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A Brief Overview of Corrosion Prevention and Inhibition: Past, Current and Future Technologies

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Abstract

Corrosion is a process that degrades metal-based materials because of chemical reactions to their surrounding environment. For that reason, it causes serious problems across various industries, namely reduced material quality, increased maintenance costs, and extensive safety concerns. This paper presents a concise overview of corrosion prevention and inhibition methods, focusing on key strategies, such as material selection and the use of protective coatings, cathodic protection, and corrosion inhibitors. Furthermore, nano coatings, eco-friendly inhibitors, smart materials, corrosion modeling, and self-healing materials are also discussed as part of current advancements. In-depth understanding and appropriate implementation of these suggested methods is essential for extending material lifespan and improving operational efficiency of the overall industrial systems.

Keywords: corrosion; inhibition; metal; nano material; prevention.

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INTRODUCTION

Corrosion is an electrochemical process that reduces construction material's quality, particularly metals, when they react with environmental components, such as oxygen, water, and salts. Therefore, it causes significant challenges in various sectors, namely construction, maritime, oil and gas, automotive, and infrastructure, leading to extensive safety concerns, high maintenance costs, and low operational efficiency (Yuan & Pehkonen, 2006). In fact, the global corrosion cost has been predicted to surpass 3% of the world's GDP annually, emphasizing the necessity for effective corrosion management approaches (Koch *et al.* 2016).

Corrosion commences when oxidation occurs on metal surfaces. Oxidation is generally accelerated in humid, saline, or fluctuating temperature environments. Corrosion causes a drastic weakening in structural strength, shortening asset lifecycle, and can lead to disastrous failures if not properly managed. Corrosion can lead to downtime in an industrial setting, product contamination, and trigger serious risks to worker health and safety.

There are many conventional and modern approaches to prevent corrosion. The conventional methods include the selection of corrosion resistant materials, barriers and coatings, cathodic protection systems (Li *et al.* 2024), and inhibitors (including both synthetic and natural substances) to slow down the corrosion rates in aqueous and atmospheric environments (Al-Amiery *et al.* 2023). Meanwhile, modern corrosion prevention methods focus on smart coating, self-healing materials, nanotechnology, and physical-chemical modeling to enhance predictive ability and sustainability (Sanyal *et al.* 2024). With growing global environmental regulations and industry requirements for sustainability, the use of green inhibitors and waste-derived feedstock is gaining more attraction from both researchers and industries. Consequently, it is pivotal to develop multifunctional, adaptable corrosion protection methods to warrant asset longevity and compliance with the global environmental regulations (Patel *et al.* 2025). This paper provides a short overview of various evolving practices and discusses the essential approaches and outlook for corrosion prevention and inhibition.

CONVENTIONAL AND MODERN CORROSION PREVENTION METHODS

Material selection and protective coatings

Corrosion protection employing corrosion-resistant alloys (e.g. stainless steel, aluminum, and titanium) is vital, especially in saline, oxidative, and humid environments (Choudhary & Singh, 2025). When materials are selected based on their compatibility with the exposed environment, less frequent maintenance and replacement will be needed. Moreover, a protective coating (organic coatings (epoxy, polyurethane), metallic coatings (zinc, aluminum), and ceramic or polymer coatings, advanced materials), is commonly utilised to provide effective barrier between a metal surface and a corrosive environment. Recently, hybrid and nano-structured coatings have exhibited greater corrosion resistance due to their compact morphology and excellent adhesion performance in the coatings (Dehghani *et al.* 2024). Generic nano-coatings exist, providing self-assembled, uniform coatings restricting moisture or ions from penetrating into the substrate (Benea & Mardhare, 2008).

Cathodic protection (CP)

Cathodic protection is an electrochemical process in which a metal surface is formed as the cathode of an electrochemical cell. In principle, either sacrificial anodes (galvanic CP) or impress current cathodic protection (ICCP) systems are used in a CP method to protect pipelines, storage tanks, offshore platforms, etc. (Matchor). In fact, CP systems are highly advantageous because they are very effective when applied in conjunction with coatings, as they extend the life of the coating and significantly reduce the costs required for maintenance and repairs. Basically, the effectiveness of CP depends on the proper design and sustained monitoring of the system.

