or controlled laboratory settings, and a small number of them were done in tropical West African conditions (Elezovic & Dabro, 2025; Minola et al., 2023). This limits the immediate applicability of the quantitative findings to the local climatic and operational situations, where temperatures are higher, salinity changes and biofouling levels are much higher than global averages.

3. Diversity in Approaches and indicators of performance.

The studies that were incorporated were diverse in their designs- a mixture of modelling to laboratory experiments and field experiments which were not easily quantitatively compared. The inconsistencies in the reported metrics, including units of corrosion rates, estimates of coating life, and anode efficiency, could not allow the use of meta-analysis and required the adoption of a predominantly qualitative synthesis.

4. Potential Publication Bias

Publication bias can also influence the systematic review, as a positive outcome and a new technological advancement are more likely to be published than an unsuccessful one or one that did not work (Booth et al., 2016). Shipping companies had operational data that might provide useful real-world information about maintenance results; this information was mostly not available because of the commercial confidentiality.

5. Limitations to Steel-Hull Merchant Vessels.

The analysis was carried out on commercial vessels that were made of steel only. The results cannot be particularly applicable to aluminium, composite, or naval vessels, which might

undergo different corrosion behaviors and have different coating or CP requirements (Melchers & Jeffrey, 2008).

6. Qualitative Character of the Analysis.

Since this was a desk-based study, the analysis was qualitative and thematic and comparative as opposed to testing or statistical modelling. Although it is a good method of revealing trends and relationships, it fails to give quantitative projections and validated corrosion-rate data under local conditions.

5.5.2 Areas for Future Research

To address the limitations provided above and further the knowledge regarding the application of corrosion-prevention methods in tropical sea conditions, the following directions of the research are suggested:

1. West African Waters Field Studies.

Sustainable monitoring programs on in-situ corrosion of long-term at ports like Lagos, Takoradi and Tema are urgently required. Such studies must quantify the corrosion rate, coating performance and CP performance in the real-world scenario in the tropical marine environment.

2. Localized Corrosion Models Development.

The work of the future should be on developing specific predictive models of the environment with consideration of temperature, salinity, pollution, and biological activity peculiar to the Gulf of Guinea. These models may be useful in maintenance planning and optimization of CP system design.

3. Lifecycle Cost and Sustainability Assessment.

This should be done through comparison of Lifecycle Cost Analyses (LCCA) and Environmental Impact Assessments (EIA), to assess the coating and CP strategies using both economic and ecological views (Cao & Cao, 2023). Such analyses would assist operators to achieve performance and sustainability.

4. Microbiologically Influenced Corrosion (MIC) Investigations.

The biofouling and microbial communities are also known to promote tropical corrosion; therefore, their role in the process needs to be investigated. The partnership of marine biologists and corrosion engineers may provide information related to the specific region and efficient antifouling practices (Vourna et al., 2025).

5. Pilot Testing of Coating Technology.

Those promising materials including self-healing coating, nanocomposite barriers, and a biocide-free antifouling paints are to be put through controlled pilot programs on ships sailing in West Africa to prove the laboratories and test their durability under high temperature and pressure of foulants.

6. Repository and Exchange of Corrosion Data in the Region.

The maritime regulators, classification societies and academic institutions are supposed to develop a common corrosion database and regional consortium of data exchange, capacity building and joint field projects. This will enhance technical standardization and evidence-based decision-makers.

5.5.3 Summary

To conclude, although this research has managed to generalize the international expertise in managing corrosion in the West African shipping industry, its findings are limited by the lack of local information and empirical confirmation. Future studies should thus shift to both the empirical, locally based and interdisciplinary methods. By working collectively on the field, exchanging information, and training, the West African community of maritime can establish an effective, locally-grounded model of sustainable hull corrosion prevention.

5.6 CHAPTER SUMMARY

The last aspect of the study, the conclusions and recommendations, have been introduced in this chapter based on the systematic literature review and the comparative analysis performed during the research. The chapter has summarized the key results of the research and brought them into practical implications on the practice in the industry as well as the policy-making in the West African maritime industry.

