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Corrosion and Its Multifaceted Implications: A Comprehensive Review of Mechanisms, Mitigation Strategies, and Industrial Applications

Masood Amiri Koshkeki

Sustainable Infrastructure, Department of Civil and Construction Engineering, Swinburne University of Technology, Melbourne, Australia

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ABSTRACT

Corrosion remains one of the most pervasive and economically burdensome challenges confronting modern industry, inflicting annual global costs estimated at approximately US$2.5 trillion, equivalent to 3.4% of the world's Gross Domestic Product . This comprehensive review synthesizes current knowledge on corrosion mechanisms, mitigation strategies, and industrial applications across critical sectors including oil and gas, marine infrastructure, wastewater treatment, and civil engineering. The analysis systematically examines electrochemical principles governing corrosion thermodynamics and kinetics, establishing that while thermodynamics predicts corrosion spontaneity through Gibbs free energy calculations, kinetics determines the actual degradation rate . Key corrosion morphologies uniform, pitting, crevice, galvanic, intergranular, stress corrosion cracking, and microbiologically influenced corrosion are characterized with emphasis on their distinct initiation mechanisms and propagation dynamics. Advanced mitigation approaches are critically evaluated, including protective coatings achieving >90% corrosion reduction, inhibitor systems demonstrating >95% efficiency in controlled environments, cathodic protection methodologies, and emerging self-healing technologies based on layered double hydroxide nanocarriers that exhibit 95-99.9% inhibition efficiency . Particular attention is devoted to green corrosion inhibitors derived from renewable sources and hybrid systems combining organic and inorganic functionalities for enhanced synergistic protection. The review further examines monitoring technologies, from non-destructive testing to AI-driven predictive models achieving reliability metrics exceeding 0.85 R^2. It concludes that effective corrosion management necessitates integrated, multi-layered approaches bridging laboratory mechanistic understanding with field-applicable, economically viable, and environmentally sustainable solutions.

Introduction

Corrosion, the electrochemical or chemical deterioration of metallic materials through interaction with their environment, constitutes a critical and escalating challenge across virtually every industrial sector [1-4]. This natural degradation process, often described as the reverse of extractive metallurgy, occurs when refined metals revert to their more thermodynamically stable oxide or salt forms, exemplified by the familiar rusting of iron [5-9].

The pervasive nature of corrosion manifests in catastrophic infrastructure failures, significant economic losses, profound safety hazards, and substantial environmental contamination, making its comprehensive understanding and effective

Corresponding Author:** ***Masood Amiri Koshkeki (zammasoud.amirikoshkeki.1365@gmail.com)

mitigation an imperative of modern materials science and engineering. The economic ramifications of corrosion are staggering. The National Association of Corrosion Engineers (NACE) estimates that the global annual cost of corrosion approaches US$2.5 trillion, representing approximately 3.4% of global GDP. Within the petroleum industry alone, corrosion imposes annual costs of approximately US$1.372 billion, encompassing surface pipeline and facility expenses (US$598 million), downhole tubing costs (US$463 million), and capital expenditures related to corrosion damage (US$320 million) [10-15]. Similarly, water and wastewater infrastructure faces enormous corrosion-related expenditures; Australia estimates AU$125 billion over the next two decades for sewer pipeline repairs, while New Zealand projects NZ$25 billion. These financial burdens extend beyond direct replacement and maintenance costs to encompass production losses, environmental remediation, insurance premiums, and health-related consequences from contaminant releases [16-19].

Beyond immediate economic impacts, corrosion poses severe safety risks to both personnel and the public. Corroded pipelines may rupture catastrophically, releasing flammable or toxic substances; structural failures of bridges, buildings, and transportation infrastructure have resulted in numerous fatalities globally [20-25]. The environmental dimension is equally concerning; corroded infrastructure releases heavy metals including lead, mercury, and chromium into soil and water systems, while pipeline leaks from offshore platforms and industrial facilities contaminate marine ecosystems and groundwater resources. The release of pollutants necessitates costly cleanup efforts and can result in long-term ecological damage affecting biodiversity and human health [26-30].

