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Corrosion Challenges in Hydrometallurgical Recovery of Cobalt and Nickel: A Review of Materials and Coating Solutions for Sustainable Critical Mineral Processing

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Abstract

The mineral industry is key to the development of modern industry, as it supports technologies ranging from advanced manufacturing to the aerospace sector, as well as electronics, the defense sector, and clean energy technologies. A sustainable supply of minerals such as cobalt and nickel is dependent on the recovery of these critical metals from hydrometallurgical processes. Increasing worldwide demand, alongside diminishing grades of primary ores, has heightened dependence on hydrometallurgical methods particularly high-pressure acid leaching (HPAL) and solvent extraction for the recovery of metals from lower-grade ores and mine tailings; however, owing to the aggressive operating conditions, these processes are subject to significant corrosion problems. These procedures use strong sulfate- or chloride-based solutions at high temperatures and oxidizing conditions, which are extremely corrosive to the steel and alloy equipment found in autoclaves, reactors, pipelines, and mixers. As a result, corrosion phenomena such as pitting, stress corrosion cracking, and erosion-corrosion pose significant technical and economic issues, including increased downtime, high replacement prices, and product contamination hazards. Addressing these difficulties necessitates a mix of sophisticated material selection, protective coatings, and process optimization, making corrosion control an important enabler for long-term cobalt and nickel production. This paper critically evaluates current methods, identifies gaps, and proposes sustainable corrosion control based on developments in corrosion mechanisms, process conditions, and protective materials.

Keywords: Critical Mineral Processing; High-Pressure Acid Leaching (HPAL); Hydrometallurgical Metal Recovery; Laterite Processing; Corrosion Mitigating Strategies; Smart Anti-Corrosive Coatings

1. Introduction

Cobalt and nickel are critical metals, indispensable for a myriad of modern technologies, ranging from high-performance batteries in electric vehicles and portable electronics to advanced superalloys in aerospace and catalysts in various industrial processes. This pervasive utility has led to a significant surge in their global demand, necessitating the development and optimization of efficient and sustainable extraction methods (1). Hydrometallurgical processes have emerged as a favored approach for the recovery of these valuable metals due to their inherent selectivity, lower energy consumption, and reduced environmental footprint compared to traditional pyrometallurgical routes. However, the very nature of hydrometallurgy, which involves aqueous solutions, presents formidable challenges, particularly in the realm of material degradation (2,3). Hydrometallurgical operations for cobalt and nickel extraction are characterized

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by extremely aggressive chemical environments. Processing equipment is routinely exposed to highly corrosive conditions, including solutions with very low pH (high acidity), elevated concentrations of chloride or sulfate ions, the presence of strong oxidants, and often high temperatures and pressures. Such harsh conditions accelerate various forms of corrosion, leading to premature equipment failure, compromised operational safety, increased maintenance costs, and potential environmental contamination due to leaks and spills. Therefore, effective corrosion control is paramount for the economic viability, safety, and environmental sustainability of cobalt and nickel hydrometallurgical facilities (4,5).

This review aims to provide a comprehensive synthesis of the intricate corrosion mechanisms prevalent in cobalt and nickel hydrometallurgy. Furthermore, it evaluates the performance of various materials and coating solutions designed to withstand these aggressive environments. The goal is to identify and propose pathways for advancing corrosion control strategies, thereby contributing to more sustainable and efficient critical mineral processing. The discussion will draw upon recent advancements in corrosion science and engineering, including insights into surface modification, novel coating technologies, and the application of corrosion inhibitors.

Recent research has extensively explored various strategies to mitigate corrosion in industrial settings. The role of surface roughness in influencing coating adhesion and overall corrosion protection has been critically reviewed, highlighting its importance in the longevity of protective layers (6). Advanced coating technologies, such as those incorporating halloysite nanotubes, have been investigated for their potential in smart coating applications, offering enhanced barrier properties and self-healing capabilities (7). Electroless Ni-B and composite coatings have also garnered significant attention, with detailed reviews on their formation mechanisms, properties, and diverse applications in corrosive environments (8). The development of nanocomposite coatings, particularly polymer/inorganic variants, has shown superior corrosion protection performance, attributed to their enhanced barrier properties and improved mechanical strength (9) Furthermore, the concept of smart anti-corrosive coatings, which can respond to environmental stimuli, represents a promising frontier in corrosion prevention (10). Beyond coatings, the use of natural and synthetic inhibitors has been a subject of intense research. Plant biomaterials have been explored as eco-friendly corrosion inhibitors for industrial metals, offering sustainable alternatives to synthetic chemicals (11). Similarly, the application of surfactants as anticorrosive materials has been comprehensively reviewed, demonstrating their efficacy in forming protective films on metal surfaces (12).

This review integrates these diverse findings to present a holistic view of corrosion challenges and solutions pertinent to the hydrometallurgical recovery of cobalt and nickel. By understanding the specific corrosive environments and the mechanisms of material degradation, coupled with an evaluation of cutting-edge protective technologies, this article seeks to inform future research and development efforts towards robust and sustainable material selection for critical mineral processing.

2. Hydrometallurgical Processes for Cobalt and Nickel

Hydrometallurgical processing has become the dominant route for extracting cobalt and nickel from lateritic ores and secondary resources, offering superior selectivity and environmental control compared to pyrometallurgical methods. Nickel laterites represent 60-70% of global terrestrial nickel resources, with their processing presenting unique challenges due to complex mineralogy, high iron and magnesium content, and variable nickel grades typically ranging from 1.0% to 2.5%. The selection of appropriate extraction technology depends critically on ore mineralogical composition, with limonitic laterites amenable to atmospheric leaching while saprolitic laterites require high-pressure acid leaching (HPAL) to achieve acceptable recoveries (13).

Leaching represents the primary extraction step where valuable metals are solubilized from solid matrices into aqueous solutions. Whittington and Muir (14) provided comprehensive analysis of pressure acid leaching of nickel laterites, documenting that HPAL typically operates at temperatures between 245°C and 270°C under pressures of 3.5 to 5.0 MPa, using sulfuric acid at concentrations of 200-400 kg per tonne of ore to achieve nickel extraction efficiencies exceeding 95% with simultaneous cobalt recovery of 85-90%. These severe conditions create exceptionally aggressive corrosion environments characterized by high temperatures, low pH (often below 1.0), elevated sulfate concentrations exceeding 100 g/L, and the presence of ferric iron as a strong oxidant, necessitating titanium-lined or solid titanium autoclave construction (14). Meanwhile, atmospheric acid leaching using sulfuric acid at 90°C effectively extracts nickel and cobalt from limonitic zones, while subsequent ferric chloride leaching enhances recovery from refractory silicate minerals. This two-stage approach achieves nickel and cobalt recoveries exceeding 90% while reducing overall acid consumption by 250-350 kg per tonne ore compared to single-stage aggressive leaching. However, the introduction of chloride in the second stage creates pitting and crevice corrosion challenges, requiring higher-grade alloys such as AL-6XN or Hastelloy C-276 where chloride concentrations exceed 50 g/L (15). Stopić and Friedrich (16) examined atmospheric pressure leaching alternatives operating at temperatures below 100°C, which present less severe corrosion conditions and lower capital costs but typically achieve lower nickel recoveries (75-85%) and require longer residence times of 4-8 hours compared to 45-90 minutes for HPAL. The authors noted that atmospheric leaching systems involve open or vented vessels where vapor spaces experience alternating wet-dry cycling and exposure to acidic mists, creating conditions conducive to vapor phase corrosion and waterline attack.

