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Fundamentals, Sustainable Strategies, and Emerging Technologies of Metal Protection and Corrosion Prevention: A Comprehensive Review

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ABSTRACT

Corrosion is an intricate physicochemical process that gradually degrades and reduces the practical and engineering integrity of metallic substances or materials through exchange with their immediate environment. Mechanisms such as aggressive chemical species, electrochemical reactions, moisture, and extreme dissolved salt concentrations accelerate material deterioration, which often leads to structural and material failures. Corrosion impacts are widespread across critical sectors including manufacturing, production, energy, transportation, and civil infrastructure. This study presents a comprehensive review of corrosion science, corrosion monitoring techniques, and emerging artificial intelligence (AI)-driven approaches for corrosion prevention and corrosion management. Information on trends and patterns of publications on corrosion was systematically collected, synthesized, and refined from journals, conference proceedings, theses, books, and other credible scientific sources published between 1800 and June 2026. Universal academic search aggregators, engines, discipline-specific and regional repositories were utilised to identify and produce relevant papers. The review identified major forms of corrosion as atmospheric, cavitation, erosion, fatigue, fretting, galvanic, intergranular, microbiological, pitting, stress or cracking, selective leaching, chemical, electrochemical, and waterline. It was established that there are four phases of publications on corrosion and corrosion-related topics. Corrosion prevention methods depend on several factors. It was revealed that heterocyclic corrosion inhibitors include C_5H_5N, $C_3H_4N_2$, $C_7H_6N_2$, $C_2H_3N_3$, C_4H_4S, C_3H_3NS, C_3H_3NO and $C_6H_5N_3$. The study concludes that early corrosion prediction, coupled with effective monitoring and control strategies, can substantially reduce economic losses, while AI-driven approaches offer practical advantages over traditional methods of corrosion prevention, particularly in inaccessible or hazardous environments.

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INTRODUCTION

Metals are widely utilised in engineering and industrial applications based on the strength, durability, and versatility of these metals. However, most of these metals tend to degrade to their structurally and thermodynamically stable forms, such as hydroxides, sulphides, or oxides, through corrosion processes (Abdallah et al., 2026; Abdulmutaali et al., 2025). Corrosion causes massive economic losses at both national and local levels or globally. In general, it is estimated that 3.0 to 4.0 % of the world's Gross Domestic Product (GDP) annually is lost due to corrosion processes (Abu Orabi et al., 2024; Chen et al., 2025).Figure 1 presents detail explanation and fundamentals of corrosion processes. Corrosion is the regular deterioration of metals, alloys, and metallic-alloy substances. The process is due to the electrochemical or chemical reactions of these substances with their immediate environment (Chmielewska-Śmietanko and Sartowska, 2025; Chouhan et al., 2013; Eissa et al., 2024). The presence of corrosion occurs in several forms of atmospheric corrosion, such as uniform corrosion, stress corrosion, pitting corrosion, erosion corrosion, crevice corrosion, selective corrosion, intergranular corrosion, fretting corrosion, cracking or corrosion fatigue, waterline corrosion, and galvanic corrosion. Each of these forms of corrosion is influenced by a multifaceted interaction of environmental and operational factors and materials (Fehintola, 2021; 2026). Figure 2 presents a detailed explanation and mechanism of corrosion processes.

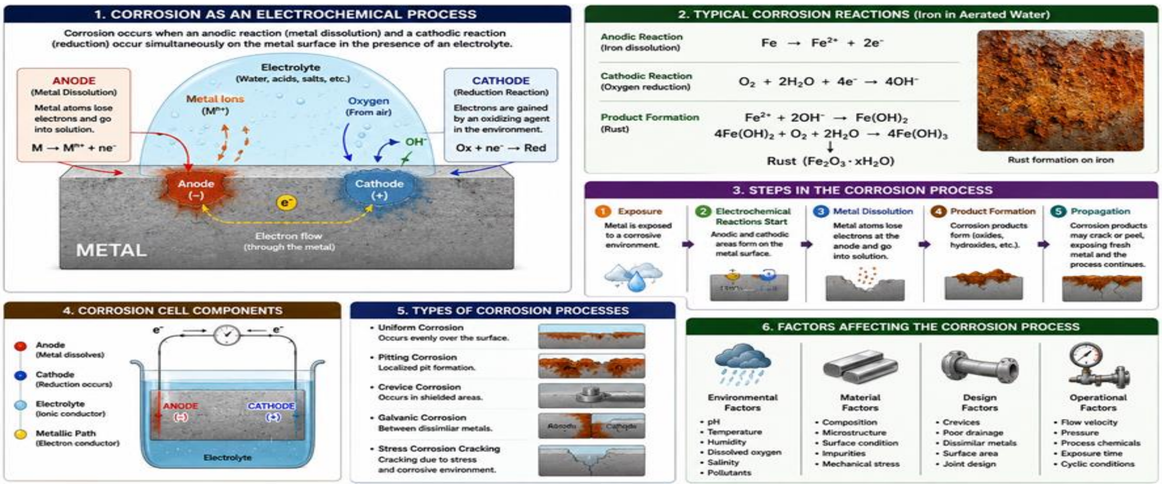

Figure 1: A detailed explanation and fundamental of corrosion processes (adopted from Abdallah et al., 2026; Abdulmutaali et al., 2025)

Figure 2: Metal protection, mechanism and corrosion prevention techniques (adopted from Abu Orabi et al., 2024; Chen et al., 2025