The complexity of corrosion phenomena arises from the interplay of multiple influencing parameters. Environmental factors including temperature, pH, chloride and sulfide ion concentrations, humidity, and dissolved oxygen levels critically determine corrosion susceptibility and rates [31-40]. Operational parameters such as flow velocity, pressure, and hydrodynamic conditions significantly influence mass transfer, wall shear stress, and protective scale stability. Material properties including composition, microstructure, surface condition, and electrochemical characteristics dictate intrinsic corrosion resistance. In many industrial contexts, these factors combine synergistically, accelerating degradation through mechanisms such as erosion-corrosion, stress corrosion cracking, and microbiologically influenced corrosion [41-50].

Acknowledging the multifaceted nature of corrosion challenges, substantial research efforts have focused on developing effective mitigation strategies. These encompass design improvements to eliminate crevices and stress concentrators, environmental modifications through deaeration or pH adjustment, electrochemical protection via cathodic or anodic methods, application of protective coatings, and use of corrosion inhibitors [51-60]. Recent advances include self-healing coatings incorporating stimuli-responsive nanocarriers, green inhibitors derived from renewable sources, and AI-driven predictive monitoring systems. However, significant gaps persist between laboratory-scale inhibitor efficiencies exceeding 95% and field performance constrained by variability in service conditions, temperature fluctuations, and microbial activity.

This comprehensive review aims to synthesize current mechanistic understanding of corrosion phenomena with critical evaluation of established and emerging mitigation technologies. It is structured to first establish fundamental electrochemical principles governing corrosion thermodynamics and kinetics, followed by systematic classification of corrosion types and their characteristic mechanisms. Subsequently, it examines state-of-the-art protection strategies with emphasis on performance metrics, limitations, and industrial applicability. Particular attention is devoted to bridging the gap between laboratory mechanistic studies and practical industrial implementation, addressing challenges of scalability, long-term durability, and environmental compliance. The review concludes with future perspectives, highlighting the imperative for standardized testing protocols, data-driven discovery approaches, and sustainable, circular-economy-compatible corrosion management solutions.

Literature Review

Historical Context and Foundational Knowledge:

Scientific investigation of corrosion spans over 150 years, establishing fundamental principles that remain relevant to contemporary research and industrial practice. Early studies by Faraday established the electrochemical nature of corrosion processes, laying groundwork for understanding oxidation-reduction reactions occurring at anodic and cathodic sites on metallic surfaces. Subsequent development of the Nernst equation enabled quantitative prediction of electrode potentials as functions of temperature and reactant activities, providing thermodynamic frameworks for assessing corrosion susceptibility. The seminal work of Pourbaix introduced potential-pH diagrams mapping corrosion, passivation, and immunity regions for metals in aqueous environments, establishing a foundational tool for corrosion prediction and materials selection. The economic significance of corrosion was systematically quantified through landmark studies including the 1949 Hoar Report for the United Kingdom and, more recently, the comprehensive 2013 NACE IMPACT study estimating US$2.5 trillion global corrosion costs. These investigations established that implementing existing corrosion prevention technologies could reduce global corrosion costs by 15-35%, representing annual savings of US$375-875 billion. The NACE study further categorized corrosion costs across sectors: utilities (34.7%), transportation (21.5%), infrastructure (16.4%), government (14.6%), and production/manufacturing (12.8%), highlighting the universal impact across all industrial domains.

Corrosion Mechanisms: Electrochemical Foundations:

Modern understanding recognizes corrosion as fundamentally electrochemical in nature, comprising two distinct half-reactions occurring simultaneously: anodic oxidation where metal atoms lose electrons to form cations, and cathodic reduction where electrons are consumed, typically by oxygen or hydrogen ions. These reactions must proceed at equal rates to maintain electroneutrality, with the corrosion potential representing the mixed potential where anodic and cathodic reaction rates are balanced. Thermodynamics predicts corrosion spontaneity through Gibbs free energy calculations ($\Delta G=-nFEcell\Delta G=-nFEcell$), where negative $\Delta G\Delta G$ values indicate thermodynamically favorable corrosion. However, thermodynamics provides no insight into corrosion rates, which are governed by kinetics including activation polarization, concentration polarization, and ohmic resistance.

