J. Chem. Eng. Energy Mater., **(2026),** Volume 2, Issue 1, 58-72

Journal of Chemical Engineering and Energy Materials (JCEEM)

Journal homepage: https://www.jceem.com/

DOI: https://doi.org/10.5281/zenodo.21700214

Advances in Corrosion Science: From Fundamental Electrochemical Processes to Innovative Protective Technologies

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Article info
Received: 14.05.2026
Accepted: 27.07.2026
Available Online: 28.10.2026
Checked for Plagiarism: Yes

Keywords:
Corrosion mechanisms, smart coatings, self-healing materials, nanotechnology, machine learning, corrosion monitoring

ABSTRACT

Corrosion, the electrochemical degradation of metals, remains a critical global challenge with annual economic losses estimated at 3.4-5% of GDP in industrialized nations. This comprehensive review synthesizes recent advances in corrosion science, spanning fundamental electrochemical mechanisms to innovative protective technologies. The electrochemical framework governing corrosion thermodynamics and kinetics is examined through the lens of recent discoveries, including the role of passive film breakdown in localized attack and the emergence of microbiologically influenced corrosion as a pervasive threat across industries. Advanced characterization techniques, including electrochemical impedance spectroscopy and atomic force microscopy, have provided unprecedented insights into nanoscale corrosion initiation and propagation. The review systematically evaluates three transformative protection paradigms: smart self-healing coatings achieving market projections of USD 10.4 billion by 2028 through autonomous damage repair; MOF-oligomer nanocomposites that synergistically integrate pH-triggered inhibitor release with redox-mediated passivation, demonstrating inhibition efficiencies of 75.62% and self-healing improvement of 229.67% ; and AI-driven monitoring frameworks achieving R^2 >0.99 prediction accuracy for dynamic corrosion rate forecasting . Particular attention is devoted to sustainable solutions, including green inhibitors derived from renewable sources, nanotechnology-based multifunctional coatings, and integrated digital twin systems that bridge physics-based simulation with real-time IoT sensing. The review concludes that next-generation corrosion management requires convergent approaches combining mechanistic understanding, advanced materials, data-driven analytics, and environmental sustainability.

Introduction

Corrosion, defined as the electrochemical or chemical deterioration of metallic materials through interaction with their environment, constitutes one of the most pervasive and economically burdensome challenges confronting modern industry and infrastructure [1-8].

This natural degradation process, often described as "reverse metallurgy," occurs when refined metals revert to thermodynamically stable oxide or salt forms, exemplifying the fundamental drive toward lower energy states [9-17]. The consequences of corrosion extend far beyond material loss, encompassing catastrophic infrastructure failures, significant economic disruption, profound safety hazards, and substantial environmental contamination [18-26].

Recent estimates from the World Corrosion Organization indicate that corrosion accounts for approximately 5% of GDP in industrialized nations,

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with global costs exceeding 4.2% of world GDP. The Association for Materials Protection and Performance (AMPP) estimates that implementing existing corrosion prevention technologies could generate global savings of approximately USD 875 billion, representing 35% of total corrosion costs.

The fundamental understanding of corrosion has advanced substantially since Faraday's seminal electrochemical investigations [27-35]. Modern corrosion science recognizes corrosion as comprising two half-reactions occurring simultaneously: anodic oxidation (metal dissolution) and cathodic reduction (typically oxygen or hydrogen ion consumption). Thermodynamics, through Gibbs free energy calculations and Pourbaix diagrams, enables prediction of corrosion spontaneity, while kinetics governs actual degradation rates through activation and concentration polarization mechanisms. The concept of passivity where metals spontaneously form protective oxide films has proven critical for alloy design, yet passive films remain susceptible to breakdown in aggressive environments containing chloride ions or other DE passivating species [36].

The diversity of corrosion morphologies demands tailored mitigation approaches. Uniform corrosion, the most predictable form, enables straightforward lifetime prediction through corrosion allowance methods [37-50]. However, localized forms including pitting, crevice, intergranular, and stress corrosion cracking pose particular dangers due to their hidden nature and potential for sudden catastrophic failure. Microbiologically Influenced Corrosion (MIC) has emerged as an especially complex challenge, involving biofilm formation, microbial metabolism, and dynamic electrochemical-microbial interactions that produce unpredictable degradation patterns across marine, oil and gas, and water treatment environments.

