Journal of Chemical Engineering and Energy Materials (JCEEM)

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

DOI: https://doi.org/10.5281/zenodo.21701236

Microbiologically Influenced Corrosion (MIC): Mechanisms, Detection, and Control Strategies in Industrial Systems

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Article info

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

Keywords:
Microbiologically influenced corrosion, sulfate-reducing bacteria, biofilms, extracellular electron transfer, corrosion monitoring

ABSTRACT

Microbiologically influenced corrosion (MIC) represents one of the most complex and destructive forms of material degradation, accounting for approximately 20% of global corrosion-related economic losses. This comprehensive review systematically examines the multifaceted nature of MIC, from fundamental mechanistic understanding to advanced detection methodologies and sustainable control strategies. The electrochemical framework governing MIC involves distinct mechanisms including extracellular electron transfer (EET-MIC), metabolite-mediated corrosion (M-MIC), and biofilm-driven microenvironmental alterations. Sulfate-reducing bacteria (SRB) emerge as primary culprits, responsible for approximately 75% of production well corrosion issues and 50% of pipeline system failures in the oil and gas sector. Recent advances in molecular biology, including multi-omics approaches (genomics, transcriptomics, proteomics) and gene editing technologies, have provided unprecedented insights into corrosion-related genes, proteins, and metabolic pathways. Detection methodologies have evolved from traditional culture-based techniques to sophisticated biosensors, electrochemical monitoring, and AI-driven predictive frameworks achieving >98% detection accuracy. Mitigation strategies encompass biocides, nanomaterials, coatings, quorum sensing inhibition, and emerging enzymatic remediation approaches. The review concludes that effective MIC management requires integrated, interdisciplinary approaches combining mechanistic understanding, advanced monitoring, and sustainable control technologies.

Introduction

Corrosion represents one of the most pervasive and economically burdensome challenges confronting modern industrial infrastructure, with annual global costs estimated at approximately $2.5 trillion, equivalent to 3-4% of GDP in industrialized nations [1]. Within this macrocosm, microbiologically influenced corrosion (MIC) stands as an exceptionally aggressive variant, accounting for an estimated 20% of aggregate corrosion losses worldwide [2].

Unlike purely abiotic electrochemical corrosion, MIC involves the dynamic interaction between microorganisms and metal surfaces, resulting in accelerated degradation through complex biological-electrochemical mechanisms that remain incompletely understood [3]. The ubiquity of MIC spans virtually all industrial sectors. In the oil and gas industry, MIC manifests extensively across extraction, transportation, and processing operations, causing structural damage to pipelines, storage tanks, and drill rods, potentially triggering fires, explosions, and significant economic losses.

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Statistical analyses indicate that 75% of production oil well corrosion issues and 50% of pipeline system failures are attributed to MIC. Marine environments, water utilities, offshore infrastructure, railways, and even biomedical implants face similar threats from diverse microbial communities [4-10]. The railway sector exemplifies the hidden nature of MIC, where open toilets and animal feces on tracks create conditions for microbial corrosion, compromising rail steel integrity and service life. The complexity of MIC arises from the intricate interplay of multiple factors: microbial species composition, biofilm structure, metabolic activities, environmental conditions (temperature, pH, salinity, humidity), and material properties. Unlike conventional corrosion driven by physicochemical interactions, MIC exhibits significantly more complex behaviors due to the central role of biofilms structured layers of microorganisms that alter local electrochemical environments through metabolite production, oxygen depletion, electron harvesting, and creation of differential aeration cells [11-20]. The dynamic and multifactorial nature of microbial-material interactions makes MIC notoriously difficult to predict, detect, and control using traditional approaches [21].

Recent technological advances have revolutionized MIC research and management. Advanced microbial technologies including multi-omics (genomics, transcriptomics, proteomics), gene editing, and biosensing provide unprecedented insights into corrosion mechanisms. Nanomaterials offer precision engineering capabilities for biofilm disruption and targeted biocide delivery [22-30]. AI-driven monitoring frameworks and IoT sensors enable real-time, predictive corrosion management with exceptional accuracy. These developments herald a paradigm shift from reactive repair to proactive, sustainable MIC management. This comprehensive review aims to synthesize current understanding of MIC across four interconnected domains: fundamental mechanisms of microbial corrosion, advanced detection and monitoring methodologies, state-of-the-art mitigation strategies, and future perspectives. Particular emphasis is placed on emerging technologies that bridge laboratory mechanistic understanding with field-applicable, environmentally sustainable solutions [31].