Use of corrosion inhibitors

Corrosion inhibitors are additives typically present in low concentrations that decelerate the corrosion process, primarily in closed systems, such as boilers, cooling water circuits and oil pipelines. Regarding corrosion management, inhibitors play effective roles in different ways, namely by forming a passive film, modifying the pH, or interrupting electrochemical processes (Ramya & Mohana, 2024).

In the past few years, attention has been drawn to the development of green inhibitors derived from natural materials, such as plant extracts, tannins, and amino acids, due to their low toxicity and exceptional biodegradability (Rami *et al.* 2022). The green inhibitors also provide comparable, if not better inhibition efficiency than the synthetic inhibitors, with increased health and environmental safety. To correctly choose the type of inhibitor, one should consider the type of metal, the acidic environment, and the operating conditions.

EMERGING TECHNOLOGIES AND OUTLOOK

Smart materials and self-healing coatings

Smart materials have emerged as a new substance in corrosion inhibition as they can change (or respond) to environmental variables, including pH, humidity, salinity, and mechanical failure. Upon activation, smart materials can liberate corrosion-inhibiting agents or form barriers that inhibit corrosion, thereby giving corrosion resistance in real-time (Firoozi *et al.* 2025). The preponderance of studies has focused on self-healing coatings, which are a subcategory of smart material that employs healing agents (e.g. epoxy, inhibitors) containing microcapsules or vascular networks. When cracks are formed, the self-healing agent is liberated and permits the coating to repair itself autonomously. As a result, the integrity of the coating is sustained and leads to extending the coating shelf life (Zhang *et al.* 2018). Thus far, the application of internal self-healing has received most attention in reducing maintenance cycles and improving the longevity of coated materials.

Remarkable progress in computational corrosion science has led to more accurate modelling of corrosion mechanisms across various environmental and operating conditions. Popular mathematical modeling techniques, such as finite element analysis (FEA).

Table 1. Comparison of Corrosion Prevention Technologies

Technology Category	Applied Technologies	Efficiency	Cost	Environmental Impact	Typical Use Cases
Past (Conventional)	Oil-based coatings, Galvanization, Bituminous layers	Low–Moderate	Low	High (VOC emissions, heavy metals)	Construction, pipelines, storage tanks
Current (Modern)	Epoxy coatings, ICCP, Organic inhibitors	Moderate–High	Moderate	Moderate (some synthetic chemicals)	Offshore platforms, marine vessels, automotive
Emerging (Future)	Smart coatings, Nano-inhibitors, Green-inhibitors, AI-based monitoring				

Computational modelling and predictive analytics
FEA is a numerical method that divides complex structures into smaller, manageable elements
to analyze corrosion behavior under various stress conditions, density functional theory (DFT). It allows for the study of corrosion atom adsorption on metal surfaces and can be used to predict corrosion behavior, adsorption ability, catalytic activity, and molecular dynamics (MD) simulation have shown accurate prediction of corrosion rates, studied the efficiency of inhibitors, and optimized selections of materials (Li *et al.* 2024). It allows scientists to observe the interactions and movements of these tiny particles over time, providing insights into the behavior of molecular systems that are often challenging to observe experimentally. These tools provide engineers with the opportunity to simulate long-term corrosion behavior; thereby, they can decrease their reliance on empirical testing and decrease the time to develop protective systems.

COMPARATIVE EVALUATION

Corrosion prevention strategies have evolved slowly over time from the basic physical barrier system to multi-functional, environmental systems. Table 1 presents various corrosion control technologies, which are evaluated based on four points of consideration (efficiency, cost, environmental effects, and usual use in industry
Conventional corrosion prevention systems are mostly utilized to protect equipment, such as water pipes, storage tanks, etc. These systems comprise galvanization, oil coatings or bituminous layers with little more than passive protection through barriers blasting corrosive attacks on the environment, which provide little long-term protection in aggressive environments. These systems were low cost, low tech, comparing the benefits and contributions of using high-risk materials, i.e. VOCs or heavy metals (Revie & Uhlig, 2008). Modern technologies employ synthetic polymers (such as epoxy coatings), cathodic protection systems like the impressed current cathodic protection systems (ICCP), and organic inhibitors to provide more efficient and durable corrosion prevention. These technologies are widespread in high-demand industries such as offshore oil platforms and car assembly, where levels of protection have improved. These materials are of an affordable cost and create fewer environmental challenges while also greatly increasing the longevity of metal structures (Sinko, 2014).
Innovations, including smart coatings that self-heal, nano composite inhibitors, or sustainable, plant-extract and biomolecule-based corrosion inhibitors lead to new guidance in corrosion mitigation, providing autonomous response to environmental stimuli or damage while extending protection to numerous construction materials without requiring specific maintenance (Tallman *et al.* 2019) (Verma *et al.* 2018). Adoption has generally lagged due to the high cost of initial installation. However, if these technologies demonstrate sustainment, precision, and minimal environmental impacts, they may be well suited for high-value implementations, such as aerospace, biomedical implants, and smart infrastructure systems.