2.1. Separation, Purification, and Metal Recovery

Following leaching, metal-bearing solutions undergo purification through solvent extraction or ion exchange. Solvent extraction employs organic extractants such as Di-(2-ethylhexyl) phosphoric acid (D2EHPA) and Bis(2,4,4-trimethylpentyl) phosphinic acid also known as Cyanex 272 that selectively complex with target metal ions at specific pH values, with nickel preferentially extracted at pH 4.5-6.0 while cobalt extraction occurs at slightly lower pH. The process equipment experiences corrosion at aqueous-organic interfaces under turbulent mixing conditions, requiring careful materials selection for mixer-settlers, columns, and associated pipelines (2) Metal recovery occurs through precipitation or electrowinning. Mira and Huang (17) demonstrated selective sequential precipitation for separating manganese, cobalt, and nickel from acid mine drainage treatment by-products, achieving separation through staged pH adjustment: manganese as MnO_2 at pH 8.5, cobalt hydroxide at pH 10.5, and nickel hydroxide at pH 11.5, producing products with purities exceeding 95%. The authors' work on secondary resource processing illustrates the growing importance of circular economy approaches, recovering valuable metals from materials containing 0.5-1.5% cobalt and 1-3% nickel that would otherwise require costly disposal.

2.2. Operating Conditions and Corrosion Challenges

HPAL operations create some of the most aggressive corrosion environments in industrial metallurgy. HPAL solutions typically contain 50-150 g/L sulfuric acid (pH < 1), 80-120 g/L dissolved iron (predominantly as Fe^{3+}), and high concentrations of magnesium and aluminum at 245-270°C and 3.5-5.0 MPa pressure. These conditions ensure that protective oxide films on most engineering alloys are thermodynamically unstable, with solution redox potentials exceeding +600 mV driving rapid uniform and localized corrosion. Even slight temperature excursions above design values exponentially increase corrosion rates according to Arrhenius kinetics, potentially causing millimeters of metal loss within hours (14). Chloride ions, when present even at moderate concentrations, are particularly problematic as aggressive promoters of localized corrosion mechanisms including pitting and crevice corrosion in stainless steels and some nickel-based alloys. The combination of low pH and high chloride creates synergistic effects where acid dissolution removes protective films while chloride ions prevent their reformation (13). For equipment specific considerations, HPAL autoclaves are the most corrosion-critical equipment, requiring titanium or titanium-clad construction for vessels, internal piping, and agitator components. Heat exchangers experience temperature gradients, two-phase flow, and solid particle erosion, requiring titanium tubes with appropriate thickness allowances. Slurry pumps handling abrasive, acidic laterite pulps typically employ hard-faced impellers and elastomer linings to resist combined chemical and mechanical degradation (14). In slurry systems, Erosion-corrosion rates increase nonlinearly with slurry velocity and solids concentration, with damage concentrated at flow direction changes, pipe elbows, and agitator blades. Mitigation strategies include reducing flow velocities below critical thresholds (typically <2-3 m/s), using wear-resistant materials such as ceramic linings, and designing flow paths to minimize turbulence (16)

2.3. Materials Selection and Economic Considerations

Commercially pure titanium (Grades 1-4) represents the only practical material for HPAL autoclave vessels and internals, offering corrosion rates typically below 0.1 mm/year at 245-270°C in sulfuric acid with high ferric iron. Higher-grade titanium alloys such as Ti-0.2Pd (Grade 7) are specified for particularly aggressive zones such as acid injection points (14). A 3-6 mm titanium liner bonded to carbon steel provides corrosion resistance comparable to solid titanium at substantially reduced cost, though proper design is critical to prevent catastrophic corrosion of the underlying steel substrate (13) For atmospheric leaching operations, Stopić and Friedrich (16) recommended less expensive materials including high-silicon cast iron (14-17% Si), rubber-lined carbon steel, fiber-reinforced plastic (FRP), or thermoplastic linings (HDPE, polypropylene, PVDF). However, Li et al. (15) found that chloride-bearing solutions eliminated several materials options, with Type 316L stainless steel experiencing severe pitting when exposed to combined sulfuric acid and ferric chloride, necessitating super austenitic stainless steels or high-nickel alloys.

HPAL becomes favorable for laterite ores containing >1.5% nickel despite capital costs 3.5-4.5 times higher than atmospheric leaching. Corrosion-related costs, including materials premiums, maintenance, and planned replacements, represent 15-25% of total operating costs, underscoring the economic importance of effective corrosion management. Energy consumption differs significantly: HPAL consumes 1.5-2.5 GJ/tonne ore versus 0.5-0.8 GJ/tonne for atmospheric leaching (13). Le and Lee (2) incorporated life cycle analysis methodology, demonstrating that environmental impacts must be assessed across the entire process chain. While hydrometallurgical processing avoids SO_2 emissions from pyrometallurgical smelting, it generates larger volumes of aqueous wastes. HPAL generates 3-5 tonnes of neutralized residue per tonne of nickel produced, containing elevated iron, aluminum, and magnesium concentrations requiring secure disposal in tailings facilities. Inadequate neutralization or containment failures can result in long-term environmental contamination (13)

Table 1 Comparison of Hydrometallurgical Technologies for Nickel-Cobalt Laterite Processing