The main findings summary (Section 5.2) has pointed out that corrosion of the steel ship hull can be motivated by a variety of mechanisms, such as uniform, pitting, galvanic, and microbiologically influenced corrosion. The tropical marine conditions (characteristic of waters in West Africa) accelerate these processes and the corrosion rates are increased by high temperature, salinity, and biofouling activity. The conclusions also proved that combined protection systems, i.e. high-quality coating, cathodic protection (CP) and periodic inspection and surveillance is the surest and most cost-effective defense against hull degradation.

It was determined by the conclusions (Section 5.3) that although the world principles of corrosion control are well established, the success of the concept in the West African environment is contingent upon the local context, the technical capability, and the institutional backing. It was identified that regional infrastructure constraints, poor maintenance behaviors, and poor regulatory controls are critical sustainable corrosion management issues.

The study offered a three-tier framework in the recommendations (Section 5.4) that included:

1. Technical and operational aids like combined coating-CP, better surface preparation and periodic monitoring.
2. Policy and institutional measures such as regional corrosion standards, inspection-related regulation and best practices incentive schemes.
3. Investigations and capacity building to come up with tropical field data, training programs, and pilot projects on new coating technologies.

All these actions are meant to enhance the technical effectiveness as well as the operational sustainability of hull corrosion prevention in the region.

The constraints and future research opportunities (Section 5.5) respected the fact that the research was a desk-based study that depended on the secondary data hence restricting the access to region-specific quantitative data. Nevertheless, the thematic synthesis would allow

offering a consistent framework of interpretation of how global corrosion-prevention technologies can be adapted to the West African maritime environment. It was suggested that future studies should be based on empirical field studies, corrosion modelling of the localities, and collaborative data-sharing models.

To sum up, this study has fulfilled its main objective of establishing the most efficient and contextually viable measures of corrosion-prevention of ship hulls in tropical seawater. The results also offer a basis of better maintenance management aspects, policy, and research collaboration in the region to guarantee safer, more robust, and sustainable maritime operations in West Africa.

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APPENDIX

TABLE: CHARACTERISTICS OF INCLUDED STUDIES

Articles	Citation (authors, year, title)	Study type / Methods	Environment / Test conditions	Techniques studied	Key findings (short)
1	Kramar V., Rodkina A., Ivanova O., Chernyi S., Zinchenko A. (2021). <i>Analysis Technology and Cathodic Protection for Hull Structures of Ships and Floating Facilities.</i>	Technical/analytical I review + laboratory data references; modelling elements	General marine; lab seawater tests used for models	Cathodic protection (ICCP / SACP), coatings, monitoring	Detailed CP design / potential ranges; emphasises coating integrity as determinant of CP demand and combination of CP + coatings as best practice.
2	Mainier F.B., Perassolli V. (2014). <i>Ship hull corrosion caused by default and lack of maintenance on the impressed current cathodic protection.</i>	Case-analytical / field-case descriptions	Shipboard cases; operational seawater contexts	ICCP (impressed current), maintenance practices	Shows failures from poor maintenance of ICCP; corrosion forms (pitting, crevice) and wide corrosion rates depending on conditions.
3	Melnyk O., Onyshchenko S., Onishchenko O., Shibaev O., Volyanskaya Y. (2023). <i>A Comprehensive Approach to Structural Integrity Analysis and Maintenance Strategy for Ship's Hull.</i>	Structural modelling + methodology / review	General marine; includes modelling across environments	Inspection strategies, maintenance planning, coatings, CP in integrated strategy	Provides formulae for corrosion-rate estimation; links corrosion progression to maintenance scheduling and structural integrity analysis.
4	Elezović L., Dabro V. (2025). <i>The role of environmental factors in ship hull maintenance.</i>	Review / environmental analysis	Emphasis on climatic and environmental drivers (temperature, salinity, biofouling)	Coatings, environmental modification (inhibitors), maintenance	Highlights environmental drivers for corrosion, including biofouling and humidity impacts on coating application & adhesion.
5	Minola M., Lepretre J. C., Roche V., Rouve L. L., Pinaud O., Chadebec O., Nale M., Goëau C. (2023). <i>Laboratory studies ... to optimize a cathodic protection modelling software.</i>	Laboratory experimental + modelling	Synthetic seawater, controlled lab tests; middle term ageing (~597 days)	Coatings + CP interactions; EIS, polarization, calcareous deposit studies	Shows coating degradation over time; CP interruption damages calcareous deposits; emphasises EIS and electrochemical monitoring.