CASE STUDIES AND REAL-WORLD EXAMPLES

Real-world instances demonstrate effective corrosion control methods highlight the significance of preventive control and monitoring incorporating structural integrity and safety of operations. For instance, the offshore oil platforms in the North Sea
have a combination of the impressive current cathodic protection (ICCP) and epoxies integrated into their engineered systems for the protection of substantial construction in the harsh offshore marine environment. The ICCP is such that it affords a remarkable extension in service life of the asset(s) as compared to that without an ICCP. Maintenance and operational downtime during maintenance in an offshore environment can be substantial costs (Malchers, 2005). In the aerospace arena, the major manufacturers, Boeing, Airbus, etc. the utilization of chromate-free nanostructured coatings on aluminum alloys have reported positive results of incorporating elements of hazard free processes that were previously

embodied by hexavalent chromium as well as contributing to sustainable and environmentally compliant alternatives. These examples describe similar corrosion resistance alternatives with respect to aviation safety and regulatory requirements (Bierwegen *et al.* 2003). Akashi Kaikyo Bridge that has challenged operational governance because of severe weather with intensive exposure to salt laden winds and the southeastern part of Japan located in the seismic active area, is effectively employing multilayer corrosion control with high bonded zinc content paint primer, fluoropolymer topcoats, and in place real-time corrosion monitoring systems (Kawanishi, 2000).
Conversely, there are several catastrophic failures that exemplify the consequences of insufficient corrosion management. The Silver Bridge in West Virginia collapsed in 1967 (46 deaths) due to unknown corrosion cracking on an element of a suspension chain link, an incident aggravated by ineffectively established inspection procedures for infrastructure and structures (NTSB, 1971). The minor attention to corrosion management cannot be written off as a coincidence, however, as intergranular corrosion was a contributory factor to Aloha Airlines Flight 243 in 1988, as an in-flight structural failure from fatigue cracks in the fuselage caused an explosive decompression mid-flight (NTSB, 1989). A systemic failure aspect of corrosion was also the contributory factor in the outcome of the Baltimore tunnel fire in 2001, with compromised drainage infrastructure during and after that made delaying flooding and damage impossible (American Society of Civil Engineers, 2003). These examples show what is technically feasible in corrosion management and prevention, and the consequences of dismissal of corrosion management within a structural design and maintenance framework (Melchers, 2005)

QUANTITATIVE PERFORMANCE METRICS

Quantitative metrics are important for the performance and cost-effectiveness of corrosion-of-construction-material corrosion mitigation technologies. One of the most used performance measures is inhibitor efficiency (IE %), often denoted as the percentage decrease in the corrosion rate by a protective species. It has been reported in numerous studies that green corrosion inhibitors derived from plants (e.g., Azadirachta indica (neem) or *Zingiber officinale* (ginger)) achieve efficiencies greater than 90% in acidic environments; in fact, green inhibitors can rival some synthetic inhibitors (Verma *et al.* 2018). For instance, showed a bio-based inhibitor derived from *Ocimum tenuiflorum* achieved better than 93.4% protection for mild steel in 1 M HCl, with an overall better environmental impact (Quraishi & Anshari, 2017).