Literature Review

Historical Context and Economic Significance:

Scientific investigation of MIC spans several decades, with early research linking corrosion to microbial activity through observations of accelerated steel degradation in environments harboring sulfate-reducing bacteria (SRB). The seminal recognition that microorganisms could influence corrosion rates transformed understanding of material degradation in natural and engineered environments [32-34]. Over subsequent decades, researchers identified diverse microbial species involved in corrosion, including bacteria, fungi, and archaea, and established fundamental mechanisms governing microbial-metal interactions. The economic significance of MIC has been systematically quantified through industry studies and government reports [35-45]. The global corrosion expenditure attributable to MIC is estimated at approximately 20% of total corrosion costs, translating to hundreds of billions of dollars annually. Within the oil and gas sector, MIC-related damages to pipelines, storage tanks, and processing equipment represent substantial operational costs and safety risks. The US gas pipeline industry alone incurs billions of dollars in annual losses from MIC. Replacement of steel affected by corrosion contributes significantly to global CO_2 emissions, with MIC playing a substantial role in this environmental footprint.

Key Microorganisms and Metabolic Pathways

MIC is driven by diverse microbial consortia rather than isolated species, forming complex synergistic or competitive metabolic relationships within biofilms. The primary corrosive microorganisms are categorized based on oxygen requirements and metabolic pathways:

- ✓ **Sulfate-Reducing Bacteria (SRB):** SRB are considered the primary cause of MIC in pipeline systems, responsible for approximately 75% of production well corrosion issues. These anaerobic bacteria utilize sulfate as terminal electron acceptor, producing hydrogen sulfide (H_2S) that accelerates cathodic depolarization and promotes hydrogen embrittlement [46-55]. The metabolic product ferrous sulfide (FeS) is typically detected in rust layers of corroded steel.
- ✓ **Sulfur-Oxidizing Bacteria (SOB):** SOB oxidize sulfur compounds, generating sulfuric acid that creates highly corrosive acidic microenvironments. These bacteria often coexist with SRB in biofilm communities, creating synergistic corrosion effects.
- ✓ **Metal-Oxidizing Bacteria:** Iron-oxidizing bacteria contribute to corrosion through oxidation of ferrous to ferric ions, creating differential aeration cells that drive localized pitting.
- ✓ **Other Microorganisms:** Aerobic bacteria, fungi, and archaea participate in MIC through various mechanisms including organic acid production, oxygen depletion, and creation of concentration cells.

MIC Mechanisms

After decades of research, scientists have identified several mechanisms explaining MIC, primarily categorized into three frameworks:

- ✓ **Extracellular Electron Transfer MIC (EET-MIC):** This mechanism involves bacteria utilizing electrons derived from iron oxidation for metabolic processes such as sulfate reduction [56-70]. Two routes of electron transfer are utilized: direct electron transfer (DET), where bacteria make direct contact with the metal surface or connect via pili, and mediated electron transfer (MET), where soluble electron transfer mediators (e.g., c-type cytochromes) shuttle electrons from the steel surface to the cell wall. The oxidation of Fe couples with sulfate reduction to produce ferrous sulfide.
- ✓ **Metabolite-MIC (M-MIC):** This mechanism involves microorganisms producing deleterious metabolites that facilitate corrosion reactions [71-80]. The primary route involves biofilm formation on metal surfaces, where extracellular polymeric substances (EPS) create gradients of chemical species and pH that facilitate galvanic microcell formation on the steel surface, exacerbating corrosion.
- ✓ **Biodegradation-MIC (BD-MIC):** This involves breakdown of organic macromolecules by microorganisms to obtain nutrients, occurring readily in the presence of organic contaminants serving as nutrients, oxidants, moisture, optimal pH, and favorable temperature.