The concept of passivity, where metals spontaneously form thin oxide films that dramatically reduce corrosion rates, has attracted substantial attention since Faraday's early observations of iron in concentrated nitric acid. Passive films, typically 1-10 nm thick, act as physical barriers to ion transport and electron transfer, reducing corrosion rates by orders of magnitude compared to active dissolution. However, passive films are susceptible to localized breakdown in aggressive environments containing chloride ions, leading to pitting, crevice corrosion, and stress corrosion cracking. Understanding the structure, composition, and stability of passive films has become critical for alloy design and corrosion prevention strategies.

Corrosion Classification and Morphologies:

Corrosion manifests through diverse morphologies, each with characteristic mechanisms requiring specific mitigation approaches. Uniform corrosion, representing the most common and predictable form, occurs evenly across metal surfaces, enabling straightforward lifetime prediction through corrosion allowance methods. In contrast, localized corrosion forms including pitting, crevice, and intergranular attack are particularly dangerous due to their hidden nature and potential for sudden, catastrophic failure. Pitting corrosion, characterized by small cavities or pits on passive metal surfaces, initiates through passive film breakdown, typically by chloride ions, and propagates through autocatalytic mechanisms where the pit interior becomes acidified and highly aggressive. Stress corrosion cracking combines tensile stress with a corrosive environment, leading to unexpected failure often without significant visible corrosion.

Microbiologically Influenced Corrosion (MIC) has emerged as a critical concern in industries ranging from oil and gas pipelines to marine infrastructure and water treatment facilities. Microorganisms, including bacteria, fungi, and archaea, form biofilms on metal surfaces that alter local chemistry, create concentration cells, and produce corrosive metabolites including acids and hydrogen sulfide. Sulfate-reducing bacteria (SRB) are particularly aggressive, generating hydrogen sulfide that accelerates cathodic depolarization and promotes hydrogen embrittlement. Aerobic bacteria such as iron-oxidizing bacteria create differential aeration cells, driving pitting corrosion through concentration cell mechanisms. The complexity of MIC requires integrated approaches combining materials selection, biocide treatment, biofilm disruption strategies, and advanced monitoring techniques.

Corrosion in Critical Industrial Environments:

- ✓ **Oil and Gas Industry:** The oil and gas sector is arguably the most corrosion-affected industry, facing aggressive environments characterized by carbon dioxide (CO_2CO_2), hydrogen sulfide (H_2SH_2S), high temperatures, high pressures, and multiphase flow conditions. Sweet corrosion (CO_2-driven) is prevalent in production systems, governed by temperature-dependent mechanisms where increasing temperature initially accelerates corrosion but may subsequently promote protective iron carbonate scale formation. Sour corrosion (H_2S-driven) produces hydrogen embrittlement and stress corrosion cracking, necessitating specialized materials and inhibition strategies. Flow dynamics critically influence corrosion rates through effects on mass transfer, wall shear stress, and protective scale erosion; turbulent flow and high velocities generally increase corrosion rates while also potentially removing protective films.
- ✓ **Water and Wastewater Systems:** Corrosion in water infrastructure imposes substantial economic and public health

burdens. Treated water and wastewater environments contain diverse corrosive species including chlorides, sulfates, dissolved oxygen, and microorganisms. Industrial wastewater particularly challenges infrastructure due to the presence of hazardous elements including acids, alkalies, heavy metals, and organic compounds. Chemical coagulation treatment processes, widely used for contaminant removal, can either exacerbate or mitigate corrosion depending on coagulant selection and dosage. Studies demonstrate that polyacrylamide-aluminum sulfate combinations provide optimal corrosion protection while achieving 21% reduction in total dissolved salts. Recycled water systems present additional challenges from halide ion concentrations, with chloride and fluoride ions accelerating Q235A steel corrosion rates to peak levels at specific concentrations.

- ✓ **Marine and Offshore Environments:** Coastal and offshore installations face severe corrosion challenges from chloride-rich seawater, varying temperatures, tidal and wave action, and biological fouling. Pitting and crevice corrosion of passive alloys are particularly aggressive in marine environments due to chloride ion attack on protective oxide films. The small ionic radius and high mobility of chloride ions destabilize passive films through formation of soluble metal-chloride complexes and acidification of pit microenvironments.

Environmental and Sustainability Dimensions:
The environmental implications of corrosion extend beyond infrastructure damage to encompass resource consumption, greenhouse gas emissions, and toxic releases. Production and replacement of corroded materials require substantial energy inputs, contributing to carbon emissions and resource depletion. Leaks from corroded infrastructure release hydrocarbons, heavy metals, and chemicals into ecosystems, with lasting impacts on biodiversity and human health. Regulatory pressures have increasingly restricted use of traditional corrosion inhibitors including chromates and lead-based compounds, driving development of environmentally acceptable alternatives.