Recent technological advances have revolutionized corrosion protection strategies. Smart self-healing coatings, incorporating microcapsules, nanocontainers, or vascular networks, can autonomously detect and repair damage through stimuli-responsive release of corrosion inhibitors or healing agents. Metal-organic framework (MOF) based systems demonstrate dual functionality: pH-triggered inhibitor release and redox-mediated passivation [51-60]. Nanotechnology-based coatings, incorporating graphene, layered double hydroxides, or ceramic nanoparticles, provide enhanced barrier properties and multi-functional protection. Concurrently, digital transformation has introduced AI-driven monitoring frameworks, IoT sensing, and digital twin technologies that enable predictive corrosion management with unprecedented accuracy [61-70]. This comprehensive review aims to synthesize current mechanistic understanding with critical evaluation of emerging protection technologies. It is structured to first establish fundamental electrochemical principles and corrosion classification, followed by systematic examination of transformative technologies including smart coatings, MOF-based systems, nanotechnology solutions, and AI-enabled monitoring [71-80]. Particular attention is devoted to sustainable, environmentally compatible approaches and integrated frameworks that bridge laboratory mechanistic understanding with field-applicable, economically viable solutions.

Literature Review

Historical Foundations and Economic Significance:

Scientific investigation of corrosion spans over 150 years, establishing fundamental electrochemical principles that remain central to contemporary research and industrial practice. Faraday's pioneering work established the electrochemical nature of corrosion, enabling understanding of oxidation-reduction reactions occurring at anodic and cathodic sites on metallic surfaces. The subsequent development of the Nernst equation provided thermodynamic frameworks for predicting electrode potentials as functions of temperature and reactant activities, laying foundations for corrosion susceptibility assessment [81-90]. Pourbaix's introduction of potential-pH diagrams mapping corrosion, passivation, and immunity regions represented a landmark contribution, providing a foundational tool for corrosion prediction and materials selection [91-100].

The economic significance of corrosion systematically quantified through major studies including the seminal NACE IMPACT study and subsequent analyses. The World Corrosion Organization estimates corrosion accounts for approximately 5% of GDP in industrialized nations, with global costs exceeding 4.2% of world GDP. Replacement of steel affected by corrosion accounted for an estimated 1.6-3.4% of global CO_2 emissions in 2021, while new steel production contributed approximately 10.5% of total emissions a figure forecast to rise to 27.5% of global manufacturing emissions by 2030. The US Department of Defense reported that every $1 invested in corrosion protection for helicopter wash systems generated a return of $31 within two years, illustrating the substantial economic benefits of proactive corrosion management [101-110].

Electrochemical Mechanisms and Corrosion Classification:

Modern understanding recognizes corrosion as fundamentally electrochemical, comprising anodic and cathodic half-reactions proceeding at equal rates to maintain electroneutrality. Thermodynamics predicts corrosion spontaneity through Gibbs free energy calculations ($\Delta G = -nFEcell \Delta G = -nFEcell$), while kinetics determines corrosion rates, governed by activation polarization, concentration polarization, and ohmic resistance. The concept of passivity spontaneous formation of thin oxide films (typically 1-10 nm) that dramatically reduce corrosion rates has attracted substantial research attention. However, passive films are susceptible to localized breakdown in aggressive environments containing chloride ions, leading to pitting, crevice, and stress corrosion cracking [111-120].

Corrosion manifests through diverse morphologies, each with characteristic mechanisms requiring specific mitigation approaches. Pitting corrosion, characterized by small cavities 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 corrosive environments, leading to unexpected failure often without significant visible corrosion. Microbiologically Influenced Corrosion involves microorganisms forming biofilms that alter local chemistry, create concentration cells, and produce corrosive metabolites including acids and hydrogen sulfide [121].

Microbiologically Influenced Corrosion: A Complex Challenge:

MIC has emerged as a critical concern across industries, characterized by dynamic interactions between microbial communities, biofilms, and metallic surfaces. 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 through concentration cell mechanisms. The complexity of MIC requires integrated approaches combining materials selection, biocide treatment, biofilm disruption strategies, and advanced monitoring techniques.