Corrosion is a major challenge and problem in big and small industries such as oil and gas, chemical processing, transportation, marine engineering, water treatment, and infrastructure development. Corrosion is a major cause of economic losses, equipment failures, environmental pollution, and safety hazards. Therefore, corrosion protection is essential to ensure the longevity, reliability, and safety of engineering materials and structures (Li et al., 2015; Liu et al., 2021; Chouhan et al., 2013; Jawad et al., 2026; Fehintola, 2021, 2026). In summary, corrosion is an inevitable natural process, but its impact can be significantly reduced through effective metal protection and corrosion prevention strategies (Chouhan et al., 2013; Li et al., 2015). Literature such as Jumbo-Egwurugwu et al. (2026); Kamal et al. (2026); Koufi et al. (2026); Kang et al. (2024); provides data and information on the importance of metal protection and corrosion control, the relationship between metal protection and corrosion control, and suspended development goals (Figures 3 and 4), but information and data on types of corrosion protection, protection mechanisms, chemistry of corrosion protection, corrosion inhibitor chemistry, cathodic protection chemistry, and trends and patterns of publications on corrosion protection are limited. The main aim of this review is to critically synthesise the fundamentals and mechanisms of corrosion, conventional and emerging metal-protection strategies, corrosion-inhibitor chemistry, cathodic protection, monitoring techniques, and recent advances in sustainable, nanotechnology, and artificial-intelligence-driven corrosion prevention, while identifying current research trends, limitations, and future directions. The key objectives of this review are to provide information on types of corrosion protection, protection mechanisms, chemistry of corrosion protection, corrosion inhibitor chemistry, cathodic protection chemistry, and trends and patterns of publications on corrosion protection.

Literature Search and Review Methodology

The main tool exploited for recognising relevant literature in this review study was universal academic search aggregators, engines, discipline-specific and regional repositories such as Public Library of Science, Web of Science, E-Theses Online Service, Google Scholar, CORE or Royal Society of Chemistry were utilised to identify and create relevant papers. Citation managers such as Mendeley, EndNote, and Zotero were utilised to annotate, store, and tag the articles downloaded. Articles between 1800 and June 2026 with the keywords were sorted based on publication year, relevance, subject area, or keyword to avoid information overload using Google Scholar https://scholar.google.com/scholar?q=Corrosion+and+Protection&hl=en&as_sdt=0,5&as_rr=1). The keywords, such as types of corrosion, chemistry of corrosion, corrosion and science, machine learning in corrosion, application of artificial intelligence in corrosion science, deep learning, corrosion in material science, simulation of corrosion, different models using artificial neural network (ANN), random forest (RF), support vector machine (SVM), and optimization, were utilised individually and in combination. In the research and articles, peer-reviewed articles written and published in English were considered, downloaded, and evaluated. Review papers, conference and workshop abstracts, and studies and findings not directly relevant or related to the keywords were not included. Figure 5 presents the flowchart of the literature search and review methodology.

Main Body of the Review, Research Findings and Discussion

The results of the research findings are presented and discussed as follows:

Fundamentals, Mechanisms of Corrosion and Classification of Corrosion

Corrosion occurs when a metal returns to its thermodynamically stable state, usually as an oxide, hydroxide, or sulphide. An electrochemical corrosion cell consists of an anode (which is the site of metal oxidation), a cathode (which is the site of the reduction reaction), an electrolyte (which is the conductive medium), a metallic path (electron flow pathway), and an anodic reaction (Ghali et al., 2007; Gillet al., 2026; Guma and Dele, 2025). In corrosion prevention, there are several techniques or ways to evade corrosion, but these techniques or ways involve the utilisation of precautions to preserve metal surfaces secluded from corrosive situations, environments, and conditions (Guo and Rong, 2026; Hamid and Gomaa, 2025; Jaddoa et al., 2025; Jasim et al., 2025; Jones, 1996). Figures6and 7 show the patterns and trends of cumulative publications, cumulative publications by year, and publications per year on metal protection and corrosion prevention. The figure shows that a total of 225956 articles, workshops, conference proceedings, books of abstracts, and books were published between 1800 and June 2026. The Figure revealed that there are four phases in the publications on the subject matter and keywords.

Conventional and Emerging Metal-Protection Methods

The result of the search established that research on corrosion prevention and metal protection has grown significantly over the past three or four decades. The trend and pattern of recent and relevant publications can be grouped into four as follows:

i. *1970–2000:* Publication trend in this group focuses on specific areas such as traditional coatings (conventional coating), cathodic protection, and chromate inhibitors. The trend was a normal linear.
ii. *2000–2010:* Publication pattern and trend in this group focus on specific areas such as nanostructured coatings, green inhibitors, and polymer composites. The trend here was semi-logarithmic-linear.
iii. *2010–2020:* Research and publication trends in this group focus on specific areas such as smart coatings, self-healing coatings, nanotechnology, and surface engineering. The trend in this case was exponential, in which the growth of publications was increasing at higher rates
iv. *2020– 2026:* Studies and publication patterns and trends in this group focus on specific areas such as sustainable corrosion protection, bio-based inhibitors, artificial intelligence in corrosion monitoring, graphene-based coatings, machine learning prediction models, digital corrosion management, green corrosion inhibitors, nanocomposite coatings, graphene coatings, self-healing materials, smart sensors, corrosion monitoring systems, AI-assisted corrosion prediction, marine corrosion protection, pipeline corrosion mitigation, and hydrogen-induced corrosion. In this section, the trend of publication was found to be logarithm pattern (Odeyemi and Alaba, 2025; Okuma et al., 2026; Omran and Abdel-Salam, 2020). These previous studies on corrosion protection can be categorised as follows (Osta et al., 2026; Oyetola, 2026; Pyun, 2020; Ridwan et al., 2026; Rodrigo et al., 2026; Roscher et al.,2024;Ruiz et al., 2024; Schweitzer, 2009):