Parameter	**Atmospheric Acid Leaching**	**HPAL**	**Combined AAL-$FeCl_3$**	**References**
Temperature/Pressure	60-95°C / 0.1 MPa	245-270°C / 3.5-5.0 MPa	80-90°C / 0.1 MPa	Stopić & Friedrich (16); Whittington & Muir (14); Li et al. (15)
pH Range	1.5-2.5	<1.0 (typically 0.3-0.8)	1.5-2.5	Zhang et al.(13); Whittington & Muir (14)
Residence Time	4-8 hours	45-90 minutes	5 hours total	Stopić & Friedrich (16); Li et al. (15)
Ni Recovery / Co Recovery	75-85% / 70-80%	90-98% / 85-95%	90-94% / 88-93%	Zhang et al. (13); Li et al. (15)
Primary Corrosion Mechanisms	Uniform acid dissolution; vapor phase corrosion; waterline attack	Severe high-T acid attack; oxidative corrosion from Fe^{3+}; SCC potential	Acid attack; Cl^--induced pitting and crevice corrosion	Stopić & Friedrich (16); Whittington & Muir (14)
Critical Equipment Materials	High-Si cast iron; rubber-lined steel; FRP; 316L SS (Cl^--free)	Titanium (Gr 2, 7); Ti-clad steel	Stage 2 requires AL-6XN or Hastelloy C-276	Zhang et al. (2024); Whittington & Muir (2000); Li et al. (2025)
Acid Consumption	400-600 kg/tonne ore	350-500 kg/tonne ore	250-350 kg/tonne ore	Stopić & Friedrich (2016); Li et al. (2025)
Energy Consumption	0.5-0.8 GJ/tonne ore	1.5-2.5 GJ/tonne ore	0.7-1.0 GJ/tonne ore	Whittington & Muir (2000); Zhang et al. (2024)
Capital Cost (Relative)	Low (1.0×)	Very High (3.5-4.5×)	Medium (1.3-1.8×)	Zhang et al. (2024)
Applications	Lower-grade limonitic laterites	Medium-high grade saprolitic laterites	Limonitic laterites; selective processing	Zhang et al. (2024); Whittington & Muir (2000)

Notes: FRP = Fiber-Reinforced Plastic; SS = Stainless Steel; SCC = Stress Corrosion Cracking; AAL = Atmospheric Acid Leaching

3. Methodological Approaches

The investigation of corrosion behavior and protective coating performance employs diverse methodological approaches providing complementary insights into corrosion mechanisms and materials performance. Electrochemical techniques represent the cornerstone of modern corrosion research, with Verma et al. (18), Umoren et al. (11), and Salleh et al. (19) utilizing potentiodynamic polarization, electrochemical impedance spectroscopy (EIS), and linear polarization resistance (LPR) measurements to evaluate corrosion inhibitors and assess inhibition efficiencies exceeding 90% for plant extracts in acidic media. Gravimetric and immersion testing provide quantitative assessment of long-term corrosion rates, with Fayyad et al. (20), Barati and Hadavi (8), and Sajjadnejad et al. (19) employing weight loss measurements following ASTM standards to evaluate electroless nickel coatings and composites over exposure periods ranging from 168 hours to several months. Surface characterization techniques including scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), and X-ray diffraction (XRD) enable high-resolution analysis of coating microstructure, composition, and phase identification, with Fayyad et al. (20) and Barati and Hadavi (8) utilizing these methods to reveal nodular coating morphology, grain sizes of 20-50 nm, and crystallization behavior upon heat treatment. Advanced characterization reviewed by Es-Soufi et al. (21) includes transmission electron microscopy (TEM), X-ray photoelectron spectroscopy (XPS), and Fourier-transform infrared spectroscopy (FTIR) for nanoscale and chemical state analysis. Croll (6) employed profilometry and atomic force microscopy to assess surface roughness effects on coating adhesion, while Sajjadnejad et al. (19) reviewed tribological testing methods including pin-on-disk and tribocorrosion testing for evaluating combined wear and corrosion resistance.

Computational modeling approaches complement experimental methods by providing molecular-level insights into corrosion mechanisms. Verma et al. (18) and Umoren et al. (11) reviewed density functional theory (DFT) calculations and molecular dynamics (MD) simulations to understand inhibitor-metal surface interactions, with quantum chemical parameters such as HOMO-LUMO energy gaps and adsorption energies exceeding 40 kJ/mol correlating with inhibition efficiency. Pourhashem et al. (22) discussed equivalent circuit modeling of EIS data to extract coating degradation parameters and predict service life, demonstrating that coating resistance decreasing below 10^6 $\Omega \cdot cm^2$ indicates imminent failure. Industrial field studies and failure analysis provide critical validation of laboratory findings, with Whittington and Muir (14) documenting case studies from operating HPAL facilities showing equipment lifetimes and failure modes, while Little et al. (23) emphasized that microbially influenced corrosion field studies reveal degradation mechanisms not replicated in laboratory settings. Le and Lee (2) discussed post-failure examination methodologies including visual inspection, metallographic sectioning, and chemical analysis of corrosion products to identify degradation mechanisms. Systematic optimization studies employ response surface methodology and design of experiments, with Li et al. (15) optimizing leaching process parameters, while Cui et al. (10) and Xiaoqing et al. (24)demonstrated multi-scale integration from molecular computational studies through nanoscale characterization to macroscale industrial feasibility assessment, ensuring successful translation from laboratory discoveries to practical applications.