Recent advances in molecular biology have significantly enhanced MIC understanding. Multi-omics approaches, including genomics, transcriptomics, and proteomics, have identified corrosion-related genes, proteins, and metabolic pathways. Gene editing technologies enable functional characterization of microbial factors driving corrosion. However, the dynamic and multifactorial nature of microbial-material interactions continues to present challenges for prediction and control, necessitating interdisciplinary collaboration across microbiology, materials science, and corrosion engineering.

Smart and Self-Healing Coatings:

Smart self-healing coatings represent a transformative advancement in corrosion protection, offering dynamic responses to environmental stimuli including pH fluctuations, temperature changes, and mechanical damage. These intelligent systems are typically defined by three interconnected actions: (1) damage detection (stimulus sensing), (2) response activation (triggering release of active agents), and (3) repair or restoration of affected areas. Self-healing coatings are classified into autonomous and non-autonomous systems, with intrinsic mechanisms involving reversible bonds and extrinsic mechanisms employing encapsulated healing agents.

Market projections indicate the self-healing coatings market is expected to reach approximately USD 10.4 billion by 2028, driven by applications across automotive, construction, and aerospace sectors. Recent developments include pH-responsive coatings for metal substrates, which are versatile and easily combined with other stimulants for diverse applications from industrial equipment to biomedical devices. The integration of sustainable inhibitors, including plant-based phytochemicals, further underscores the shift toward environmentally friendly solutions [122].

Nanotechnology and Advanced Materials:

Nanotechnology has inspired a new generation of protective coatings with superior performance. Inorganic nanoparticles including silica, titania, and ceria enhance barrier density and adhesion, while layered clays and double hydroxides impart tortuous diffusion paths and inhibitor release capability. Carbon-based nanomaterials graphene, graphene oxide, and carbon nanotubes offer unique two-dimensional or fibrous architectures creating highly effective barriers, though their long-term behavior depends strongly on dispersion, orientation, and defect control. Metal-organic frameworks (MOFs) have emerged as promising nanocontainers for corrosion protection, constructed from organic linkers and metal ions through strong coordination bonds. UiO-66, a representative Zirconium-based MOF, exhibits outstanding thermal stability, high surface areas, tunable chemical frameworks, and pH-responsive behavior. Tetra aniline-functionalized UiO-66 nanocomposites demonstrate dual functionality: pH-triggered inhibitor release (13-fold increase under alkaline conditions) and redox-mediated passivation enhancing protective film formation. Conductive polymers and hybrid composites integrate active passivation with structural reinforcement, while self-healing nanocontainer systems autonomously restore protection at damaged sites.

AI-Driven Monitoring and Digital Twins:

Recent advances in artificial intelligence and IoT technologies have revolutionized corrosion monitoring, enabling transition from static prediction to dynamic, data-driven intelligence. Distributed fiber optic sensors (DFOS) provide continuous measurements over distances exceeding 100 km, enabling both global and local damage assessment. Machine learning models automate analysis of DFOS data, achieving detection accuracy >0.98 for cracks and corrosion, with prediction capabilities of 7 minutes ahead for cracks and 21 hours ahead for corrosion.

Integrated monitoring frameworks combining physics-based simulation, IoT sensing, and deep learning demonstrate exceptional performance. Hybrid SSA-CNN-BiGRU models achieve R^2=0.99165 and RMSE = 0.01283 for corrosion rate prediction, effectively capturing nonlinear feature interactions and temporal dependencies. These frameworks support transition from reactive repair to proactive intervention through dynamic early warning mechanisms and cloud-based data integration. Digital twin technologies, combining physical modeling with real-time monitoring and predictive analytics, offer transformative potential for infrastructure integrity management.

Methodology

This comprehensive review developed through systematic analysis of peer-reviewed literature indexed in major scientific databases including Scopus, Web of Science, Science Direct, PubMed, and Google Scholar. The search strategy employed combinations of keywords including "corrosion mechanisms," "electrochemical corrosion," "smart coatings," "self-healing coatings," "nanotechnology corrosion protection," "microbiologically influenced corrosion," "corrosion monitoring," "machine learning corrosion," and related terms. Particular emphasis was placed on studies published between 2020 and 2026, while seminal earlier works were included were mechanistically or historically significant. The literature screening process involved identification of peer-reviewed research articles, review papers, and industry reports. Studies 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 chosen based on clear presentation of experimental methodology, characterization results, and performance metrics. Publications lacking sufficient methodological detail or quantitative performance data excluded. Priority given to studies examining fundamental mechanisms, emerging protection technologies, and field-applicable monitoring approaches.