Corrosion Prevention Techniques

There are three main categories or classes of corrosion prevention techniques, which are anodic, cathodic, or mixed corrosion inhibitor procedures. In anodic or cathodic techniques, corrosion reactions are stopped by separating the metal surface or varying the activation energy of the reduction-oxidation (redox) process during corrosion (Abu Orabi et al., 2024; Jumbo-Egwurugwu et al., 2026; Kamal et al., 2026; Kang et al., 2024). In the case of mixed corrosion inhibitors, (substance or chemical that reduce the corrosion rate) are used to reduce the corrosion rate. In some cases, the majority of corrosion inhibitors known are expensive, poisonous, and non-biodegradable compounds (Abu Orabi et al., 2024; Roscher et al., 2024; Koufi et al., 2026). Figures 8 and 9 show metal protection, corrosion prevention techniques, and factors that influence corrosion. Metal protection and corrosion prevention are processes that involve applying scientific and engineering principles to reduce or minimize corrosion rates of metallic materials and prolong the service life of metallic structures and equipment. The utilization of protective materials on metals increases the service life of metallic materials and structures (Kalu et al., 2025). Such protective materials are critical because these protective materials guard surfaces against corrosion, weather factors, tears, and other forms of corrosion (Chmielewska-Śmietanko and Sartowska, 2025; Chouhan et al., 2013; Eissa et al., 2024). These protective materials can be grouped in three groups as follows: conventional, advanced and smart protective materials. All these groups have different features, utilisation techniques, and merits. These groups of protective materials can be explained as follows:

Conventional Protective Materials

Conventional protective materials are eras-old common materials. These materials include galvanizing, Bituminous materials, paints, varnishes, and Lacquers (Kalu*etal.,*2024; 2025; Lozrt *et al.,* 2025),

Advanced Protective Materials

These applications of modern protective materials and technologies, which increase the performance of metallic materials and the lifespan of metallic substances. Advanced protective materials offer enhanced protective qualities over normal protective materials. These materials include polymer-based protective materials, ceramic protective materials, grade ceramic protective materials, and nano-protective materials(Muthu, 2026; Nrior et al., 2026), and

Smart Protective Materials

Smart protective materials respond to changes in environmental issues or to damage. These protective materials provide new systems or functions. These are new protection techniques or technologies for protecting metallic materials, which are smart protective materials. These protective materials include self-healing of the metallic materials, stimuli-responsive materials, antimicrobial materials and anti-corrosive materials (Fernández-Solis et al., 2015; Gajagouni et al., 2026; Muthu, 2026; Nrior et al., 2026).

Figure 3: Importance of corrosion control and metal protection (adopted from Morsy et al., 2026; Mubeen et al., 2026)

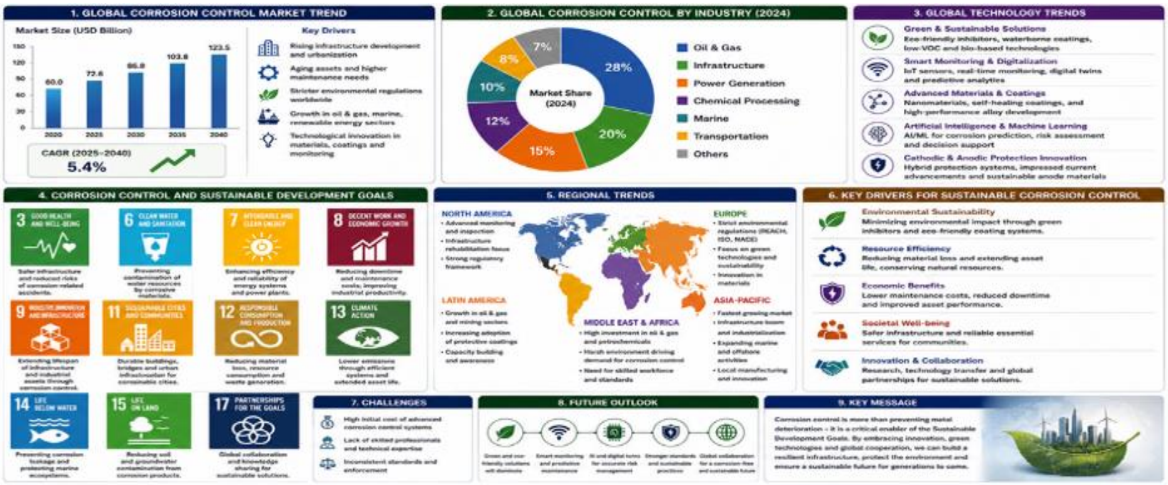

Figure 4: Global trend on corrosion control and sustainable development goals (adopted from Muthu, 2026; Nrior et al., 2026; Morsy et al., 2026; Mubeen et al., 2026)