Alongside performance, lifecycle cost analysis (LCCA) is an important consideration when selecting materials and corrosion control methods. Traditional coatings and sacrificial anodes appeal to purchasers due to the low initial cost. However, the shorter lifespan results in a frequency of maintenance, thereby maintaining high cumulative costs. Advanced polymer coatings, ICCP systems, and nanocomposite barriers may be more expensive, but their realistic service lives, rates of failure, and large initial investment hours (Yamashita & Miyuki, 2007) result in lower total lifecycle costs (LCC). A comprehensive LCCA on non-reinforced marine steel structures found that the capital costs of ICCP systems were greater than pure galvanic protection, which resulted in annual LCC being lower than traditional systems by 25%-35% over 30 years (Koch *et al.* 2016). Combined performance rate reductions with investments into LCC suggest a convergence of funding required to develop and implement effective durable corrosion control systems (Li, S et all., 2024)

ENVIRONMENTAL AND SUSTAINABILITY FOCUS

The evolution of corrosion prevention technologies aligns with the increasing focus on sustainability and regulatory compliance. Conventional corrosion inhibitors (e.g., chromates, phosphates, and heavy metal materials), while effective, pose significant threats to the environment due to toxicity and persistence (Yehia *et al.* 2021). Researchers and industries are looking into "green" corrosion inhibitors, such as extracted plant materials, amino and fatty acids, and some biodegradable polymers, as replacements for prior corrosion inhibitors. The "green" inhibitors often had good inhibition efficiencies (generally >90% inhibitive efficiency in acidic media) and still met the environmental safety standards (Verma *et al.* 2017). Several inhibitors that appear promising as sustainable corrosion control agents with low toxicity include Azadirachta indica, Lawsonia inermis, and various essential oil extracts (Quraishi & Anshari, 2017).

At the same time, global governing bodies have also supported this transition with regulations. For instance, the European Union has the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulation which obligates a risk assessment of chemicals to support transition efforts to safer alternatives (European Chemicals Agency, 2020). In the USA, the Environmental Protection Agency (EPA) promotes this decision-making process in several ways, including promoting corrosion inhibitors branded as Safer Choice products, and restricting chemicals designated as persistent, bio-accumulative and toxic (U.S. Environmental Protection Agency, 2023). Regulatory frameworks have accelerated innovation in the commercial development of green inhibitors and non-toxic coating systems, which blends corrosion science in a larger context than corrosion science, and enables practices that transcend corrosion prevention to include sustainability, environmental protection, occupational safety, and circular economy practices. Sustainability is increasingly becoming a scientific, regulatory, and ethical requirement in corrosion prevention practice.

VISUAL AND DIAGRAMS

Illustrations and diagrams are essential to elucidate complex corrosion processes and to elucidate complex inhibition systems. Corrosion processes such as uniform corrosion, pitting, crevice corrosion, and stress corrosion cracking all involve an electrochemical reaction at the metal–electrolyte interface. The electrochemical pathways can be illustrated with electrochemical pathway diagrams, which show the anodic and cathodic sites, electric field, and paths of electron transfer and ion migration (Revie & Uhlig, 2008). These illustrations also elucidate the function of inhibitors, which is to either block active sites on metals (by adsorbing the surface) or to create a passive film, thus further slowing the corrosion process.

Although the existence of schematic depictions of multilayer smart coatings (Figure 1) has been useful in representing the structure and autonomous damage repair interfaces of next-generation protective systems, smart coatings can be multilayered (e.g., a primer layer that contains corrosion inhibitors, an intermediate barrier, and a functional layer that has nanocontainers or pH-sensitive enclaves that retransmit an inhibitor as a result of damage or another environmental trigger (Montemor, 2014). Schematic representations of these multilayer systems provide a glimpse into the stimuli-responsive attributes of the coatings and display how the synergy of multiple layers work together. Given the recent trends in visual communication in materials science, these schematics are explanatory visualizations, and 'drawings' or 'designs' for creating better corrosion-resistant surfaces.

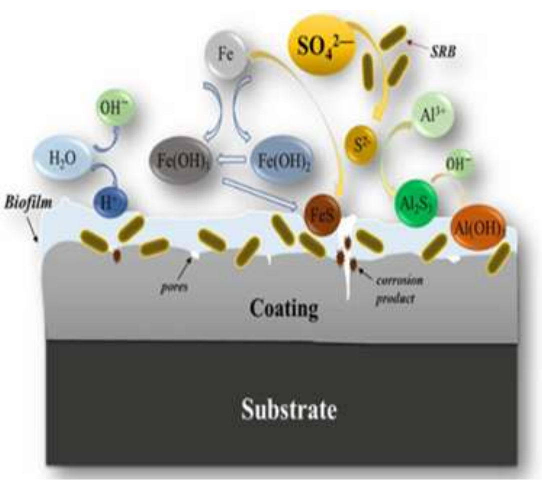

Figure 1. Visual corrosion mechanism (Chu Shi, 2022)