Environmental and sustainability considerations examined through analysis of regulatory requirements (including REACH regulations), green chemistry principles, and lifecycle assessment approaches. Market projections and economic analyses extracted from industry reports and published market analyses.

Results

Table 1. Comparative Performance of Smart Self-Healing Coating Systems

Coating Type	Mechanism	Healing/Inhibition Efficiency (%)	Key Advantages	Primary Limitations	Industrial Applications
Microcapsule-Based	Autonomous-extrinsic	80-95	Rapid localized repair, proven technology	Limited healing cycles, capsule scalability	Automotive, construction
MOF-Oligomer Nanocomposite	pH-triggered release + redox passivation	75.62% (inhibition), 229.67% (healing improvement)	Dual functionality, long-term durability	Complex synthesis, scalability challenges	Marine, oil & gas pipelines
Vascular Network Systems	Continuous healing agent supply	85-95	Multiple healing cycles, large-volume repair	Manufacturing complexity, network integration	Aerospace, high-value infrastructure
Shape Memory Polymers	Non-autonomous intrinsic	70-85	Reversible healing, no encapsulated agents	Limited to specific damage types, activation requirements	Automotive, consumer goods
LDH-Based Systems	Ion-exchange triggered release	95-99.9	Autonomous repair, long-term stability	Premature release, dispersion uniformity	Marine protective coatings

Data compiled from references.

Analysis of Table 1: The comparative analysis reveals substantial progress in smart coating technologies, with each system offering distinct mechanisms and performance characteristics. Microcapsule-based systems demonstrate 80-95% healing efficiency through autonomous-extrinsic mechanisms, representing the most mature and proven technology for industrial applications. However, limited healing cycles and capsule scalability present challenges for extended service life requirements.

MOF-oligomer nanocomposite systems represent a significant innovation, integrating pH-triggered inhibitor release with redox-mediated passivation. UiO-66-PDA@TANI demonstrated 75.62% corrosion inhibition efficiency in saline solution and 229.67% healing improvement in artificial defect experiments, indicating localized protection beyond pristine coatings. The system's dual functionality rapid inhibitor delivery via pH-induced framework disintegration and passivation film regeneration via enhanced TANI redox cycling provides both immediate and long-term protection.

Vascular network systems enable multiple healing cycles through continuous healing agent supply, achieving 85–95% efficiency with application to high-value infrastructure requiring extended service life. Shape memory polymers, operating through non-autonomous intrinsic mechanisms, offer reversible healing without encapsulated agents, though limited to specific damage types. LDH-based self-healing systems exhibit exceptional performance (95–99.9% inhibition efficiency) through ion-exchange triggered release mechanisms, representing a frontier technology.

Table 2. Nanotechnology-Based Corrosion Protection Approaches

Nanomaterial Type	Protection Mechanism	Efficiency	Key Properties	Application Mode	Development Status
Silica Nanoparticles	Barrier enhancement, adhesion improvement	85-95%	High surface area, tunable porosity	Coating filler	Commercial
Graphene/Graphene Oxide	Barrier (2D architecture), active inhibition	90-98%	Impermeable, high aspect ratio	Coating additive	Emerging commercial
Layered Double Hydroxides	Tortuous path, inhibitor release	95-99.9%	Ion exchange capacity, self-healing	Coating additive	Research/Development
Carbon Nanotubes	Barrier, mechanical reinforcement	80-90%	High aspect ratio, conductivity	Coating filler	Research
Ceramic Nanoparticles (TiO_2, CeO_2)	Barrier density, UV stability	85-95%	Hardness, chemical stability	Coating additive	Commercial
Conductive Polymers (PANI, TANI)	Redox-mediated passivation	75-90%	Electron conduction, film formation	Coating filler	Research

Data compiled from references.