Biofilm Formation and Micro environmental Alteration

Biofilms represent the central feature distinguishing MIC from conventional corrosion. Sessile microbial populations within biofilms not only generate corrosive byproducts (organic acids, sulfides) but also alter local electrochemical gradients through electron harvest, oxygen depletion, metabolite accumulation, and ion selectivity]81-90\. The nature and severity of MIC are closely linked to microbial species, abundance, and spatial organization within the biofilm. The EPS matrix serves multiple functions in MIC: encapsulating both live and dead cells, creating diffusion barriers that protect microorganisms from biocides (conferring 100-1000 times greater resistance than planktonic counterparts), and establishing local microenvironments with distinct pH, redox potential, and ionic flux. These biofilm-induced alterations effectively bypass conventional protective barriers through clandestine metabolic pathways, making MIC an insidious threat.

Environmental and Operational Factors:

MIC is influenced by multiple environmental and operational factors that create conditions favorable for microbial growth and corrosion. Temperature, pH, humidity, and salinity significantly affect corrosion rates. In oil and gas pipelines, dynamic environmental chemistries, coating disbandment, scale/deposit accumulation, and degradable carbon sources from agricultural/industrial activities provide alternate nutrients boosting microbial metabolism. Synergistic effects between hydrogen permeation, cathodic overprotection, and stray AC current exacerbate MIC in steel pipes [91-100]. These multi-factor couplings complicate prediction and control, necessitating integrated management approaches.

Research Gaps and Challenges

Despite substantial progress, several research gaps persist in MIC science and engineering. The dynamic and multifactorial nature of microbial-material interactions, combined with diverse microbial communities, presents challenges for prediction and control. Corrosion in hidden places and beneath materials remains difficult to detect, requiring routine inspections and advanced techniques [101-110]. Environmental factors such as temperature and humidity greatly influence corrosion rates, complicating standardization of testing protocols. Development of field-relevant, standardized testing methods and integration of advanced microbial technologies with corrosion engineering represent ongoing priorities.

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 including "microbiologically influenced corrosion," "biocorrosion," "sulfate-reducing bacteria," "biofilms," "quorum sensing," "corrosion monitoring," "corrosion mitigation," "nanomaterials," "AI corrosion monitoring," and related terms. 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 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 fundamental mechanisms, emerging protection technologies, and field-applicable monitoring approaches. Quantitative data synthesis focused on inhibitor efficiencies, coating performance metrics, corrosion rate measurements, and monitoring accuracy. Performance metrics including inhibition efficiency (%), biofilm reduction, detection accuracy, and prediction reliability (R^2 values) were extracted and analyzed where available. For nanotechnology and molecular biology applications, specific attention was given to reported performance metrics, mechanisms of action, and scalability considerations. Electrochemical and mechanistic analysis drew upon established principles including electrochemical impedance spectroscopy, potentiodynamic polarization, and biofilm characterization methods. Molecular biology techniques including 16S rRNA sequencing, metagenomics, and gene editing approaches were evaluated for their contributions to MIC understanding. Environmental and sustainability considerations were examined through analysis of regulatory requirements, green chemistry principles, and lifecycle assessment approaches.

Results

Table 1. Primary Corrosive Microorganisms and Metabolic Characteristics

Microorganism Type	Metabolic Pathway	Oxygen Requirement	Key Corrosive Products	Primary Mechanism	Industrial Prevalence
Sulfate-Reducing Bacteria (SRB)	Sulfate Reduction	Anaerobic	H_2S, FeS	EET-MIC, Cathodic Depolarization	Oil/Gas, Marine (75% of well corrosion)
Sulfur-Oxidizing Bacteria (SOB)	Sulfur Oxidation	Aerobic	H_2SO_4	Acid Production	Pipelines, Cooling Systems
Iron-Oxidizing Bacteria	Iron Oxidation	Aerobic/Microaerophilic	Fe^{3+}, Organic Acids	Differential Aeration	Marine, Water Systems
Methanogens	CO_2 Reduction	Anaerobic	CH_4, H_2	Hydrogen Consumption	Oil/Gas, Subsurface
Acid-Producing Bacteria	Fermentation	Anaerobic/Aerobic	Organic Acids	Local pH Reduction	Multiple Industries
Fungi	Organic Matter Degradation	Aerobic	Organic Acids, Enzymes	Biodegradation, pH Change	Pipelines, Storage

Data compiled from references.