Green corrosion inhibitors derived from renewable, biodegradable sources have emerged as promising sustainable alternatives. Plant extracts, essential oils, agricultural wastes, microbial metabolites, amino acids, and naturally occurring compounds containing heteroatoms (N, O, S, P) or conjugated systems exhibit variable but significant inhibition efficiencies. Mechanisms include adsorption onto metal surfaces through physisorption, chemisorption, or mixed modes, creating protective barriers limiting corrosive species access. However, performance varies significantly with extract composition, temperature, flow conditions, and electrolyte complexity, presenting challenges for standardization and industrial deployment.

Research Gaps and Future Directions:
Despite substantial progress, several research gaps persist in corrosion science and engineering. Standardized, field-relevant testing protocols remain underdeveloped, hindering translation of laboratory findings to industrial applications. Mechanistic understanding of corrosion under extreme conditions high temperature, high pressure, transient multiphase flow remains incomplete. Integration of high-fidelity mechanistic models with field-applicable predictive tools requires further development, particularly for microbiologically influenced corrosion and its complex biological-electrochemical interactions. Development of circular-economy-compatible inhibitors and coatings, emphasizing renewable feedstocks, biodegradability, and recyclability, represents an emerging priority area. Artificial intelligence and machine learning approaches offer promising avenues for accelerated inhibitor discovery, corrosion rate prediction, and optimization of protection strategies.

Methodology
This comprehensive review was developed through systematic analysis of peer-reviewed literature indexed in major scientific databases including Scopus, Web of Science, ScienceDirect, PubMed, and Google Scholar. The search strategy employed combinations of keywords such as "corrosion mechanisms," "corrosion mitigation," "corrosion inhibitors," "green corrosion inhibitors," "self-healing coatings," "microbiologically influenced corrosion," "corrosion monitoring," and "industrial corrosion applications." Particular emphasis was placed on studies published between 2015 and 2026, while seminal earlier works were included were mechanistically or historically significant. The literature screening process involved identification of relevant peer-reviewed research articles, review papers, and industry reports. Studies were selected based on relevance to the review scope, methodological rigor, completeness of reported experimental conditions, mechanistic significance, and applicability to industrial contexts. Representative studies for comparative analysis were chosen based on clear presentation of experimental methodology, characterization results, and performance metrics. Publications lacking sufficient methodological detail or quantitative performance data were excluded. Priority was given to studies examining corrosion in industrially

relevant environments, including oil and gas production, wastewater treatment, marine applications, and reinforced concrete structures.

Quantitative data synthesis focused on inhibitor efficiencies, coating performance metrics, and corrosion rate measurements. Data were categorized according to corrosion type, environment, protection strategy, and application sector. Performance metrics including inhibition efficiency (%), corrosion rate (mm/year), and protective film stability (hours of protection) were extracted and analyzed. For self-healing and advanced coating technologies, specific attention was given to reported inhibition efficiencies (≥95%), durability (hundreds to thousands of hours), and barrier property improvements. Modeling studies were evaluated based on reported accuracy metrics including R^2 values, with reliability metrics exceeding 0.85 considered acceptable for predictive applications.

Thermodynamic and electrochemical analysis drew upon established principles including Nernst equation application (E=Eo−RTnFln(aproductsareactants)E=Eo−nFR Tln(areactantsaproducts)), Gibbs free energy calculations (ΔG=−nFEcellΔG=−nFEcell), and consideration of activation energy effects on corrosion kinetics. Adsorption behavior of inhibitors was evaluated through isotherm analysis including Langmuir, Temkin, and Frumkin models, with free energies of adsorption (ΔGads∘ΔGads∘) used to assess adsorption spontaneity and mode.

Industrial cost and economic impact data were extracted from NACE studies, industry reports, and government statistics to provide comprehensive context for corrosion management priorities. Costs were reported in US dollars (USD) and converted where necessary using appropriate exchange rates. Environmental and sustainability considerations were examined through analysis of regulatory requirements, green chemistry principles, and lifecycle assessment approaches.