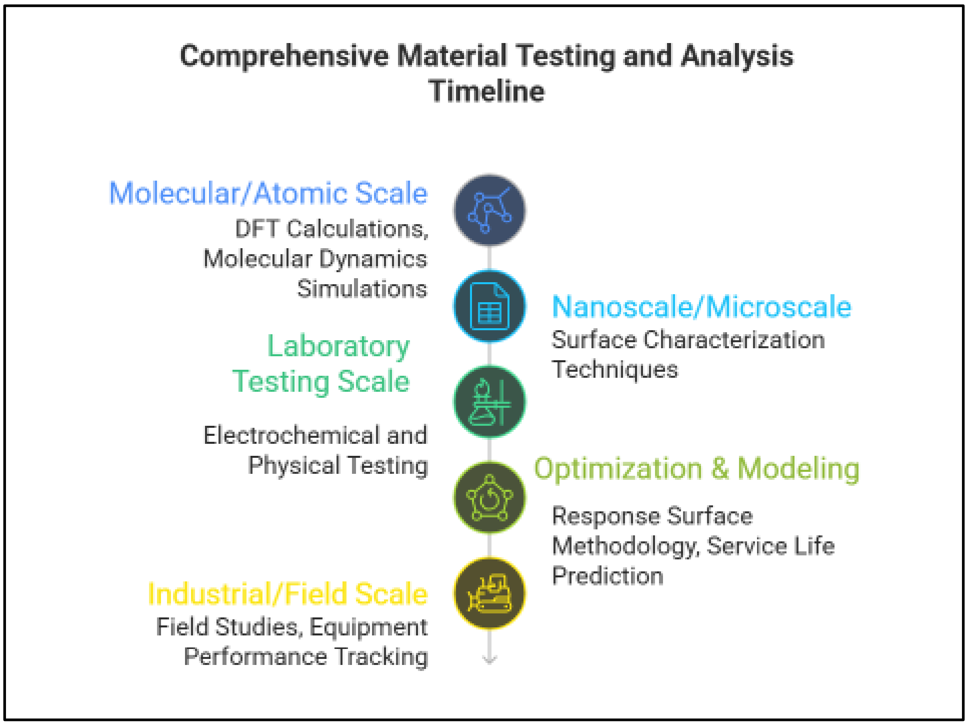

Figure 1 Multi-Scale Methodological Approach to Corrosion Research

4. Key Findings and Perspectives on Coating Technologies and Solutions

4.1. Advanced Coating Technologies and Smart Materials

Smart coatings have become a ground-breaking method of corrosion prevention because of their capacity to react dynamically to environmental cues. These coatings integrate functionalities such as self-healing and corrosion sensing, significantly extending the service life of metal substrates. Advancements in nanostructured coatings have further enhanced protective capabilities by leveraging unique nanoscale properties (10). The integration of two-dimensional nanomaterials has opened new frontiers in coating technology. Xiaoqing et al. (24) explored self-healing two-dimensional MXene coatings for corrosion protection on metals, examining design strategies and mechanisms. MXenes, a relatively new class of two-dimensional transition metal carbides and nitrides, offer exceptional properties including high electrical conductivity, hydrophilicity, and mechanical strength, making them ideal candidates for next-generation corrosion protection systems. The self-healing capabilities of MXene-based coatings derive from their ability to autonomously repair microcracks and defects through various mechanisms, including the controlled release of corrosion inhibitors and the dynamic reformation of protective layers (24). Complementary to this, nanoceramic coatings exhibit excellent resistance attributed to their dense microstructure and chemical stability (21). Incorporating polymer/inorganic nanocomposite systems also leads to improved corrosion resistance through synergistic effects. These hybrid materials leverage the processing advantages and flexibility of polymers while incorporating the barrier properties, mechanical reinforcement, and active corrosion protection capabilities of inorganic nanoparticles (22).

4.2. Green and Sustainable Corrosion Inhibition Technologies

The shift toward environmentally sustainable corrosion protection has gained significant momentum in recent years, with plant-based materials emerging as promising alternatives to conventional synthetic inhibitors. Verma et al. (18) provided a comprehensive overview of plant extracts as environmentally sustainable and green corrosion inhibitors for metals and alloys in aggressive corrosive media, establishing the foundational framework for understanding phytochemical interactions with metal surfaces. Umoren et al.(11) and Salleh et al. (25) support these findings by emphasizing the eco-friendly nature and efficacy of plant-based inhibitors for industrial applications. The convergence of these studies underscores a paradigm shift in corrosion science, where environmental considerations are increasingly integrated with technical performance requirements. The phytochemical compounds present in plant extracts—including alkaloids, flavonoids, tannins, and polyphenols—function as effective corrosion inhibitors through adsorption mechanisms that form protective molecular layers on metal surfaces, offering biodegradable and non-toxic alternatives to traditional chromate-based treatments (11)(25) The use of surfactants as anticorrosive agents also aligns with green chemistry principles, offering tailored functionalities for corrosion mitigation (12)

4.3. Electroless and Electrodeposited Nickel-Based Coatings

Nickel-based coatings, particularly those applied by electroless plating and electrodeposition, are widely utilized for corrosion and wear protection. Fayyad et al. (20) reviewed recent advances in electroless-plated Ni-P and its composites for erosion and corrosion applications, highlighting the autocatalytic deposition process that enables uniform coating thickness on complex geometries without requiring external electrical current. The amorphous or nanocrystalline structure of electroless Ni-P coatings provides superior corrosion resistance compared to their crystalline counterparts, while the incorporation of dispersed particles creates composite coatings with enhanced mechanical and tribological properties (20) Barati and Hadavi (8) extend this understanding to Ni-B and composite coatings, detailing their formation mechanisms and property enhancements. Ni-B coatings offer distinct advantages over Ni-P systems, including higher hardness, improved wear resistance, and better high-temperature stability, making them particularly suitable for demanding applications in automotive, aerospace, and chemical processing industries. The review emphasizes the importance of optimizing bath composition, operating parameters, and post-deposition heat treatment to achieve desired coating properties (8). Furthermore, electrodeposited nickel matrix composites exhibit favorable wear and tribological characteristics, critical for demanding engineering applications (19)

4.4. Surface Preparation and Coating Adhesion

The long-term performance of protective coatings is fundamentally dependent on their adhesion to substrate surfaces, making surface preparation a critical factor in coating system design. Surface topography influences mechanical interlocking, wetting behavior, and interfacial bonding strength (6). The research demonstrates that optimal surface roughness represents a balance between maximizing mechanical anchoring through increased surface area and avoiding defect formation from entrapped air or contaminants in surface valleys. Surface preparation methods such as grit blasting, chemical etching, and plasma treatment each produce characteristic roughness profiles that must be matched to specific coating systems and application requirements to ensure optimal adhesion and corrosion protection performance.

4.5. Cold Spray Technology for Corrosion Protection

Innovative coating techniques such as cold spray deposition and additive manufacturing have gained attention for their potential to produce coatings with superior corrosion resistance. Hassani-Gangaraj et al. (26) critically review cold spray coatings, noting benefits like minimal thermal impact and dense deposit formation, which contribute to enhanced corrosion protection. The cold spray process offers unique advantages including minimal thermal distortion, preservation of feedstock material properties, the ability to deposit oxygen-sensitive materials, and the capability to repair corroded structures in situ. The high-velocity impact of particles creates dense, well-bonded coatings with minimal porosity and oxide content, while the kinetic energy-driven deformation produces strong metallurgical bonds at particle interfaces without the phase transformations and thermal stresses associated with thermal spray processes.

4.6. Life Cycle Assessment and Sustainability Considerations

Sustainable development in corrosion protection also requires comprehensive life cycle analysis (LCA) to evaluate environmental impacts of recovery and coating processes. Le and Lee (2) review hydrometallurgical recovery methods integrated with LCA, offering perspectives on minimizing ecological footprints while maintaining process efficiency. While this study focuses on catalyst recovery, the methodological framework applies equally to corrosion protection systems, where the environmental burden of coating production, application, service life, and disposal must be evaluated holistically. This sustainability-oriented approach encourages the development of coating systems that not only provide effective corrosion protection but also minimize environmental impact throughout their entire life cycle, from raw material extraction through manufacturing, application, service, and eventual recycling or disposal.

5. Case Studies: Failures and Performance Issues

5.1. Scaling and Residue Formation in Autoclave Operations

Scaling and residue formation are major operational problems in high-pressure acid leaching (HPAL) facilities. They have a big effect on the performance of equipment, the way it corrodes, and the overall cost of the process. Whittington and Muir (14) documented extensive industrial experience demonstrating that autoclave leaching operations inevitably lead to scale buildup on internal surfaces, heat exchanger tubes, and agitator components, with the most problematic scale types including alunite ($KAl_3(SO_4)_2(OH)_6$), jarosite ($KFe_3(SO_4)_2(OH)_6$), silica (SiO_2), and gypsum ($CaSO_4{\cdot}2H_2O$). When the leach solution's dissolved species reach supersaturation under the high temperatures and pressures of HPAL operations, they form these scales. They then fall onto equipment surfaces, where they cause a lot of problems with how the equipment works. By creating thermal insulation between the heat transfer surface and the process fluid, the authors highlighted how scale accumulation reduces heat transfer efficiency.