Analysis of Table 1: The comparative analysis reveals the diversity of microorganisms contributing to MIC, each with distinct metabolic pathways and corrosion mechanisms. SRB emerge as the most significant corrosive microorganisms, accounting for approximately 75% of production well corrosion issues and 50% of pipeline system failures. Their anaerobic sulfate reduction pathway produces hydrogen sulfide, which accelerates cathodic depolarization and promotes hydrogen embrittlement through ferrous sulfide formation. The prevalence of SRB across oil and gas, marine, and water treatment environments reflects their metabolic versatility and adaptability to diverse conditions. Sulfur-oxidizing bacteria (SOB) and iron-oxidizing bacteria represent additional significant groups, generating acidic environments and concentration cells that drive localized pitting and crevice corrosion. Methanogens, while less studied, contribute through hydrogen consumption and methane production in subsurface environments. Acid-producing bacteria and fungi, though often overlooked, play important roles in MIC through organic acid production and enzymatic degradation of protective coatings. The presence of mixed microbial consortia rather than isolated species complicates prediction and control, as synergistic interactions can amplify corrosion effects beyond those of individual species.

Table 2. Detection and Monitoring Methods for MIC

Method Category	Specific Techniques	Detection Target	Accuracy/Performance	Key Advantages	Primary Limitations	Development Status
Microbial Culture	Enrichment, Isolation	Live Culturable Organisms	Medium (50-70%)	Established Protocols	Time-Consuming, Culture Bias	Mature
Molecular Biology	16S rRNA, PCR, Metagenomics	DNA/RNA	High (>95%)	Species Identification, Sensitivity	Cost, Expertise Required	Commercial
Electrochemical	EIS, LPR, ER Probes	Corrosion Rate, Mechanism	High (Real-time)	Real-Time, non-destructive	Interpretation Complexity	Mature
Microscopic	SEM, CLSM, AFM	Biofilm Structure, Morphology	Very High (Microscale)	Visual Confirmation, Resolution	Sample Preparation, Ex-situ	Research/Commercial
Biosensing	Enzyme-Based, DNA-Based	Specific Metabolites, Organisms	High (Targeted)	Real-Time, Rapid, Specific	Limited Multiplexing	Emerging
Image Processing	AI/ML Algorithms	Surface Condition, Pitting	>98% Detection Accuracy	Automated, Scalable	External Surfaces Only	Emerging
ATP Analysis	Bioluminescence	Total Microbial Activity	Medium-High	Rapid, Simple	No Species Information	Commercial

Data compiled from references.

Analysis of Table 2: The comparative analysis demonstrates significant evolution in MIC detection capabilities, from traditional culture-based methods to advanced molecular and biosensing technologies. Traditional culture methods, while providing established protocols, are limited by time requirements (days to weeks) and culture bias where only certain microorganisms grow under laboratory conditions. Molecular biology techniques, including 16S rRNA gene sequencing and metagenomics, offer high sensitivity (>95%) and accurate species identification, though at higher cost and requiring specialized expertise.

Electrochemical methods including EIS and LPR provide real-time corrosion rate monitoring with high accuracy, though interpretation requires electrochemical expertise. Microscopic techniques (SEM, CLSM, AFM) offer invaluable visual confirmation of biofilm structure and corrosion morphology at microscale resolution, but require extensive sample preparation and are typically ex-situ [111].

Emerging technologies show particular promise for MIC monitoring. Image processing with AI/ML algorithms achieves >98% detection accuracy for cracks and corrosion, with predictive capabilities for proactive maintenance. Biosensing technologies enable real-time, rapid detection of specific metabolites or organisms, though multiplexing remains limited. ATP analysis provides rapid quantification of total microbial activity but lacks species-level information. The trend toward integration of multiple complementary techniques is increasingly recognized as necessary for comprehensive MIC assessment.