Results

Table 1. Comparative Performance of Corrosion Inhibitor Systems

Inhibitor Type	Mechanism	Efficiency (%)	Key Advantages	Primary Limitations	Industrial Applications
Traditional Inhibitors	Chromate-based passivation	85-98	High reliability, established protocols	Toxicity, disposal concerns, environmental persistence	Cooling systems, oilfield
Green Organic Inhibitors	Mixed adsorption (physisorption/chemisorption)	70-92	Low toxicity, renewable resources	Performance variability, temperature/flow sensitivity	Mild acidizing, water treatment
Hybrid Inhibitor Systems	Synergistic (organic + inorganic)	90-98	Enhanced durability, multifunctionality	Complexity, cost, formulation challenges	Marine, oil & gas pipelines
LDH-Based Self-Healing	Ion-exchange triggered release	95-99.9	Autonomous repair, long-term stability	Scalability, premature release issues	Protective coatings, aerospace

Data compiled from references.

Analysis of Table 1: The comparative analysis reveals a clear performance hierarchy among inhibitor categories, with traditional chromate-based systems achieving 85-98% efficiency but facing increasing regulatory restrictions due to toxicity and environmental persistence. Green organic inhibitors, derived from renewable sources such as plant extracts, alginate, chitosan, and neem, exhibit efficiencies ranging from 70-92%, with significant variability attributed to extract composition and environmental conditions. Their primary limitations include temperature sensitivity, flow-dependent performance, and electrolyte complexity effects. Hybrid inhibitor systems, combining organic compounds with inorganic additives such as nanoparticles or rare-earth salts, achieve 90-98% efficiency through synergistic mechanisms, offering enhanced durability and multifunctionality including anti-biofouling and self-healing properties. Notably, layered double hydroxide (LDH)-based self-healing systems exhibit remarkable efficiencies exceeding 95%, with some formulations reaching 99.9% inhibition. These systems function through ion-exchange mechanisms triggered by local environmental changes, releasing corrosion inhibitors precisely at damage sites. However, challenges persist including scalability, dispersion uniformity, and premature release during processing.

Table 2. Pipeline Corrosion Mitigation Strategies and Performance Metrics

Protection Method	Mechanism	Corrosion Reduction (%)	Service Life Extension	Key Requirements	Cost Range (USD/m²)
Protective Coatings	Physical barrier	>90%	10-25 years	Surface preparation, cure conditions	15-100
Cathodic Protection	Electrochemical polarization	85-95%	15-30 years	Electrical continuity, monitoring	5-50
Internal Coatings	Barrier + inhibitor	85-95%	8-20 years	Flow conditions, adhesion	20-150
Corrosion Allowance	Sacrificial thickness	N/A (passive)	5-20 years	Design thickness, inspection	1-10 (initial)
Dehydration/Treatment	Environmental modification	70-90%	5-15 years	Dehydration systems, monitoring	Varies
Material Selection	Alloy corrosion resistance	90-99%	25-50 years	Alloy cost, weldability	100-1000+

Data compiled from references.

Analysis of Table 2: Pipeline corrosion protection employs diverse strategies spanning passive barrier approaches to active electrochemical control. Protective coatings, including epoxy, polyurethane, and polymer-based systems, achieve >90% corrosion reduction through physical barrier mechanisms. Coating performance critically depends on surface preparation quality, application conditions, and adhesion, with costs ranging from US$15-100/m². Cathodic protection, either through sacrificial anodes or impressed current systems, provides 85-95% corrosion reduction through electrochemical polarization, effectively suppressing anodic reactions. Service life extensions of 15-30 years are achievable with proper system design and monitoring.

Internal corrosion control remains challenging due to the aggressive nature of transported fluids and limited access for maintenance. Internal coatings and linings provide 85-95% protection but require careful adhesion management under flow conditions. Dehydration and chemical treatment reduce water content or neutralizes corrosive species, achieving 70-90% corrosion reduction though at operational costs. Corrosion allowance represents a passive strategy wherein pipeline walls are designed with additional thickness to accommodate anticipated corrosion over service life, providing 5-20 years of reliable service at low initial cost. Material selection, including use of corrosion-resistant alloys and stainless steels, offers superior performance (90-99% corrosion reduction) and extended service life (25-50 years) but at substantially higher initial costs (US$100–1000+ per square meter).