Analysis of Table 2: Nanotechnology-based approaches demonstrate significant corrosion protection enhancement through diverse mechanisms. Silica nanoparticles and ceramic oxides (TiO_2, CeO_2) primarily function through barrier enhancement and adhesion improvement, achieving 85-95% efficiency and representing commercially mature technologies. Carbon-based nanomaterials graphene, graphene oxide, and carbon nanotubes offer unique architectures creating highly effective barriers, with graphene achieving 90-98% efficiency through impermeable 2D architecture. However, long-term performance depends critically on dispersion, orientation, and defect control.

Layered double hydroxides (LDHs) represent a particularly promising technology, achieving 95-99.9% inhibition efficiency through ion-exchange triggered inhibitor release and tortuous diffusion paths. LDH-based systems function through ion-exchange mechanisms triggered by local environmental changes, releasing corrosion inhibitors precisely at damage sites, enabling autonomous self-healing functionality.

Conductive polymers including polyaniline (PANI) and its short-chain analogue tetra aniline (TANI) provide protection through redox-mediated passivation, promoting formation of protective metal oxide layers. TANI, with shorter and more ordered molecular architecture, demonstrates enhanced electron transfer efficiency compared to PANI, capturing electrons released at anodic corrosion sites to facilitate compact Fe_2O_3/Fe_3O_4 passivation film formation. The integration of MOF structures with TANI further enhances electron transport and redox cycling efficiency, representing an emerging research frontier.

Table 3. Electrochemical Monitoring and AI Prediction Technologies

Technology	Accuracy	Application	Key Advantages	Development Status	Data/Output Type
LPR Sensors	±5-10%	Uniform corrosion rate	Rapid, non-destructive	Mature	Real-time corrosion rate
ER Probes	±1-5%	General corrosion monitoring	Robust, real-time	Mature	Cumulative metal loss
EIS	High sensitivity	Mechanistic characterization	Detailed kinetic information	Mature	Impedance spectra
NDT (UT, AET)	±0.1 mm wall loss	Structural integrity	In-service inspection	Commercial	Wall thickness, defects
DFOS Monitoring	>98% accuracy	Distributed strain/temperature	Continuous long-haul coverage	Emerging	Spatiotemporal strain
AI Hybrid Models (SSA-CNN-BiGRU)	$R^2>0.99$	Dynamic corrosion prediction	Nonlinear feature extraction	Development	Corrosion rate forecasting
IoT + Cloud Systems	Real-time	Remote continuous monitoring	Integration, early warning	Emerging	Multi-parameter data

Data compiled from references.

Analysis of Table 3: Corrosion monitoring technology evolution demonstrates progression from discrete measurements to continuous, integrated, and predictive systems. Traditional techniques including LPR sensors (±5-10% accuracy), ER probes (±1-5%), and EIS provide valuable real-time data with established commercial application. Non-destructive testing methods including ultrasonic testing and acoustic emission provide high-accuracy (±0.1 mm) wall loss measurements for structural integrity assessment. Distributed fiber optic sensors represent a transformative technology, enabling continuous strain and temperature measurements over distances exceeding 100 km. Machine learning analysis of DFOS data achieves >98% detection accuracy and enables prediction capabilities (7 minutes ahead for cracks, 21 hours ahead for corrosion). The integration of spatiotemporal measurements with generative AI techniques improves data quality and mitigates dataset imbalance issues.

AI hybrid models demonstrate exceptional performance for dynamic corrosion prediction. The SSA-CNN-BiGRU framework, combining swarm intelligence optimization (SSA) with convolutional neural networks (CNN) for feature extraction and bidirectional gated recurrent units (BiGRU) for temporal dependency capture, achieved $R^2=0.99165$ with RMSE=0.01283. IoT-enabled data transmission with cloud integration supports real-time corrosion monitoring and early warning capabilities, enabling transition from reactive repair to proactive intervention.

Table 4. Corrosion Inhibitor Systems: Performance and Sustainability

Inhibitor Type	Mechanism	Efficiency (%)	Environmental Profile	Key Advantages	Limitations
Traditional Chromate-Based	Passivation, oxide film formation	85-98	Highly toxic, persistent	High reliability, established protocols	Toxicity, regulatory restrictions
Green Organic (Plant Extracts)	Adsorption (physisorption/chemisorption)	70-92	Low toxicity, renewable	Biodegradable, sustainable	Performance variability
MOF-Based Inhibitors	pH-responsive release + metal ion passivation	75-90	Moderate toxicity	Controlled release, dual function	Complexity, cost

Bio-Based Surfactants	Adsorbed film, interface modification	70-85	Biodegradable, renewable	Environmentally compatible	Production costs, stability
Hybrid Organic-Inorganic	Synergistic (barrier + inhibition)	90-98	Moderate toxicity	Enhanced durability, multifunctionality	Complexity, formulation challenges
Ionic Liquids/Deep Eutectic Solvents	Adsorption, interface modification	80-95	Variable toxicity	Tunable properties	Cost, environmental data limited

Data compiled from references.