Table 3. MIC Mitigation Strategies and Performance

Mitigation Strategy	Mechanism of Action	Efficiency (%)	Key Advantages	Primary Limitations	Development Status
Biocides (Chemical)	Cell Death/Inhibition	70-95	Broad Spectrum, Established	Resistance, Toxicity, EPS Barrier	Mature
Nanomaterials-Based	ROS Generation, Membrane Disruption	85-98	Targeted, multi-modal	Cost, Environmental Fate	Emerging
Surface Coatings	Physical Barrier, Anti-Adhesion	80-95	Passive Protection, Durable	Degradation, Defects	Commercial
Cathodic Protection	Electrochemical Polarization	70-85	Established, Reliable	Shielding, Overprotection	Mature
Quorum Sensing Inhibition	Biofilm Prevention	70-90	Novel, Anti-Biofilm	Scalability, Microbial Adaptation	Research
Enzymatic Remediation	Biofilm Disruption, Biocide	75-90	Sustainable, Biodegradable	Specificity, Stability	Research
Material Selection	Alloy Resistance	85-99	Long-Term Protection	High Cost, Not Universal	Commercial
Phage Therapy	Targeted Bacterial Lysis	70-85	Specific, No Resistance	Scalability, Delivery	Research

Data compiled from references.

Analysis of Table 3: The comparative analysis reveals a diverse array of MIC mitigation strategies, each with distinct mechanisms, performance characteristics, and limitations. Traditional biocides remain the industrial standard, achieving 70-95% efficiency through broad-spectrum antimicrobial action. However, the EPS matrix grants biofilms 100-1000 times greater resistance than planktonic microorganisms, necessitating elevated dosages that create cross-resistance and severe ecotoxicological risks. Surface coatings provide passive physical barrier protection (80-95% efficiency), though coating degradation, delamination, and pinhole defects create MIC initiation sites.

Nanomaterials-based strategies represent an emerging paradigm shift from broad-spectrum poisoning to precision interfacial engineering. Inorganic nanoparticles (Ag, Cu, ZnO) achieve 85-98% efficiency through reactive oxygen species generation, ion release, and membrane disruption, bypassing traditional resistance pathways [112-122]. The high specific surface area, tunable surface chemistries, and size-dependent properties of nanomaterials enable targeted biofilm disruption and smart, stimuli-responsive release.

Quorum sensing inhibition (QSI) and enzymatic remediation represent novel, sustainable approaches still in research phases. QSI prevents microbial communication and biofilm formation, making microorganisms vulnerable to other treatments. Enzymatic remediation offers biodegradability and environmental compatibility, though specificity and stability present challenges. Material selection using MIC-resistant alloys provides long-term protection (85-99% efficiency) at substantial cost. The trend toward integrated, multi-layered strategies combining active and passive protection appears essential for effective MIC management in complex industrial environments.

Table 4. Advanced Technologies and Future Directions

Technology	Application	Performance Metrics	Key Innovations	Challenges	Expected Impact
AI/ML Monitoring	Predictive Corrosion Management	$R^2 > 0.85$, >98% Accuracy	Pattern Recognition, Multi-Data Integration	Validation, Data Quality	High
IoT Sensors	Real-Time Remote Monitoring	Continuous, Low-Cost	Integration, Early Warning	Data Management, Power	Moderate-High
Multi-Omics	Mechanistic Understanding	Gene/Protein/Pathway Identification	Systems-Level Understanding	Integration, Field Applicability	High

Gene Editing	Strain Characterization	Functional Characterization	Mechanism Elucidation	Model Development	Moderate
Smart Nanocoatings	Active/Responsive Protection	>95% Efficiency	Stimuli-Responsive, Self-Healing	Scalability, Stability	High
Digital Twins	Comprehensive Corrosion Management	Real-Time, Predictive	Physical Model + Monitoring	Complexity, Validation	Very High
Biocontrol Microbes	Sustainable Mitigation	70-85% Efficiency	Living Functional Biofilms	Field Performance, Regulation	Moderate
Sustainable Biocides	Environmentally Compatible	75-90% Efficiency	Biodegradable, Low Toxicity	Cost, Performance	Moderate-High

Data compiled from references.