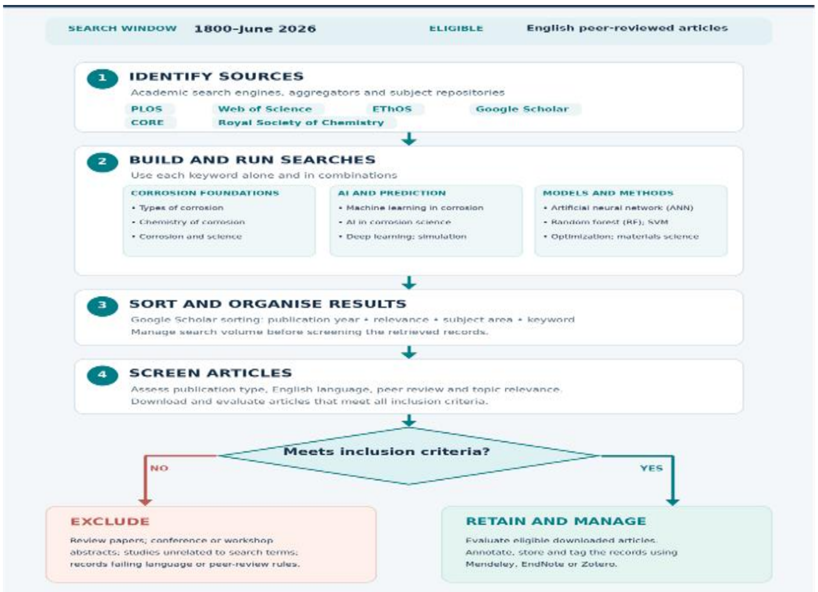

Figure 5: the flowchart of the literature search and review methodology

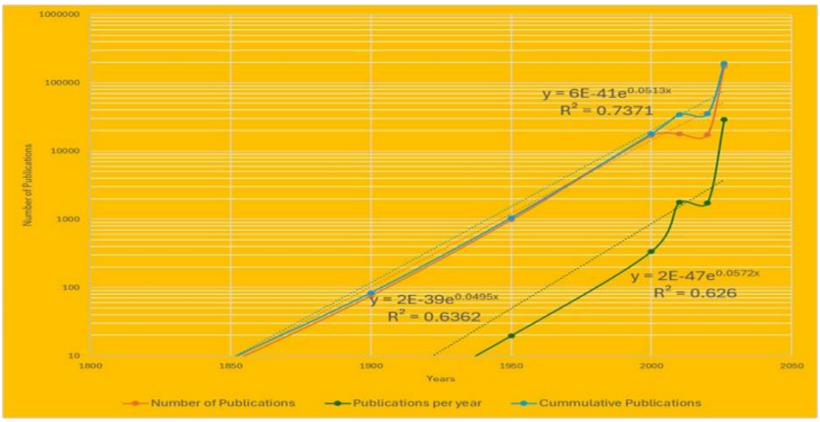

Figure 6: Trend of publications on corrosion and corrosion-related issues between 1800 and 2026

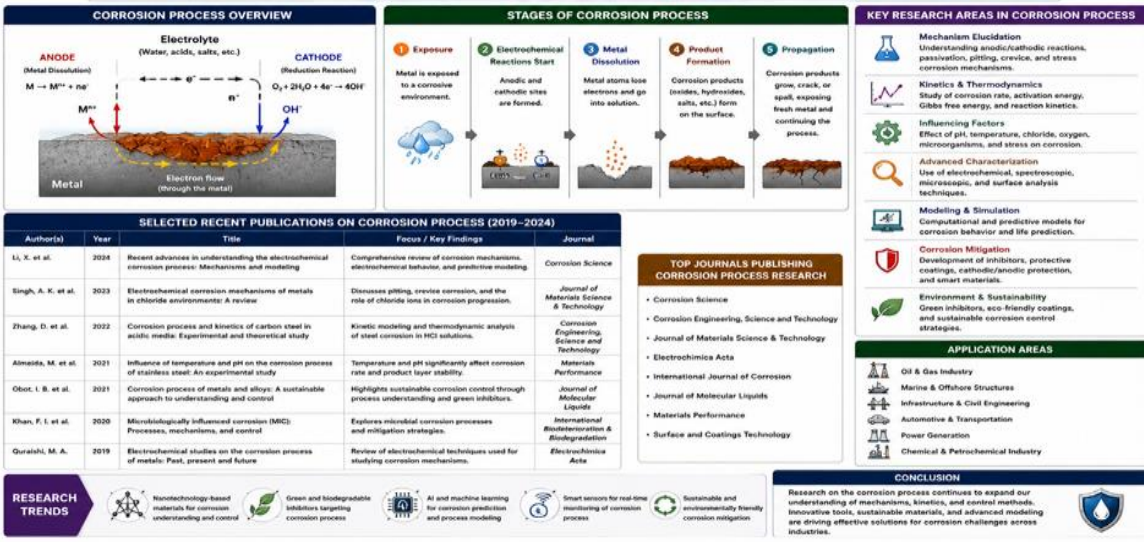

Figure 7: The trend of publications on Corrosion processes (adopted from Melchers, 2020; Kucharlapati et al., 2025; Liu et al., 2026; Manu et al., 2025)