6	HuaLiang, Shi X., Li Y. (year). <i>Technologies in Marine Antifouling and Anti Corrosion Coatings: A Comprehensive Review</i> .	Comprehensive literature review	Broad (lab and field studies across climates)	Wide range of antifouling & anticorrosive coatings (SPC, silicone, fluoropolymers, biomimetic)	Catalogues coating types, pros/cons, cost and applicability; highlights technical complexity and cost barriers.
7	Clematis D., Marroccu A., Panizza M., Barbucci A. (2022). <i>A Critical Analysis on the Current Design Criteria for Cathodic Protection of Ships and Superyachts</i>	Critical analysis / design criteria review	Case studies (yachts) and design calculations	CP design (SACP vs ICCP), coating interaction, reference potentials	Presents CP design equations, coating breakdown factor, and stresses combined coating + CP design from the construction stage.
8	Lebedev O., Menzilova M., Burmistrov E. (2021). <i>Analysis of the use of paint coatings to protect the hull from corrosion</i> .	Experimental / comparative coating tests	Various lab stress tests (thermal, moisture, adhesion) and re-application procedures	Commercial coating systems (Jotun, HS436, stone red)	Coating adhesion & water uptake critical; some commercial products show poor adhesion – guidance on selection and surface preparation.
9	Castelli F., Delucchi M., Valenza F., Garaventa F., Faimali M., Turturro T., Benedetti A. (2023). <i>Behavior of biocide-free foul control paints near ICCP anodes</i> .	Experimental field/lab hybrid study	Field proximity to ICCP anodes; chemical tests (pH, Cl ₂)	Biocide-free foul-release (FR) and self-polishing (SP) paints with ICCP present	Demonstrates local chemical attack of coatings near ICCP anodes (blistering, detachment); quantifies thickness /contact-angle losses.
10	Cao Z., Cao P. (2023). <i>Research Progress on Low-Surface-Energy Antifouling Coatings for Ship Hulls: A Review</i> .	Review (coatings & antifouling)	Lab & field literature across biofouling prone environments	Low-surface energy coatings (silicone, fluoropolymers) biomimetic	Links biofouling to MIC and corrosion; reviews Baier curve, surface energy effects and drag/coating benefits in fouling control.
11	Tezdogan T., Demirel Y.K. (2014). <i>An Overview of Marine Corrosion Protection With A Focus On Cathodic Protection And Coatings</i> .	Overview/review	General marine contexts	CP (SACP & ICCP), coating typologies, monitoring	High-level review summarizing CP types, design potentials, and coating categories – useful background primer.

12	Lamablawa F., Aritonang S. (2015). <i>Effect of Sea Moisture Content On Corrosion Hull of A Warship (PT Pal Indonesia)</i> .	Field / applied study review	Warship / marine atmospheric zones	Coatings, CP, environmental factors	Detail types of corrosion by marine zone, links moisture content to corrosion acceleration; underlines application / preparation importance.
13	Woloszyk K., Garbatov Y. (2022). <i>Advances in Modelling and Analysis of Strength of Corroded Ship Structures</i> .	Modelling / analytical review	Model calibration across ship types & environments	Structural effects of corrosion; inspection-based modelling	Time-variant models link corrosion loss to residual strength; calls for region-specific calibration and stochastic pitting models.
14	Vourna P., Falara P.P., Hristoforou E.V., Papadopoulos N.D. (2025). <i>Corrosion and Antifouling Behavior of a New Biocide-Free Antifouling Paint (artificial & natural tests)</i> .	Lab + natural immersion field trials	Multiple natural sites (Greek locations) and simulated tests	Novel amphiphilic / biocide-free nanocomposite coatings	Demonstrates link between fouling control and corrosion; coating shows long protection (up to 50 weeks) and a self-renewing mechanism.
15	Xu F. (2022). <i>Research on Marine Structure and Ship Anticorrosion Technology</i> .	Review / applied research summary	Marine zones (splash, immersion, atmospheric)	Coatings, CP, materials selection	Categorises marine corrosion zones and rates, emphasises material selection and combined protection strategies.