Table 3. Factors Influencing Corrosion in Industrial Environments

Parameter	Effect on Corrosion	Mechanism	Mitigation Approach
Temperature	Accelerates reaction kinetics; variable effect with pH	Arrhenius kinetics; scale formation influence	Material selection; specialized inhibitors
pH	Acidic environments increase corrosion; alkaline promotes passivation	H^+ concentration; oxide film stability	pH adjustment; inhibitors; coatings
Chloride Concentration	Localized corrosion (pitting, crevice)	Passive film breakdown; soluble complex formation	High-performance alloys; coatings
Flow Velocity	Mass transfer enhancement; scale erosion	Shear stress; turbulence	Flow control; erosion-resistant materials
CO_2 Content	Sweet corrosion (carbonic acid)	Iron carbonate formation; pH reduction	Dehydration; inhibitors; material selection

H_2S Content	Sour corrosion; hydrogen embrittlement	Sulfide film formation; hydrogen uptake	NACE-compliant materials; H_2S removal
Microorganisms (MIC)	Biofilm formation; localized attack	Metabolite production; differential aeration	Biocides; coatings; monitoring
Dissolved Oxygen	Cathodic depolarization	Oxygen reduction reaction	Deaeration; oxygen scavengers

Data compiled from references.

Analysis of Table 3: The complex interplay of environmental and operational parameters critically determines corrosion behavior, with each factor influencing corrosion through specific mechanistic pathways. Temperature exhibits dual effects; while generally accelerating corrosion kinetics through Arrhenius behavior, temperature may promote protective scale formation in carbonate-rich environments, reducing corrosion rates at higher temperatures. pH directly controls hydrogen ion concentration and oxide film stability; acidic environments (low pH) accelerate uniform and localized corrosion, while alkaline conditions favor formation of protective passive films. Chloride ions are among the most aggressive species, particularly for passive alloys, initiating and propagating localized attack through passive film breakdown and formation of soluble metal-chloride complexes. Flow velocity and hydrodynamic conditions influence corrosion through mass transfer enhancement and mechanical scale erosion. Turbulent flow increases corrosive species transport to the metal surface while removing protective films, promoting erosion-corrosion mechanisms. CO_2 and H_2S contents are primary drivers of sweet and sour corrosion in oil and gas operations, requiring tailored mitigation approaches. Microbiologically influenced corrosion (MIC) presents unique challenges due to biofilm formation and metabolic production of corrosive species including hydrogen sulfide, acids, and extracellular polymeric substances. Management approaches include physical removal (biocide application, pigging), environmental modification (pH adjustment, oxygen removal), and materials selection resistant to microbial attack.

Table 4. Advanced Corrosion Monitoring and Prediction Technologies

Technology	Accuracy	Application	Key Advantages	Development Status	Cost Range
ER Probes	±1-5%	General corrosion monitoring	Real-time, robust	Mature	Moderate
LPR Sensors	±5-10%	Uniform corrosion rate	Rapid, non-destructive	Mature	Moderate
NDT (UT, AET)	±0.1 mm wall loss	Structural integrity	In-service inspection	Commercial	Moderate High
Smart Pigging	±0.1-0.5 mm wall loss	Pipeline condition assessment	Full coverage, accurate	Commercial	High
IoT Sensors	±1-5%	Remote, continuous monitoring	Real-time data, integration	Emerging	Low Moderate
AI Prediction Models	R^2>0.85	Predictive maintenance	Pattern recognition, optimization	Development	Variable
Molecular/Microbial Methods	Highly specific	MIC detection	Early warning, species identification	Research	High

Data compiled from references.

Analysis of Table 4: Corrosion monitoring technology selection depends on accuracy requirements, application context, and cost constraints. Traditional techniques including electrical resistance (ER) and linear polarization resistance (LPR) sensors provide real-time, robust monitoring of general corrosion with moderate accuracy (±1-10%) and cost. Non-destructive testing (NDT) methods, including ultrasonic testing (UT) and acoustic emission testing (AET), provide high-accuracy (±0.1 mm) wall loss measurements for structural integrity assessment at moderate-to-high cost. Smart pigging technologies enable comprehensive pipeline condition assessment with

±0.1-0.5 mm wall loss detection, though at substantial cost.