Analysis of Table 4: The comparative analysis reveals significant progress toward sustainable corrosion inhibition, driven by environmental regulations and green chemistry principles. Traditional chromate-based inhibitors achieve 85-98% efficiency through established passivation mechanisms, but face increasing regulatory restrictions due to toxicity and environmental persistence. Green organic inhibitors, derived from renewable sources including plant extracts, agricultural wastes, and microbial products, demonstrate 70-92% efficiency with low toxicity and biodegradability. However, performance variability and extraction reproducibility present challenges for standardization.

MOF-based inhibitors integrate pH-responsive release with metal ion passivation, achieving 75-90% efficiency through controlled release mechanisms. Bio-based surfactants represent a promising class of green inhibitors, acting through adsorbed film formation, wettability reduction, and interface modification, with antimicrobial effects inhibiting biofilm formation. Hybrid organic-inorganic systems combine barrier properties with active inhibition, achieving 90-98% efficiency through synergistic mechanisms. Ionic liquids and deep eutectic solvents offer tunable properties for specific applications, though environmental data remains limited. The shift toward sustainable, environmentally compatible inhibitors requires continued investment in green chemistry, standardization of testing protocols, and lifecycle assessment approaches.

Discussion

Fundamental Understanding and Emerging Mechanisms:

The electrochemical framework for understanding corrosion continues to provide robust tools for predicting 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. However, significant gaps persist in understanding corrosion under extreme conditions high temperature, high pressure, complex multiphase flow which characterize many industrial applications. Mechanistic models, while sophisticated for simplified laboratory conditions, often lack robust validation for field conditions, limiting 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. Recent advances in characterization techniques including in-situ SEM, HR-TEM, and atomic force microscopy provide unprecedented insights into nanoscale corrosion initiation, enabling fundamental understanding of passive film stability and breakdown mechanisms.

Microbiologically influenced corrosion adds further complexity through the dynamic interplay of biofilm formation, microbial metabolism, and electrochemical reactions. Recent advances in molecular biology have identified corrosion-related genes, proteins, and metabolic pathways, while multi-omics approaches provide systems-level understanding of microbial corrosion mechanisms. However, the diversity of corrosive microorganisms and their variable effects across environmental conditions complicate development of universally applicable mitigation strategies.

Performance and Limitations of Smart Protection Technologies

The emergence of smart self-healing coatings represents a paradigm shift in corrosion protection, offering dynamic responses to environmental stimuli and autonomous damage repair. Market projections of USD 10.4 billion by 2028 reflect substantial industrial interest and investment. However, significant challenges persist in technology translation from laboratory to field application. Microcapsule-based systems, while demonstrating 80-95% healing efficiency in controlled environments, face limitations in healing cycle sustainability, capsule scalability, and long-term stability under variable service conditions.

MOF-based nanocomposite systems show particular promise, integrating pH-triggered inhibitor release with redox-mediated passivation. The UiO-66-PDA@TANI systems demonstrated 75.62% inhibition efficiency and 229.67% healing improvement represent significant advances, yet challenges including scalability for industrial production, dispersion uniformity, and premature release control addressed. The synergistic interplay between MOF structures and conductive oligomers enables dual protection mechanisms rapid inhibitor delivery via framework disintegration and passivation film regeneration via enhanced redox cycling. Nanotechnology-based approaches demonstrate transformative potential for corrosion protection, yet challenges persist in long-term durability assessment under realistic environmental conditions, standardized performance evaluation, and lifecycle environmental impact analysis. Carbon-based nanomaterials, while offering exceptional barrier properties through 2D architectures, show performance critically dependent on dispersion, orientation, and defect control factors that require careful optimization for commercial application.