They found that even thin scale layers of 1-2 mm can lower heat transfer coefficients by 30–50% and require more steam to maintain operating temperature. More importantly from the standpoint of corrosion, scales form occluding habitats under deposits where the composition of the bulk solution might drastically alter from localized chemical conditions. While oxygen depletion beneath deposits creates differential aeration cells that accelerate the anodic dissolution of the underlying metal, under-deposit corrosion happens when acidic species concentrate beneath scale layers, potentially resulting in localized pH values that are two to three units lower than bulk solution. In contrast to the minimal corrosion rates on clean surfaces exposed to bulk solution, Whittington and Muir (14) reported case studies from operational HPAL facilities where under-deposit corrosion produced pitting penetration rates in titanium equipment surpassing 5 mm/year. Scale management techniques include operating below saturation limits to minimize scaling, mechanical cleaning during shutdowns, and periodic acid cleaning to dissolve deposits.

However, mechanical methods run the risk of damaging titanium surfaces; operational changes may increase the use of acid or decrease the efficiency of nickel extraction; and acid cleaning can damage equipment and be less effective on silica scales. Some HPAL plants still experience scale-related shutdowns every three to six months despite these efforts, underscoring the ongoing difficulty (14).

5.2. Material Selection Pitfalls and Premature Equipment Failures

Choosing materials based on idealization rather than real operating conditions has resulted in expensive premature equipment failures, according to industrial experience across several HPAL facilities. Whittington and Muir (14) examined cases from early HPAL plants in the 1970s and 1980s, where a lack of knowledge about corrosion in high-temperature acidic environments led to autoclave failures within two to three years. Initial selections like nickel-based alloys and high-alloy stainless steels fared well in laboratory tests at lower temperatures, but they broke down quickly in real HPAL conditions, which were 250–270°C with elevated ferric iron levels. In one notable instance, agitator shafts made of Grade 316L stainless steel experienced severe pitting and stress corrosion cracking within six months at 260°C, necessitating multi-million-dollar titanium component replacements. Laboratory tests must accurately simulate real process solutions, including complex chemistries and trace impurities, while encompassing the entire spectrum of typical and abnormal operating conditions. Even if the bulk chemistry appears stable, safety considerations should be incorporated into the materials selection process to handle localized aggressive environments.

To prevent early failures, production losses, and safety hazards, prioritizing premium materials and overdesigning crucial equipment despite higher upfront costs goes a long way to curb the problem (14). Considering these lessons, autoclaves in contemporary HPAL facilities are usually made of titanium or titanium-clad construction. Despite advancements, Whittington and Muir (14) noted that materials issues persist for auxiliary equipment such as heat exchangers, slurry pumps, and control valves, where cost restricts premium material usage. Tube failures, erosion-corrosion, and cavitation damage are all ongoing challenges that influence reliability. These experiences emphasize the need to have a thorough understanding of operating circumstances, conduct realistic testing, and invest in appropriate materials to ensure long-term plant operation.

5.3. Microbially Influenced Corrosion (MIC)

Microbial activity often exacerbates metal corrosion, presenting unique challenges in industrial environments. This area remains vital for industries dealing with biocorrosion-prone systems. MIC results from the metabolic activities of microorganisms that colonize metal surfaces, forming biofilms that create localized corrosive conditions through mechanisms including the production of corrosive metabolites, generation of concentration cells, and acceleration of electrochemical reactions. The review highlights advance in understanding the molecular mechanisms of microbial electron transfer, the role of extracellular polymeric substances in biofilm formation, and the complex interactions between different microbial species in mixed consortia. Despite significant research progress, MIC remains challenging to predict, detect, and control due to the inherent complexity of biological systems and the site-specific nature of microbial colonization (23). After only three to five years of operation, carbon steel pipelines with sufficient corrosion allowances for anticipated chemical corrosion in one oil and gas case study unexpectedly experienced through-wall pitting failures. Dense biofilms containing sulfate-reducing bacteria (SRB) that can produce hydrogen sulphone at specific locations were found during post-failure analysis. These biofilms created aggressive corrosive conditions that were not expected during pipeline design. Little et al. (23) pointed out that because standard corrosion monitoring methods, such as corrosion coupons and electrochemical probes, usually measure average corrosion rates that obscure the extreme localization characteristic of MIC pitting, they were unable to identify the localized nature of MIC attack. The difficulty of anticipating and identifying MIC using traditional methods was demonstrated by the fact that by the time failures happened, some pits had penetrated several millimetres while nearby surfaces displayed little corrosion.

6. Comparative Performance of Materials and Coatings

6.1. Metallic Materials: Stainless Steels and High-Performance Alloys

6.1.1. Stainless Steel Performance and Limitations

In hydrometallurgical processes, stainless steels particularly the austenitic varieties 304, 316, and 316L are often utilized due to their cost-effectiveness and mild corrosion resistance. They function effectively in atmospheric leaching at modest chloride concentrations below 95°C. However, these steels quickly fail owing to pitting and stress corrosion cracking (SCC) in harsher conditions like high-pressure acid leaching (HPAL) or chloride-rich solutions, frequently within months of usage (14). Austenitic stainless steels such as 304 and 316 are susceptible to localized microbially influenced corrosion (MIC) brought on by aggressive biofilms formed by sulfate-reducing bacteria (SRB) (23). Despite typical corrosion tolerances, there have been instances of 316 stainless steel pipes experiencing through-wall pitting within 3–5 years. Although duplex stainless steels are more resistant to SCC and chloride-induced pitting, they are nonetheless vulnerable to MIC in the extremely acidic chloride conditions seen in the processing of nickel and cobalt (23).

6.1.2. High-Performance Nickel-Based Alloys

Nickel-based superalloys like Inconel, Hastelloy, and Monel families are very resistant to corrosion in harsh environments because they have a lot of nickel (usually 45–75%) and other metals like chromium, molybdenum, and tungsten. These high-quality alloys can be used in hydrometallurgical equipment where stainless steels aren't strong enough (14). Hastelloy C-276 (which has 57% Ni, 16% Cr, 16% Mo, and 4% W) is very resistant to sulphuric and hydrochloric acids, even at high temperatures and when oxidizing species are present. On the other hand, these high-performance alloys have limits. For example, HPAL conditions between 250 and 270°C are too high for them to work reliably, so autoclaves and other important parts must be made of titanium (14). Electroless nickel-phosphorus (Ni-P) coatings provide corrosion resistance close to solid nickel alloys at a lower cost. The high nickel content and amorphous or nanocrystalline structure eliminate grain boundaries that cause corrosion, while 8-12 wt% phosphorus enhances passivation. Optimized Ni-P coatings exhibit corrosion rates below 0.1 mm/year in 3.5% NaCl and dilute acid, with heat treatment further improving performance (20).