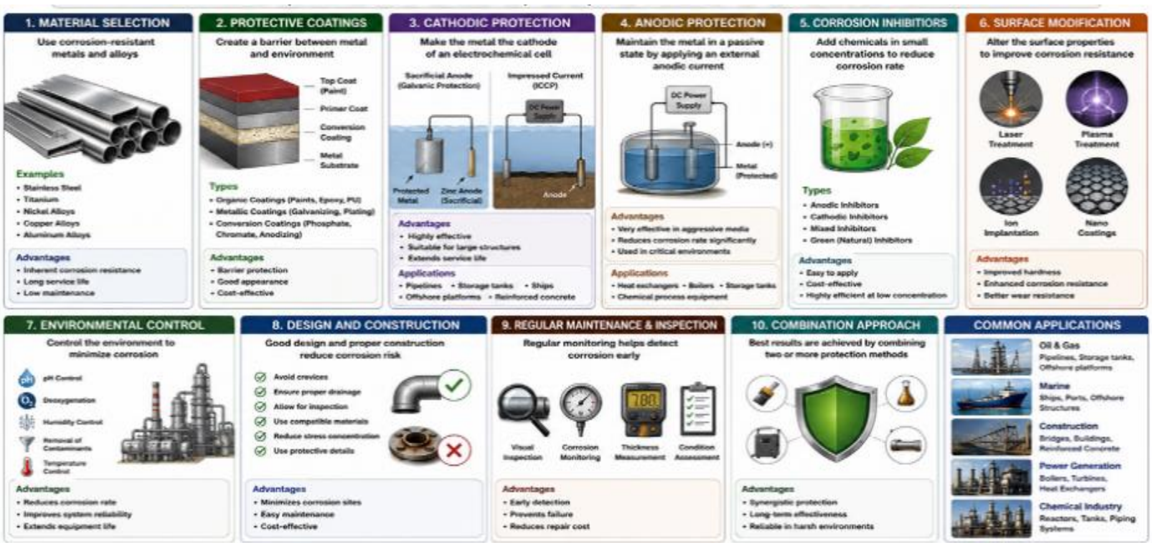

Figure 8: Corrosion control techniques and common applications (adopted from Kucharlapati et al., 2025; Let al., 2026; Manu et al., 2025)

Figure 9: Factors that contribute to corrosion and optimal corrosion control and metal protection techniques (adopted from Melchers, 2020; Kucharlapati et al., 2025; Liu et al., 2026; Manu et al., 2025)

Organic Corrosion Inhibitors and Their Mechanism

In this category, researchers and scientists have demonstrated that imidazolines and amine-based compounds or substances effectively reduce and minimise carbon steel corrosion rate in acidic environments or situations through adsorption mechanisms. The key findings are that corrosion was reduced by greater than 90%, surface protection was improved, and frequently utilised in oil and gas production.

Heterocyclic Corrosion Organic Inhibitors

are a class of organic compounds containing one or more heteroatom**s** (atoms other than carbon and hydrogen, such as nitrogen, oxygen, sulphur, or phosphorus incorporated into a cyclic (ring-shaped) molecular structure. These compounds are widely used to reduce or prevent the corrosion of metals in aggressive environments such as acidic, saline, or industrial process solutions. A heterocyclic corrosion inhibitor is an organic molecule with a ring structure containing heteroatoms that adsorb onto a metal surface, forming a protective film that isolates the metal from corrosive agents and slows down anodic or cathodic corrosion reactions. Notable examples of heterocyclic corrosion organic inhibitors are Benzotriazole, Imidazole, and Benzimidazole, 1,1'-methy1enebis(pyridinium) bromide and 1,1'-ethy1enebis(pyridinium) bromide. These atoms of heterocyclic corrosion organic inhibitors possess lone-pair electrons that facilitate adsorption onto metallic surfaces. These compounds combine the adsorption advantages of heterocyclic structures with improved biodegradability and lower toxicity, making them attractive for sustainable corrosion control. In addition, heterocyclic organic corrosion inhibitors are ring-containing organic compounds with heteroatoms that protect metals by adsorbing onto the surface and forming a barrier against corrosive attack. Their high efficiency makes them among the most widely researched and applied corrosion inhibitors in modern corrosion engineering Ruiz et al., 2024; Schweitzer, 2009; Odeyemi and Alaba, 2025; Okuma et al., 2026; Omran and Abdel-Salam, 2020). Table 1 presents further examples heterocyclic corrosion organic inhibitors, ring type, heteroatoms and chemical formulae.

Table 1: Further Examples of Heterocyclic Corrosion Organic Inhibitors, Ring Type, Heteroatoms and Chemical Formulae

Heterocyclic Compound	Ring Type	Heteroatom(s) and Chemical Formulae
Pyridine	Six-membered ring	NC_5H_5N
Imidazole	Five-membered ring	N, $NC_3H_4N_2$,
Benzimidazole	Fused aromatic ring	N, $NC_7H_6N_2$
Triazole	Five-membered ring	N, N, $NC_2H_3N_3$
Thiophene	Five-membered ring	SC_4H_4S
Thiazole	Five-membered ring	N, SC_3H_3NS
Oxazole	Five-membered ring	N, OC_3H_3NO
Benzotriazole	Fused aromatic ring	N, N, N - $C_6H_5N_3$

Nano- Coatings

Nano-coatings are advanced materials of nanoscale surface treatments that significantly improve the performance of materials by enhancing corrosion resistance, wear resistance, self-cleaning behaviour, and antimicrobial properties. In this category, researchers and scientists have demonstrated that silica and graphene nanoparticles incorporated into epoxy coatings significantly enhance the corrosion resistance of metals. The main results and findings are that these materials reduced the permeability of metallic substrates, improved the mechanical properties of metallic substances, and enhanced coating durability (Thakur et al., 2025).

Self-Healing Coatings

Self-healing coatings are smart protective materials capable of autonomously repairing damage and restoring barrier properties. Through sealing defects area and preventing the penetration of corrosive species, self-healing coatings significantly improve corrosion resistance and extend the lifespan of metals and structures. The growing application of self-healing coatings in oil and gas, marine, aerospace, automotive, and infrastructure sectors makes them one of the most promising advances in modern corrosion protection technology. In this category, researchers and scientists have demonstrated that microcapsule-based coatings release healing agents when metallic substances are damaged. The vital findings and results are that an automatic crack can be repaired, extended service life of metallic substances, and a reduction in the maintenance cost of metallic substances (Samadzadeh et al., 2010; Zhang et al., 2018). Figure 10 shows the trend of publications on metal protection and corrosion prevention techniques. Figure 11 presents the trend of publications on Corrosion protection methods, advancing sustainable solutions for durable materials and a safer future.