Emerging technologies including Internet of Things (IoT) sensors enable low-cost, remote, continuous monitoring with real-time data transmission and integration capabilities. Advanced monitoring of microbiologically influenced corrosion increasingly employs molecular methods for early detection and species identification, though at high cost and requiring specialized expertise. Artificial intelligence and machine learning prediction models, achieving reliability metrics exceeding 0.85 R^2, enable predictive maintenance and optimization of protection strategies. AI approaches show particular promise for pattern recognition in corrosion data, integration of diverse monitoring inputs, and automated anomaly detection.

Discussion

Fundamental Understanding and Knowledge Gaps:

The electrochemical framework for understanding corrosion, established over 150 years of research, provides robust tools for predicting corrosion susceptibility and designing protection strategies. Thermodynamics, through Gibbs free energy calculations and Pourbaix diagrams, enables assessment of corrosion spontaneity and identification of passivation, immunity, and corrosion regions for metal-environment systems. However, significant gaps persist in understanding corrosion under extreme conditions high temperature, high pressure, and complex multiphase flow which characterize many industrial applications. Mechanistic models, while sophisticated for simplified laboratory conditions, often lack robust validation for field conditions, limiting their predictive accuracy. The role of passive films in corrosion protection is well-recognized, yet passive film breakdown mechanisms remain incompletely understood. Chloride-induced localized corrosion, initiating through mechanisms of film thinning, mechanical breakdown, or local acidification, continues to pose challenges for predictive modeling and prevention. Microbiologically influenced corrosion adds further complexity through the dynamic interplay of biofilm formation, microbial metabolism, and electrochemical reactions. The diversity of corrosive microorganisms and their variable effects across environmental conditions complicate development of universally applicable mitigation strategies.

Performance and Limitations of Mitigation Strategies:

The comparative analysis of protection technologies reveals that each approach offers distinct advantages and limitations that must be balanced in practical applications. Protective coatings, while achieving >90% corrosion reduction, require meticulous surface preparation and application conditions for optimum performance. Coating degradation through environmental exposure, mechanical damage, and disbandment limits service life to 10-25 years, requiring regular inspection and maintenance. Cathodic protection provides reliable electrochemical protection when properly designed and maintained, but effectiveness depends on electrical continuity, electrolyte resistance, and monitoring systems. Inhibitor performance demonstrates the critical gap between laboratory and field application. While inhibitor efficiencies exceeding 95% are routinely reported in controlled laboratory media, field performance often fails to achieve equivalent protection due to temperature fluctuations, flow effects, fluid composition variability, and microbial activity. Green inhibitors, while offering environmental advantages, show particular sensitivity to these factors, with efficiency dropping significantly in aggressive or variable environments. Hybrid inhibitor systems, combining organic and inorganic components, offer potential solutions through synergistic effects that enhance stability and durability.

Self-healing coating technologies, particularly LDH-based systems, represent significant advances in autonomous corrosion protection. The demonstrated 95-99.9% inhibition efficiency and durability of hundreds to thousands of hours highlight the potential for revolutionary improvements in corrosion management. However, challenges including scalability for industrial production, long-term stability of encapsulated inhibitors, dispersion uniformity, and control of premature release must be addressed before widespread deployment becomes feasible.

Environmental and Sustainability Considerations:

The environmental and regulatory drivers toward green, sustainable corrosion management are reshaping research and industrial practice. Traditional inhibitors containing chromates, lead, cadmium, and other toxic species face increasing restrictions, creating market opportunities for environmentally acceptable alternatives. Green inhibitors derived from renewable resources, agricultural wastes, and industrial byproducts offer pathways to reduced environmental footprint, though performance variability and extraction reproducibility present significant challenges.

Biosurfactants represent a promising class of green inhibitors, acting through adsorbed film formation, wettability reduction, interface modification, and, in some cases, antimicrobial effects inhibiting biofilm formation. Their biodegradability, low toxicity, and renewable sourcing align with circular economy principles. However, production costs, extraction efficiency, and formulation stability require optimization for industrial applications.

The economic dimension of corrosion management increasingly incorporates lifecycle cost analysis, considering not only direct material replacement and maintenance costs but also environmental remediation, production losses, and health impacts. NACE estimates that implementing existing corrosion prevention technologies could reduce global corrosion costs by 15-35%, representing annual savings of US$375-875 billion. Achieving these reductions requires integrated approaches combining materials selection, design improvement, active protection, and monitoring, tailored to specific applications and environments.