6.2. Advanced Coating Systems

6.2.1. Electroless Nickel-Based Coatings

Complex shapes can be uniformly protected from corrosion and wear by electroless nickel coatings. According to Fayyad et al. (20), Ni-P coatings provide exceptional corrosion resistance due to their amorphous or nanocrystalline structure and grain sizes of 20–50 nm. While medium-phosphorus (7-9 wt%) coatings balance corrosion and wear resistance, high-phosphorus (>10 wt%) coatings perform best in acidic media. Ni-B coatings are harder (600–750 HV) and more resistant to wear than Ni-P coatings. They also corrode less frequently in alkaline media but are less resistant to acid. Heat treatment raises hardness (900–1100 HV), but if grain growth is too great, it may decrease corrosion resistance (8) Nickel matrix composites containing hard particles, such as SiC, can reduce wear rates by 50–70% while preserving corrosion resistance, depending on the particle size and dispersion (19).

6.2.2. Smart and Self-Healing Coatings

With smart coatings, passive barrier protection gives way to intelligent systems that react to environmental cues and damage. These were divided into corrosion-sensing, self-healing, and multifunctional responsive coatings by Cui et al. (10). Self-healing coatings achieve over 80% healing efficiency for minor flaws by releasing microencapsulated agents, such as epoxy or linseed oil (5–15 weight percent), in response to damage or pH changes. Vegetable oils like soybean and tung oil provide biofriendly, sustainable healing agents with 70–90% recovery in barrier properties while avoiding toxicity issues (27). In their investigation of MXene nanosheets as multipurpose fillers and nanocontainers, Xiaoqing et al. (24) found that at 0.5-2 weight percent loading, the nanosheets reduce permeability and release inhibitors in response to corrosion, increasing protection by two to three orders of magnitude through chemical release mechanisms and physical sealing.

6.2.3. Polymer and Nanocomposite Coatings

The main way that polymer nanocomposite coatings provide flexible and affordable corrosion protection is by creating a physical barrier that keeps corrosive substances away from the substrate. Performance is significantly improved by the addition of nanofillers, such as layered materials (graphene, clay, MXenes), nanoparticles (TiO_2, ZnO, SiO_2), and nanotubes (carbon nanotubes, halloysite) (22). Higher concentrations run the risk of agglomeration and defects, but optimal nanofiller loadings (0.5–5% weight percentage) improve tortuosity, mechanical strength, UV resistance, and active corrosion inhibition. Epoxy-graphene nanocoatings exhibit corrosion protection factors exceeding 10^4, and these enhancements are common in epoxy, polyurethane, acrylic, and polyester matrices. For the best protection, uniform dispersion must be achieved by high shear mixing, surface functionalization, or ultrasonication. Proper surface preparation, and balancing roughness was stressed by Croll (6) (Ra 5-10 μm for mechanical interlocking, <5 μm for defect minimization) to maximize adhesion, with grit blasting and chemical pretreatments further enhancing coating durability. Overall, nanocomposite polymer coatings provide superior barrier, mechanical, and active protection, making them highly promising for corrosion mitigation in various industrial settings.

6.2.4. Nanoceramic and Advanced Inorganic Coatings

Although ceramic coatings have outstanding hardness, thermal stability, and chemical inertness, they are brittle and present application difficulties. With a focus on advanced synthesis techniques like sol-gel, PVD (Physical Vapor Deposition), and CVD (Chemical Vapor Deposition) that yield dense, defect-free structures with superior barrier properties, Es-Soufi et al. (21)reviewed nanoceramic coatings such as TiO_2, Al_2O_3, SiO_2, CrN, and TiN. In aggressive acids, TiO_2 coatings (1–5 μm thick) exhibit corrosion rates below 0.01 mm/year and maintain their stability above 400°C, outperforming polymer coatings. When polymers break down in high-temperature, erosive, and UV-exposed conditions, nanoceramics perform exceptionally well. To increase adhesion, toughness, and corrosion resistance, hybrid or multilayer coatings that combine ceramic and ductile metallic or polymer layers are frequently necessary because brittleness restricts mechanical impact resistance and thermal cycling.

6.3. Green and Sustainable Corrosion Inhibitors

6.3.1. Plant Extract Inhibitors

Phytochemicals such as tannins, alkaloids, and flavonoids adsorb on metal surfaces to create protective films that stop corrosion reactions (18). At 200–500 ppm concentrations in acidic media, inhibition efficiencies frequently surpass 90%, matching or even outperforming synthetic inhibitors. Despite some thermal degradation, plant extracts rich in heteroatoms and π-electrons chemisorb strongly with adsorption energies over 40 kJ/mol, remaining effective up to 60-80°C (11). Although Salleh et al. (25) compiled data demonstrating 80-95% inhibition for ferrous alloys in acidic solutions at 500-2000 ppm, they issued a warning that extraction composition variability, interactions with process chemicals, foaming, and limited high-temperature stability pose challenges for industrial use.

6.3.2. Surfactant-Based Inhibitors

Surfactants inhibit corrosion by adsorbing their amphiphilic molecules onto metal surfaces, with hydrophobic tails creating water-repellent barriers. In a review of cationic, anionic, nonionic, and gemini surfactants, cationic types like quaternary ammonium compounds achieve over 85% inhibition at 10-100 ppm in acidic media by forming dense monolayers (12). Gemini surfactants, with two tails and heads, show enhanced inhibition (92-98%) due to stronger adsorption. Surfactants are water-soluble, compatible with additives, and multifunctional but can cause foaming in agitated systems, have limited stability below 80-100°C, and may interfere with hydrometallurgical separation processes.

6.4. Emerging Technologies

6.4.1. Cold Spray Coatings

Cold spray technology offers special benefits for corrosion prevention and equipment repair by enabling the solid-state deposition of metallic and composite coatings without melting. Hassani-Gangaraj et al. (26) conducted a critical review of cold spray coatings' ability to prevent corrosion by looking at the electrochemical behaviour, coating microstructure, and deposition mechanisms. Through high-velocity (500-1200 m/s) particle impact, the authors demonstrated that cold spray creates dense, well-bonded coatings with low porosity (<1-2%) and oxide content, resulting in severe plastic deformation and mechanical interlocking without thermal degradation. By using sacrificial anode mechanisms, cold spray coatings of aluminum, zinc, and aluminum-zinc alloys offer steel substrates cathodic protection. Their corrosion protection is on par with or better than that of thermal spray coatings, and they do so without the thermal stresses, phase changes, and oxidation that come with high-temperature operations.