Green Corrosion Inhibitors

Green corrosion inhibitors are eco-friendly materials, typically obtained from plant extracts, natural products, microorganisms, or biodegradable compounds, that inhibit metal corrosion by adsorbing onto the metal surface and forming a protective barrier against corrosive agents. In this category, researchers and scientists have demonstrated that plant extracts such asNeem, Henna, Garlic, and Green teahave shown high inhibition efficiencies and performance in an acidic environment. Important results and findings are that these plant extracts are environmentally friendly, biodegradable, and have low toxicity (Verma et al., 2018). Figure 12 shows a global trend of publications on corrosion control, towards sustainable, smart, and resilient corrosion management. Figure 13 shows publications on corrosion monitoring techniques, advances, applications, and research trends.

Cathodic Protection of Pipelines

Cathodic protection (CP) is an electrochemical corrosion control technique utilised to prevent the external corrosion of buried or submerged steel pipelines. In this category, numerous studies report that researchers and scientists have demonstrated that properly designed cathodic protection systems can reduce corrosion rates by over 95%. The essential

Graphene-Based Protection

Graphene-based protection is an advanced corrosion-control strategy that uses graphene and graphene-derived materials to create highly impermeable, mechanically robust, and chemically stable protective barriers. Through their exceptional barrier properties, graphene coatings and nanocomposites significantly improve the durability of metals in aggressive environments and are increasingly being adopted in oil and gas, marine, aerospace, automotive, and infrastructure applications. Continued advances in graphene production and coating technology are expected to make graphene-based protection a major component of next-generation corrosion management systems. In this category, researchers and scientists have demonstrated that graphene-based-enhanced coatings exhibit high impermeability, corrosion resistance, superior barrier performance, and improved corrosion resistance, and current research is focused on large-scale industrial implementation of graphene-based enhanced coatings (Nine et al., 2015; Ding et al.,2018).

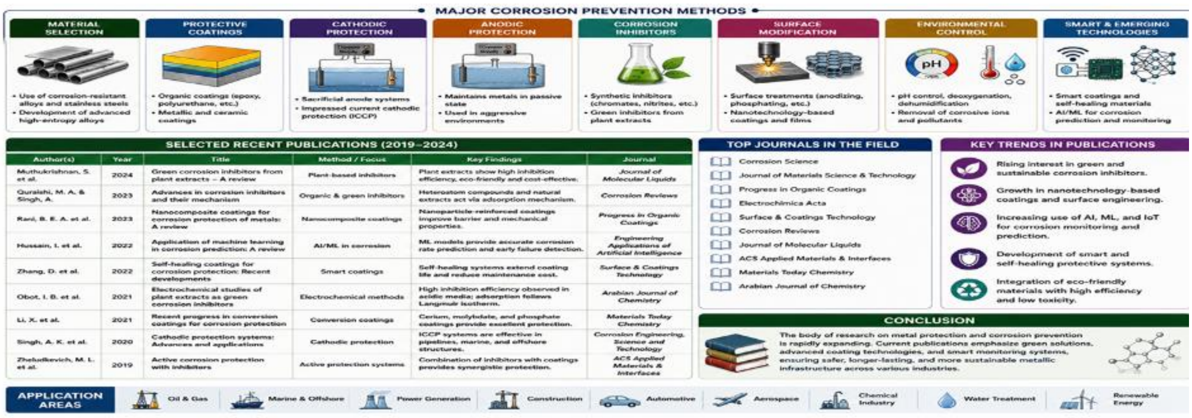

Figure 10: The trend of publications on metal protection and corrosion prevention techniques (adopted fromSyam et al., 2025; Tan et al., 2026; Thakur et al., 2026; Ulhaq Toor, 2025)

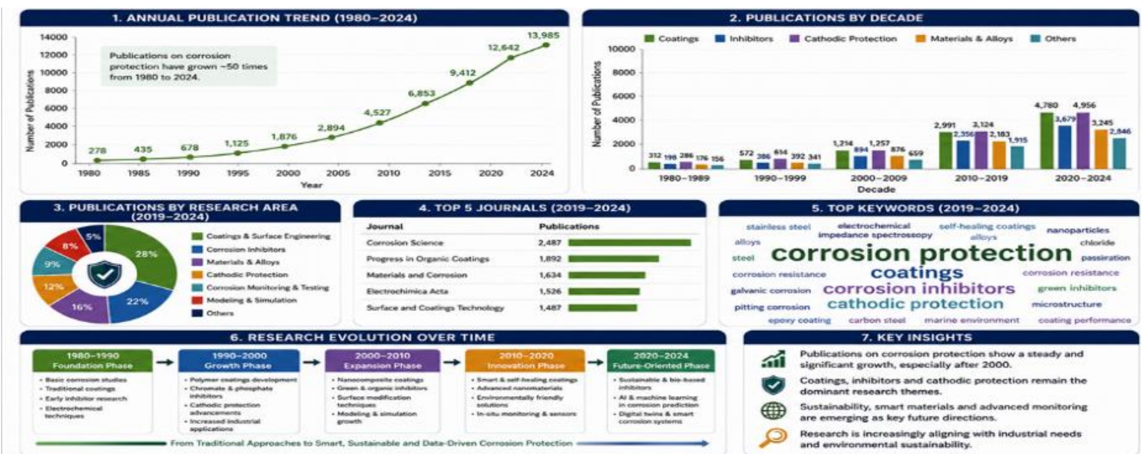

Figure 11: Trend of publications on Corrosion protection methods, advancing sustainable solutions for durable materials and a safer future (adopted fromUsman et al., 2025; Yang et al., 2026; Yuldashova et al., 2026; Zaher et al., 2024; Zhang et al., 2025)