Monitoring and Digital Transformation:

The evolution of corrosion monitoring from periodic manual inspection to continuous, remote, and AI-enabled assessment represents a transformative shift. Traditional methods including ER probes, LPR sensors, and NDT provide valuable condition data but require physical access and skilled interpretation. IoT sensors enable real-time monitoring across distributed infrastructure, with low-cost sensors and wireless data transmission facilitating comprehensive condition awareness. Machine learning and AI approaches offer pattern recognition capabilities that can identify emerging corrosion issues before visible damage occurs.

Digital twin technologies, integrating physical models with real-time monitoring data, promise predictive maintenance optimization and proactive corrosion management. However, development of robust digital twins requires validation across diverse operational conditions, integration of multiple data streams, and calibration with field performance. The evolution toward predictive, data-driven corrosion management offers potential for significant cost reduction, improved safety, and extended asset life.

Future Directions and Recommendations:

Future corrosion research and practice should prioritize several interconnected areas.

First, standardized, field-relevant testing protocols must be developed to bridge the gap between laboratory inhibitor efficiency and industrial performance.

Second, fundamental understanding of corrosion under extreme conditions high temperature/pressure, multiphase flow, mixed corrosive species requires advancement through combined experimental and modeling approaches.

Third, integration of data-driven discovery with mechanistic understanding offers accelerated inhibitor design and optimization.

Fourth, development of circular-economy-compatible inhibitors emphasizing renewable feedstocks, biodegradability, and recyclability should be prioritized.

Fifth, advancement of monitoring technologies toward real-time, predictive systems, integrated with AI and digital twins, enables proactive maintenance and optimization.

Sixth, understanding microbiologically influenced corrosion mechanisms and developing effective, environmentally acceptable mitigation strategies remains critical for industries including oil and gas, marine infrastructure, and water treatment.

Finally, interdisciplinary collaboration across materials science, electrochemistry, microbiology, data science, and industrial engineering is essential to address the complex, multifaceted challenges of corrosion in modern infrastructure.

Conclusion

This comprehensive review has systematically examined corrosion mechanisms, mitigation strategies, and industrial applications, revealing that corrosion remains one of the most pervasive and economically burdensome challenges confronting modern infrastructure. Annual global costs of US$2.5 trillion, equivalent to 3.4% of global GDP, underscore the imperative for effective corrosion management. Fundamental understanding of electrochemical principles thermodynamics predicting spontaneity, kinetics determining rates provides a robust foundation for corrosion prediction and prevention. The diversity of corrosion morphologies, from uniform and pitting to stress corrosion cracking and microbiologically influenced corrosion, necessitates tailored mitigation approaches. Protective coatings, cathodic protection, inhibitor systems, and emerging self-healing technologies each offer significant corrosion reduction, with efficiencies ranging from >90% to 99.9%. Hybrid and green inhibitor systems show particular promise, combining environmental acceptability with high performance, though challenges persist in field deployment and standardization. Advanced monitoring technologies, including IoT sensors and AI-driven prediction models with reliability exceeding 0.85 R^2, enable proactive corrosion management and optimization of protection strategies. Future research should prioritize bridging laboratory-field performance gaps, developing field-relevant standardized testing, integrating data-driven discovery with mechanistic understanding, and advancing sustainable, circular-economy-compatible inhibitor and coating technologies. The development of digital twins, combining physical modeling with real-time monitoring and predictive analytics, offers transformative potential for corrosion management. Effective corrosion management requires integrated approaches that coordinate materials selection, design, protection, monitoring, and maintenance tailored to specific industrial applications and environmental conditions. In conclusion, corrosion science and engineering have advanced substantially over 150 years of investigation, yet significant challenges remain. The dynamic interplay of environmental factors, operational conditions, and material properties demands ongoing research, interdisciplinary collaboration, and technology development. With proper implementation of existing knowledge and continued advancement of innovative solutions, substantial reductions in global corrosion costs estimated at 15-35% are achievable, delivering economic, safety, and environmental benefits across all industrial sectors.

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Authors' Contributions

All authors contributed to data analysis, drafting, and revising of the paper and agreed to be responsible for all the aspects of this work.

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