Table 2 Comparative Performance of Materials and Coating Systems

Material/Coating Type	**Corrosion Resistance**	**Wear Resistance**	**Temperature Limit**	**Cost (Relative)**	**Key Advantages**	**Primary Limitations**	**Key References**
Stainless Steels (304, 316)	Moderate; susceptible to pitting in Cl^- >500 ppm; SCC in acidic chloride	Moderate	95°C (aqueous corrosion)	Low (1.0×)	Widely available; good mechanical properties; easy fabrication	Fails in HPAL; MIC susceptible; inadequate for high Cl^-	Whittington & Muir (14); Little et al. (23)
Duplex Stainless Steels	Good; improved Cl^- resistance vs. austenitic	Good	120°C	Medium (2-3×)	Better pitting/SCC resistance; higher strength	Still MIC susceptible; limited to moderate acids	Whittington & Muir (14)
Ni-Based Alloys (Hastelloy C-276)	Excellent in acids; resists oxidizing/reducing media	Good	200-250°C	Very High (8-12×)	Broad chemical compatibility; high-T capable	Cost prohibitive for large equipment; HPAL limits	Whittington & Muir (14); Fayyad et al. (20)
Titanium/Ti Alloys	Excellent in hot acids; immune to Cl^- pitting	Moderate (galling issues)	270°C+	Very High (15-25×)	HPAL-compatible; no Cl^- limits; long life (15-20 yrs)	Very expensive; requires specialized welding	Whittington & Muir (14)

Electroless Ni-P (High P)	Excellent; <0.1 mm/yr in acids; amorphous structure	Good (450-550 HV)	80-100°C continuous	Medium (coating only)	Uniform on complex shapes; no grain boundaries; cost-effective	Temperature limited; can delaminate under thermal shock	Fayyad et al. (20)
Electroless Ni-B	Excellent; 20-40% better than Ni-P in alkaline	Excellent (600-750 HV)	100-120°C	Medium (coating only)	Higher hardness; superior wear; good alkaline resistance	Lower acid resistance vs. Ni-P; more bath instability	Barati & Hadavi (8)
Ni-P/Ni-B + Particles (SiC, Al_2O_3)	Excellent; particles enhance barrier	Excellent (50-70% wear reduction)	120-150°C (with heat treat)	Medium-High	Combined corrosion-wear protection; tailorable properties	Requires particle dispersion optimization; thickness limited	Sajjadnejad et al. (19); Barati & Hadavi (8)
Smart Self-Healing (Microcapsules)	Excellent; 80%+ healing efficiency	Variable	Polymer-dependent (60-120°C)	High	Autonomous repair; extended life; reduced maintenance	Capsule durability; healing agent compatibility; limited cycles	Cui et al. (10); Ataei et al. (27)
MXene-Enhanced Coatings	Excellent; 10^2-10^3× improvement vs. unfilled	Good	80-150°C	High (research stage)	Multi-functional; ultra-low loading (0.5-2 wt%); self-healing	Scalability; long-term stability unknown; cost	Xiaoqing et al. (24)
Polymer Nanocomposites (Graphene, Clay)	Excellent; coating resistance >10^8 Ω·cm^2	Good	60-120°C	Medium	Versatile; 80-95% permeability reduction; processable	Temperature limited; UV degradation; adhesion critical	Pourhashem et al. (22)Croll (6)
Nanoceramic (TiO_2, Al_2O_3, CrN)	Excellent; <0.01 mm/yr; chemically inert	Excellent	400°C+	High	High-T stable; wear resistant; UV resistant; long-life	Brittle; requires interlayers; application complexity	Es-Soufi et al. (21)
Plant Extract Inhibitors	Good; 80-95% inhibition at 500-2000 ppm	N/A	60-80°C	Low	Non-toxic; biodegradable; renewable; effective in acids	Extract variability; temperature limited; foaming; industrial validation needed	Verma et al. (18); Umoren et al. (11); Salleh et al. (25)
Surfactant Inhibitors	Good; 85-98% inhibition	N/A	80-100°C	Low-Medium	Water soluble;	Foaming: temperatur	Aslam et al. (12)

	(gemini surfactants)				multifunctional; low concentration	e limited; process interference potential	
Cold Spray (Al, Zn, Alloys)	Excellent; cathodic protection + barrier	Excellent	200°C+	Medium-High	Dense, low porosity (<2%); no thermal damage; in-situ repair	Equipment intensive; line-of-sight; surface prep critical	Hassani-Gangaraj et al. (26)

Performance Ratings: Excellent = superior to most alternatives; Good = adequate for many applications; Moderate = limited applicability; Cost Ratings: Relative to carbon steel baseline; coating costs exclude substrate; Temperature Limits: Maximum for reliable corrosion protection in aqueous aggressive media

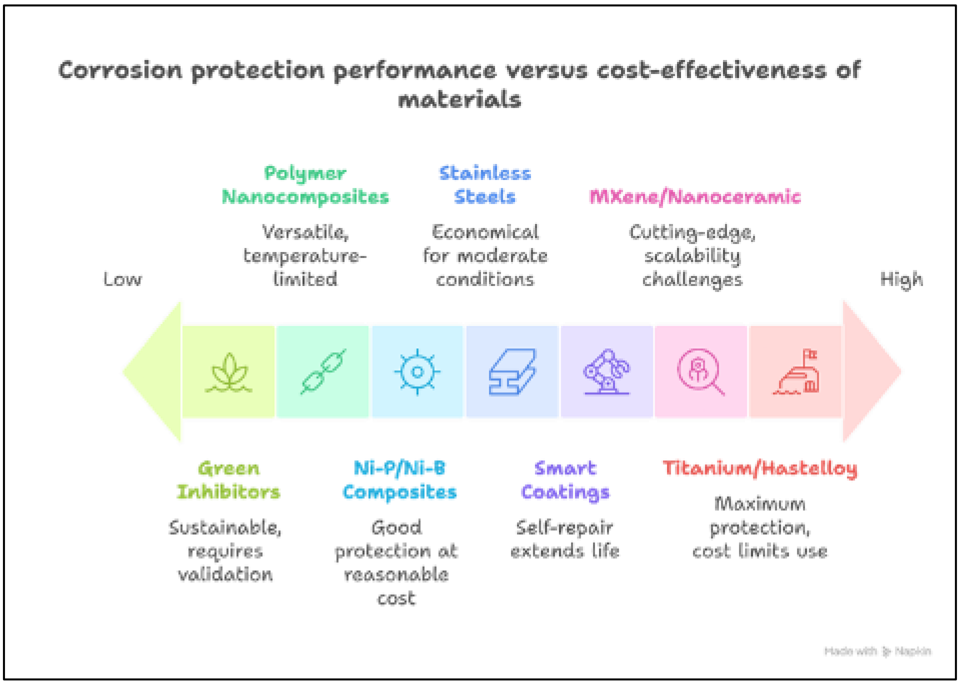

Figure 2 Performance Matrix - Corrosion protection versus cost effectiveness

7. Critical Analysis, Challenges and Research Gaps

7.1. Critical Analysis on Advances in Coating Technologies

To control corrosion in harsh hydrometallurgical settings, significant advancements have been made in advanced materials and coating systems. Different technologies provide advantages that are specific to circumstances.