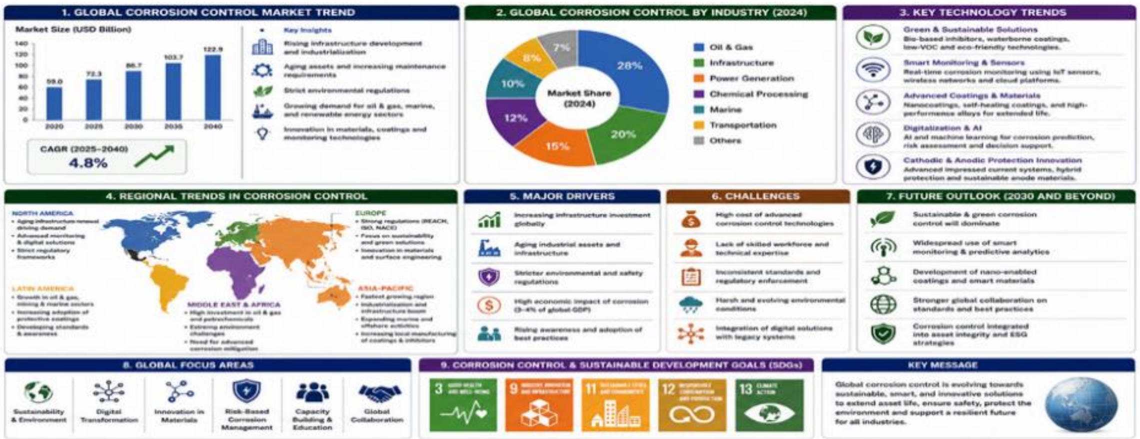

Figure 12: The global trend of publications on corrosion control, towards sustainable, smart, and resilient corrosion management (adopted from Silaban et al., 2026; Singh et al., 2025; Souza et al.,2025; Liu et al., 2026; Manu et al., 2025)

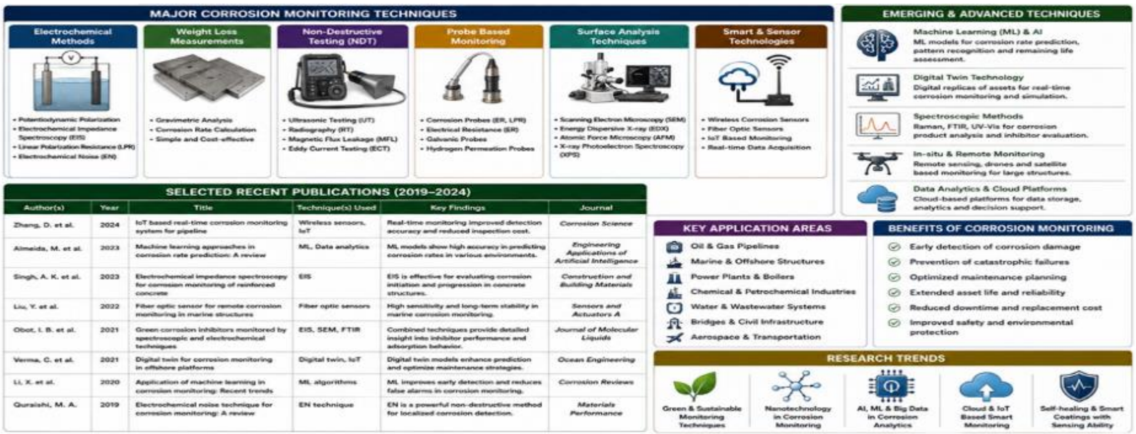

Figure 13: The Publications on corrosion monitoring techniques, advances, applications and research trends (adopted from Melchers, 2020; Kucharlapati et al., 2025; Liu et al., 2026; Manu et al., 2025)

Corrosion Protection

These previous studies on types of corrosion protection can be categorised as follows:

Material Selection

Selecting corrosion-resistant materials reduces deterioration. Typical examples are stainless steels, nickel alloys, titanium alloys, copper alloys, corrosion-resistant polymers, and fiber-reinforced composites. The major advantages of material selection are that these systems are long-term protection reduced the need for regular or routine maintenance. The key limitation is that these systems have a high initial cost (Manu et al., 2025; Nine et al., 2015; Ding et al., 2018).

Protective Coatings

Protective coatings isolate metal surfaces from corrosive environments. The essential types are metallic coatings, galvanizing (Zn coating), tin plating, chromium plating, aluminium coating, organic coatings, epoxy coatings, polyurethane coatings, vinyl coatings, coal tar coatings, inorganic coatings, ceramic coatings, glass linings and enamel coatings (Silaban et al., 2026; Singh et al., 2025; Souza et al.,2025).

Cathodic Protection (CP)

Cathodic protection technique converts the structure or the metallic substance into a cathode. The key examples are a sacrificial Anode system, which utilises more active metals such as Zinc, Magnesium, and Aluminum. Some of the applications of these systems are pipelines, storage tanks, ships, and offshore platforms. In the case of Impressed Current Cathodic Protection (ICCP), an external Direct Current power source and inert (passive) anodes are required. The key applications include long-distance pipelines, marine structures, and reinforced concrete (Silaban et al., 2026; Singh et al., 2025; Souza et al.,2025).

Anodic Protection

In anodic protection, the metallic potential of the substance is maintained in the passive region. The major applications of this system tanks with sulphuric acid, chemical reactors and process vessels. The specific advantages of anodic protection are that the system has a low current requirement and is suitable for highly corrosive acidic media(Nine et al., 2015; Ding et al. (2018).