RESEARCH GAPS AND FUTURE DIRECTIONS

Still today, there are barriers to the implementation of advanced corrosion prevention technologies, regardless of the latest advancements. While nanomaterial-based coatings and 'smart' self-healing systems are effective for corrosion prevention, they suffer from high manufacturing costs, significant questions of scale, environmental and human hazards (Kumar *et al.,* 2020). Other conventional inhibitors and their chemical active content are usually synthetic, non-biodegradable, and will persist in the environment in one form or another, often bioaccumulating into ecosystems despite contemporary environmental regulations which abhor (Verma *et al.* 2018). Another key barrier is the absence of long-term field validation, as many corrosion mitigation techniques have shown their effectiveness in the lab but have no information regarding their performance in real-world exposure outdoors (e.g. temperature, salinity, and mechanical stress) (Fattah-Alhosseini & Asgari, 2021)

For future research to address these challenges, we suggest incorporating a molecular design approach to corrosion inhibitors based on the prediction of interactions of molecules with a metal surface using existing computational methods (Revie & Uhlig, 2008), such as density functional theory or machine learning. In addition, the urgent requirement for multifunctional, environmentally compliant bio-based inhibitors that are affordable. Real-time monitoring with smart coatings enabled by nano-biosensors or electrochemical impedance spectroscopy used with advanced coatings will provide a pathway towards predictive asset maintenance for infrastructure and critical equipment. Closing these gaps will be critical to creating the next generation of corrosion protection technologies that are durable, sustainable, and smart.

CRITICAL ANALYSIS

A thorough review of corrosion protection methods has unveiled positive and negative perspectives on conventional, modern and future technologies. Conventional methods provide a cost-effective protective strategy and an easy-to-use. Durability is an additional primary consideration for replacing and maintaining the parts, especially because they are vulnerable to mechanical damage and other types of losses (Revie & Uhlig, 2008). The use of inorganic inhibitors like chromates and nitrites has been prohibited because of their toxicity and long-term detrimental effect on the biosphere. As an alternative solution, the use of green inhibitors, particularly plant extracts and amino acids, has been suggested as a more sustainable corrosion prevention strategy. In fact, their inhibition capacity is highly dependent on the extraction method, concentration and pH (Verma *et al.,* 2018).

Nanostructured coatings and smart self-healing systems are relatively recent developments in corrosion control and offer the expectation of multi-functionality, including active self-repair mechanisms, and passive self-inhibition. However, the same with many other nanotechnology products, the commercial scale application of these methods is hindered by the production costs, scalability, and risks associated with the environmental impact and leaching of the nanomaterials (Kumar *et al.,* 2020). Similarly, while electrochemical options, such as impress current cathodic protection (ICCP), can be ultimately quite effective in marine and buried environments, a successful electrochemical solution is reliant on maintenance and availability of power supply as needed (Montemor, 2014). As such, while each option has specific advantages, none comes without challenges. Therefore, the best corrosion management solution must sufficiently provide considerable efficacy, environmental compliance, costs, and long-term viability, while ultimately being suited to the conditions of the operation and operating environment (Rani et all., 2017)

CONCLUSION

Corrosion represents an ongoing and challenging risk to structural integrity, safety, and operational feasibility in diverse sectors. In this review, the history of corrosion prevention and inhibition, starting from the conventional to the modern strategies has been elaborated and discussed. A comparative evaluation based on the cost, performance efficiency and environmental impacts of the older, current, and innovative technological approaches results in a distinct move towards multifunctional and sustainable solutions that meet the regulatory criteria. Case studies of applied corrosion management systems in aerospace, marine environments and civil engineering demonstrate positive outcomes from implementing effective corrosion management, and vice versa. Although the current technologies offer considerable advantages, their implementation is restricted by the persisting problems related to cost, toxicity, and limited available data to oversee operational validity. Future research and development should focus on the design of inhibitors at a molecular level, developing biodegradable and bio-based systems, and developing monitoring systems to assess real-time performance for corrosion mitigation and management in the working environments. Overall, corrosion control should not only be regarded as an engineering issue but rather as a multidiscipline issue that continues to affect sustainability, safety, and international regulatory standards.

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