With the addition of self-healing, corrosion sensing, and stimuli-responsive features that automatically fix damage and alert users to degradation, smart coatings have advanced beyond passive protection. Due to their multifunctionality, which includes inhibitor release, nanomaterials such as MXenes further increase corrosion resistance by orders of magnitude. Sustainable alternatives are offered by biofriendly self-healing substances made from vegetable oils. Nevertheless, these developments are still mostly in the laboratory, lack industrial validation, and present real difficulties for widespread use (10,24,27). Green corrosion inhibitors made from plant extracts and surfactants exhibit robust metal surface adsorption, environmental friendliness, and excellent inhibition efficiency in the lab. Industrial adoption is hampered by problems with extract variability, temperature stability, and interactions with hydrometallurgical chemistry. There are few long-term investigations evaluating inhibitor performance in actual settings (11,12,18,19). Excellent corrosion resistance is provided by nano/microstructural control and nanoparticle inclusion in nanostructured metallic coatings, particularly electroless Ni-P. Limited coating thickness, adhesion issues, and unknown failure modes under industrial mechanical and thermal pressures are among the difficulties (20). The durability and barrier qualities of coatings are significantly improved by polymer nanocomposites containing graphene, clays, and MXenes. However, scale-up and long-term stability are complicated by temperature limitations, UV degradation, and difficulties with nanofiller dispersion (22). Advanced ceramics require intricate multilayer designs due to their brittleness and stress-induced cracking, but they also offer thermal stability and chemical inertness beyond polymer limits. Although cold spray coatings have high prices, complicated equipment, and limited application, they allow for dense, well-bonded metallic layers without thermal damage and on-site repairs (21,26).

7.2. Persistent Challenges

The application of laboratory results to industrial practice is a significant gap. Most of the research concentrates on controlled settings, neglecting the complicated chemistry of actual hydrometallurgical processes as well as temperature cycles, mechanical stress, microbial effects, and pH fluctuations. Comparability is hampered by the absence of standardized testing procedures, and accelerated testing frequently fails to forecast actual service life (10,22,23). Although ideal roughness and its long-term consequences are poorly known, surface preparation has a significant impact on coating adherence, making quality control and field performance prediction more difficult (6). Because it is difficult to differentiate microbially influenced corrosion (MIC) from abiotic corrosion, complicated microbiological populations, inefficient antimicrobial penetration, and design elements that inadvertently promote biofilms, MIC is still poorly handled. For hydrometallurgy, integrated MIC control techniques are not well developed (23). Economic and sustainability factors cause tension with technological performance. High-end solutions use expensive, energy-intensive, or environmentally hazardous materials, whereas green inhibitors address agricultural and ecological concerns. Capital and skill restrictions limit developing nations' ability to embrace innovative technology (2,18,27).

7.3. Research Gaps

Multi-year field trials comparing advanced coatings and inhibitors under actual operational stresses are desperately needed, along with cost-benefit analyses and systematic failure analysis to validate lab results (10,18,24,27). Research on plant-based inhibitors and surfactants should concentrate on the following areas: consistent extract standardization, identification of active components, process compatibility, enhancement of temperature stability, scaling extraction/formulation, and life cycle sustainability (11,18). For MIC Mechanistic Knowledge, research needs to focus on hydrometallurgical biofilms, clarify corrosion mechanisms, provide field diagnostics, evaluate material susceptibilities, and verify integrated control schemes tailored to these conditions (23). In understanding advanced manufacturing techniques, hydrometallurgical protection, feedstock engineering, process parameters, field repair procedures, hybrid coatings, and economic modeling must be optimized for cold spray and other additive techniques (26). Creating standardized methods to assess corrosion protection systems' effects on the environment, economy, and society, including embodied energy, recyclability, toxicity, and more general sustainability metrics will help in bridging the gap in lifecycle and Sustainability Frameworks (2). Moreso, forecasting deterioration and maximizing maintenance, using digital twins, computational materials design, structure-property-performance models, machine learning on corrosion datasets, and sensor data integration is another key area that gaps exist (20).

Notwithstanding the encouraging lab-scale developments in self-healing smart coatings, green inhibitors, nanostructured metals, polymer nanocomposites, ceramics, and cold spray technologies, there are still significant gaps in practical validation, mechanistic comprehension of complex corrosion, including MIC, and striking a balance between sustainability, economics, and technical requirements. For hydrometallurgical operations that produce cobalt and nickel to have dependable, economical, and sustainable corrosion protection, these issues must be addressed through cooperative, multidisciplinary research, long-term industrial trials, standardized testing, and comprehensive assessment frameworks.

8. Conclusion and Future Directions

In the hydrometallurgical recovery of cobalt and nickel, corrosion presents a serious problem that affects costs, safety, sustainability, and the environment. The harsh conditions used in laterite leaching, solvent extraction, and electrowinning processes low pH (<1), temperatures as high as 270°C, high levels of sulfate and chloride, and potent oxidants cause corrosion rates that are significantly higher than those allowed by standard design. According to case studies of HPAL facilities, corrosion-related costs make up 15–25% of operating costs, and failures put environmental and safety risks at risk. Green corrosion inhibitors, advanced coatings, process-specific problems, research, case studies, and material performance are all covered in this review. Advancements include plant-based inhibitors with 80–95% efficacy, nanostructured metallic coatings that resist erosion and corrosion, polymer nanocomposites with resistances greater than $10^8\ \Omega\cdot cm^2$, smart self-healing coatings with over 80% healing efficiency, and state-of-the-art defenses like nanoceramic coatings and cold spray deposition for extreme conditions.

There are still large gaps between laboratory results and industrial application, despite tremendous advancements. Most technologies have only been tested briefly in simplified solutions, ignoring the complexity of real-world settings with shifting chemistry, temperature fluctuations, flow variations, mechanical stresses, microbial activity, and scale formation. There are few long-term field studies spanning several years, which raises questions regarding lifecycle costs, durability, and degradation. Experience in industry demonstrates persistent problems such as under-deposit corrosion, which causes titanium to pit more than 5 mm annually, material failures due to insufficient testing, which necessitates early replacements, and microbially influenced corrosion, which causes unanticipated failures despite research. This disparity emphasizes how urgent thorough validation under real-world commercial circumstances is required.

Future research must focus on long-term field validation to prove performance and realistic lifecycle costs. Green chemistry efforts should prioritize extract standardization, active component identification, compatibility, and temperature stability to enable industrial use of plant-based inhibitors. Understanding complex degradation, especially microbially influenced corrosion, requires studying biofilms, developing diagnostic tools, and validating management strategies. Advances in cold spray and additive manufacturing will support cost-effective, durable materials and coatings tailored to hydrometallurgical needs. Life cycle analysis will guide decisions balancing performance, cost, environment, and social factors. Cross-disciplinary collaboration is vital to tackle corrosion in these systems. As hydrometallurgical operations grow to meet cobalt and nickel demand in batteries and strategic materials, effective corrosion management is key for sustainable, safe, and economically viable production supporting the global energy transition.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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