Analysis of Table 4: The emerging technologies landscape reveals transformative potential across MIC research and management. AI/ML monitoring frameworks achieve $R^2>0.85$ prediction accuracy and >98% detection accuracy for corrosion through pattern recognition and multi-data integration. Hybrid models combining swarm intelligence optimization with convolutional neural networks and bidirectional gated recurrent units capture nonlinear feature interactions and temporal dependencies, enabling predictive maintenance.
Multi-omics approaches (genomics, transcriptomics, proteomics) provide systems-level understanding of MIC mechanisms, identifying corrosion-related genes, proteins, and metabolic pathways. Integration of advanced molecular biology with corrosion engineering enables mechanistic elucidation and development of targeted mitigation strategies. Smart nano coatings incorporating stimuli-responsive nanomaterials achieve >95% efficiency through autonomous repair and triggered inhibitor release, though scalability and stability present challenges.
Digital twin technologies combining physical modeling with real-time monitoring and predictive analytics offer comprehensive corrosion management with very high expected impact. Biocontrol microbes and sustainable biocides represent emerging environmentally compatible solutions, though field performance and regulatory acceptance require further development. The convergence of these technologies promises transformative improvements in MIC management across industrial sectors.

Discussion

Fundamental Understanding and Mechanistic Complexity:

The electrochemical framework for understanding MIC continues to evolve, with recent advances revealing the extraordinary complexity of microbial-material interactions. Three principal mechanisms EET-MIC, M-MIC, and BD-MIC provide complementary explanations for corrosion acceleration, yet the dynamic interplay among these mechanisms in natural environments remains incompletely understood. Extracellular electron transfer through DET and MET pathways highlights the sophisticated metabolic capabilities of corrosive microorganisms, particularly SRB, which effectively "harvest" electrons from metal surfaces for sulfate respiration. This bioelectronic coupling between microbial metabolism and electrochemical corrosion represents a fundamental departure from abiotic corrosion processes, explaining the accelerated and localized nature of MIC attack.
The central role of biofilms in MIC cannot be overstated. EPS matrices create diffusion barriers that protect sessile populations, establish chemical gradients driving galvanic microcells, and concentrate corrosive metabolites at the metal surface. The EPS barrier confers resistance 100-1000 times greater than planktonic microorganisms, complicating biocidal treatment. Recent advances in characterization techniques in-situ SEM, HR-TEM, and AFM provide unprecedented insights into biofilm structure, composition, and dynamics. However, translating these fundamental insights into improved prediction and control remains challenging due to the dynamic, multifactorial nature of MIC in field conditions.
Microbial community composition and dynamics significantly influence MIC severity and mechanisms. The presence of multispecies consortia, including synergistic interactions among SRB, SOB, and acid-producing bacteria, creates corrosion rates exceeding those of individual species. Environmental factors temperature, pH, humidity, salinity, and nutrient availability further modulate community structure and activity. The non-linear interactions among microbial species, environmental parameters, and material properties complicate prediction and necessitate integrated, context-specific management approaches.

Performance and Limitations of Current Mitigation Strategies:

The comparative analysis reveals that current MIC mitigation strategies, while offering substantial protection, face significant limitations requiring continued innovation. Biocides remain the industrial standard, achieving 70-95% efficiency through broad-spectrum antimicrobial action. However, EPS-mediated resistance necessitates elevated dosages, creating cross-resistance, environmental toxicity, and operational costs. The emergence of biocide-resistant microbial strains further threatens long-term efficacy. Surface coatings provide passive protection but suffer from degradation, disbandment, and defect-induced failures. Cathodic protection, while effective for abiotic corrosion, can be compromised by electroactive microorganisms that depolarize cathodic surfaces through EET mechanisms.

Nanomaterials-based strategies represent a significant paradigm shift, offering precision targeting and multimodal antimicrobial action that bypass traditional resistance pathways. Inorganic nanoparticles (Ag, Cu, ZnO) achieve 85-98% efficiency through ROS generation and membrane disruption, while nanocarriers enable stimuli-responsive biocide delivery. However, challenges persist in nanomaterial scalability, dispersion uniformity, long-term stability, and environmental fate. Smart nano coatings incorporating self-healing and stimulus-responsive capabilities represent an emerging frontier, though industrial deployment requires substantial validation and optimization.