Digital Transformation and Predictive Capabilities

The integration of AI, IoT, and digital twin technologies represents a transformative shift in corrosion monitoring and management. Hybrid machine learning models achieving R^2>0.99 prediction accuracy demonstrate the potential for dynamic, data-driven corrosion forecasting. The SSA-CNN-BiGRU framework, combining physics-informed simulation with IoT sensing and deep learning, enables transition from reactive repair to proactive intervention through real-time monitoring and early warning capabilities.

Distributed fiber optic sensors provide continuous strain and temperature measurements enabling both global and local damage assessment. Machine learning analysis achieves >98% detection accuracy and enables prediction capabilities 7 minutes ahead for cracks and 21 hours ahead for corrosion supporting predictive maintenance and optimized operation management. Digital twin technologies, combining physical models with real-time monitoring data, promise transformative potential for proactive corrosion management. However, challenges persist in development of robust digital twins requiring validation across diverse operational conditions, integration of multiple data streams, and calibration with field performance. Standardized data formats, sensor calibration protocols, and machine learning model validation frameworks are needed to enable widespread adoption. The evolution toward predictive, data-driven corrosion management offers potential for significant cost reduction, improved safety, and extended asset life.

Environmental Sustainability and Green Solutions

Biosurfactants represent a promising class of green inhibitors, acting through adsorbed film formation, wettability reduction, interface modification, and 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. Plant-based phytochemical inhibitors offer sustainable alternatives, with recent research focusing on standardization of extraction protocols and performance optimization. The economic dimension of corrosion management increasingly incorporates lifecycle cost analysis, considering direct material replacement and maintenance costs, environmental remediation, production losses, and health impacts. The AMPP estimate that implementing existing corrosion prevention technologies could generate savings of approximately USD 875 billion (35% of total corrosion costs) highlights substantial economic opportunity. Achieving these reductions requires integrated approaches combining materials selection, design improvement, active protection, and monitoring, tailored to specific applications and environments.

Conclusion

This comprehensive review has examined recent advances in corrosion science, spanning fundamental electrochemical processes to innovative protective technologies. Corrosion remains a critical global challenge with annual economic losses estimated at 3.4-5% of GDP in industrialized nations, driving urgent need for effective, sustainable management solutions. Fundamental understanding of electrochemical principles thermodynamics predicting spontaneity, kinetics determining rates provides robust foundations for corrosion prediction and prevention. Three transformative protection paradigms have emerged. Smart self-healing coatings, incorporating microcapsules, MOF-based systems, and vascular networks, enable autonomous damage repair and stimuli-responsive protection. UiO-66-PDA@TANI nanocomposites demonstrate dual functionality: pH-triggered inhibitor release (13-fold increase under alkaline conditions) and redox-mediated passivation, achieving 75.62% inhibition efficiency and 229.67% healing improvement. Nanotechnology-based approaches, including carbon-based nanomaterials, LDH systems, and conductive polymers, provide enhanced barrier properties and multifunctional protection.

AI-driven monitoring frameworks have revolutionized corrosion management, with hybrid machine learning models achieving R^2>0.99

prediction accuracy for dynamic corrosion rate forecasting. Distributed fiber optic sensors with machine learning analysis enable >98% detection accuracy and predictive capabilities supporting proactive intervention. Digital twin technologies, combining physical modeling with real-time monitoring and predictive analytics, offer transformative potential for infrastructure integrity management.

Environmental sustainability has emerged as a critical driver, with green inhibitors derived from renewable sources and biodegradable materials offering reduced environmental footprint. Regulatory pressures increasingly restrict traditional toxic inhibitors, creating market opportunities for sustainable alternatives. The shift toward circular-economy-compatible solutions emphasizes renewable feedstocks, biodegradability, and recyclability.

Future research should prioritize development of standardized, field-relevant testing protocols; fundamental understanding of corrosion under extreme conditions; integration of data-driven discovery with mechanistic understanding; advancement of real-time, predictive monitoring technologies; and interdisciplinary collaboration across materials science, electrochemistry, microbiology, and data science. With continued advancement of innovative solutions and implementation of existing knowledge, substantial reductions in global corrosion costs estimated at 35% are achievable, delivering economic, safety, and environmental benefits across all industrial sectors.

Disclosure Statement

No potential conflict of interest reported by the authors.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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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