Emerging Technologies and Digital Transformation:

The integration of AI, IoT, and multi-omics technologies promises transformative improvements in MIC management. AI-driven monitoring frameworks achieve >98% detection accuracy and prediction capabilities enabling proactive maintenance. Hybrid machine learning models capture nonlinear feature interactions and temporal dependencies, supporting transition from reactive repair to proactive intervention. IoT sensors enable continuous, remote monitoring with early warning capabilities, while cloud-based data integration supports comprehensive condition awareness.

Multi-omics approaches provide systems-level understanding of MIC mechanisms, identifying corrosion-related genes, proteins, and metabolic pathways. Gene editing technologies enable functional characterization of microbial factors driving corrosion. However, integration of molecular-level insights with field-applicable monitoring and control remains challenging. Development of field-relevant, standardized testing protocols and data curation standards is essential to realize the full potential of data-driven MIC management.

Environmental Sustainability and Green Solutions:

The environmental and regulatory drivers toward sustainable MIC management are reshaping research and industrial practice. Traditional biocides face increasing restrictions due to toxicity, persistence, and bioaccumulation potential. Enzymatic remediation, quorum sensing inhibition, and biocontrol microbes represent emerging sustainable alternatives with biodegradability and environmental compatibility. Nanomaterials offer potential for targeted, low-dose delivery reducing environmental loading, though their fate and ecotoxicological effects require thorough investigation. The economic imperative for effective MIC management remains compelling. Implementation of existing corrosion prevention technologies could generate global savings of approximately USD 875 billion, representing 35% of total corrosion costs. Achieving these savings requires integrated approaches combining materials selection, design improvement, active protection, and monitoring, tailored to specific applications and environments.

Future Directions and Recommendations:

Future MIC research and practice should prioritize several interconnected areas. First, standardized, field-relevant testing protocols must be developed to bridge laboratory-field performance gaps for biocides, coatings, and emerging technologies. Second, fundamental understanding of MIC under realistic field conditions multispecies communities, fluctuating environmental parameters, hydrodynamic effects require advancement through combined experimental and modeling approaches. Third, integration of data-driven discovery (AI/ML) with mechanistic understanding offers accelerated development of targeted mitigation strategies.

Fourth, advancement of monitoring technologies toward real-time, predictive systems, integrated with AI and digital twins, enables proactive maintenance and optimization. Fifth, development of circular-economy-compatible mitigation strategies emphasizing renewable feedstocks, biodegradability, and recyclability should be prioritized. Sixth, interdisciplinary collaboration across materials science, electrochemistry, microbiology, data science, and industrial engineering is essential to address complex MIC challenges.

Conclusion

This comprehensive review has systematically examined microbiologically influenced corrosion as one of the most complex and destructive forms of material degradation, accounting for approximately 20% of global corrosion-related economic losses. The electrochemical framework governing MIC involves distinct mechanisms including extracellular electron transfer (EET-MIC), metabolite-mediated corrosion (M-MIC), and biofilm-driven microenvironmental alterations. Sulfate-reducing bacteria emerge as primary culprits, responsible for approximately 75% of production well corrosion issues and 50% of pipeline system failures in the oil and gas sector.

Recent advances in molecular biology, including multi-omics approaches and gene editing technologies, have provided unprecedented insights into corrosion-related genes, proteins, and metabolic pathways. Detection methodologies have evolved from traditional culture-based techniques to sophisticated biosensors, electrochemical monitoring, and AI-driven predictive frameworks achieving >98% detection accuracy. Mitigation strategies encompass biocides, nanomaterials, coatings, quorum sensing inhibition, and emerging enzymatic remediation approaches. Nanomaterials-based strategies, achieving 85-98% efficiency through precision targeting and multimodal antimicrobial action, represent a paradigm shift from broad-spectrum poisoning to interfacial engineering.

Challenges persist in bridging laboratory-field performance gaps, developing standardized testing protocols, and advancing sustainable, environmentally compatible solutions. Integration of data-driven discovery with mechanistic understanding, advancement of real-time monitoring technologies, and interdisciplinary collaboration across materials science, electrochemistry, microbiology, and data science are essential for future progress. With continued innovation and implementation of integrated, multi-layered approaches, substantial reductions in MIC-related costs and environmental impacts are achievable across 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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