Corrosion Inhibitors

In inhibitor systems, chemicals or substances are added to the metallic materials with the main aim of reducing corrosion rates of the specific metal substances. Typical classes of these systems are anodic inhibitors (Chromates, Nitrites, and Molybdates), cathodic Inhibitors which include Polyphosphates, Zinc salts and mixed Inhibitors such as organic amines, and imidazolines. The main applications of corrosion inhibitors are in cooling water systems, oil and gas pipelines, and boilers.

Environmental Control

In environmental control techniques, corrosion rates are reduced through some chemical reactions such as oxygen removal (reduction reaction), Moisture control, pH adjustment, Salinity reduction, and temperature control.

Design Modification

In materials Science and engineering, materials are designed or modified and developed to meet specific environmental reactions and situations such as corrosion. These engineering designs can minimize corrosion and corrosion rate. Typical examples of design modifications are specific designs to avoid crevices, prevention of stagnant zones, ensuring drainage for moisture, specific engineering functions to avoid galvanic coupling, and development of specific materials to provide access for maintenance (Melchers, 2020; Kucharlapati et al., 2025; Liu et al., 2026; Manu et al., 2025).

Corrosion Protection Mechanisms

These previous studies on types of corrosion protection mechanisms can be categorised as follows:

Barrier Protection

In barrier protection, a coating separates metal from water, oxygen, chlorides or acids is created on the metallic substance. A typical and major example is the epoxy coating on steel pipelines (Abu Orabi et al., 2024; Roscher et al., 2024; Koufi et al., 2026).

Passivation

In the case of passivation mechanisms, a thin oxide layer is formed on the surface of the metallic substance in the form of a coating and protects the surface area of the metallic substance. The main examples of passivation substances are Cr_2O_3 on stainless steel, Al_2O_3 on Aluminium, and TiO_2 on the surface of Titanium.

Electrochemical Protection

In electrochemical protection, the possibility of metallic properties of the substance is minimised to reduce corrosion rates of the substance. This mechanism involves shifting of the potential of the metallic material to reduce corrosion. The principal examples are Cathodic protection and Anodic protection (Guo and Rong, 2026; Hamid and Gomaa, 2025; Jaddoa et al., 2025; Jasim et al., 2025)

Adsorption Mechanism

In this case, corrosion inhibitors adsorbed moisture or oxygen onto the surface of the metal, which will evaporate or dry up. In addition, the absorbed material form either hydrophobic films or molecular barriers and minimised corrosion rates. This film or barrier blocks dissolution of metallic substance or diffused oxygen through diffusion processes.

Precipitation Mechanism

In this mechanism, coatings are formed as protective precipitates form on the surfaces of the metallic substance to prevent or reduce corrosion rate. The principal examples of this mechanismare$CaCO_3$ and $Zn(OH)_2$

In the chemistry of corrosion protection, oxide film formation, which acts as a barrier, is as follows:

i. Aluminium Oxide: In this case aluminium metal or atoms are oxidised to their oxides as:

$$4Al + 3O_2 \longrightarrow 2Al_2O_3 \quad (1)$$

ii. Chromium Oxide as

$$4Cr + 3O_2 \longrightarrow 2Cr_2O_3 \quad (2)$$

In the case of corrosion inhibitor chemistry, there are three categories as follows:

i. Nature: In this case, the organic inhibitors contain mainly nitrogen atoms, Oxygen atoms, Sulphur atoms and π-electrons. These key compositions perform specific roles and assignments to minimise corrosion rate. The primary examples are imidazolines, benzotriazole and amines

ii. Adsorption reaction: Adsorption Reaction is a surface phenomenon in which atoms, ions, or molecules from a gas, liquid, or dissolved substance accumulate and adhere to the surface of another material called the adsorbent. In an adsorption reaction, the substance being adsorbed (the adsorbate) forms a thin layer on the surface of the adsorbent without penetrating deeply into its bulk structure.

$$Adsorbent + Adsorbate \leftrightarrows Adsorbate - Adsorbent\ Complex \quad (3)$$

Which can be expressed as adsorption of a corrosion inhibitor (I) onto a metal surface (M):

$$M + I \leftrightarrows M - I \quad (4)$$

where: M stands for the metal surface (adsorbent), I stands for the inhibitor molecule (adsorbate) and M–I stands for the adsorbed protective layer

Chemical Adsorption (Chemisorption): Chemisorption involves formation of chemical bonds between adsorbate and adsorbent. These reactions are usually irreversible or less reversible, require high adsorption energy (typically greater than 40 kJ/mol) and often form a strong protective layer in corrosion inhibition such as:

$$Fe + Inhibitor \longrightarrow Fe - Inhibitor - complex \quad (5)$$

Physical Adsorption (Physisorption): Physisorption occurs through weak van der Waals forces. And the reaction is reversible process. This process takes place when the adsorption energy is typically less than 40 kJ/mol. In addition, the reaction favoured at low temperatures. General equation of physisorption is as follows:

$$Activated\ Carbon + Gas\ Molecules \leftrightarrows Gas - Carbon\ Surface \quad (6)$$

In corrosion control, inhibitor molecules adsorb onto the metal surface and form a protective film that blocks corrosive species such as H^+, Cl^-, O_2, and H_2O from reaching the metal surface.

$$AMetal\ Surface + Inhibitor\ Molecules \longrightarrow Protective\ Adsorbed\ Layer \quad (7)$$

This adsorbed layer reduces both anodic and cathodic corrosion reactions, thereby improving metal protection.

Cathodic Protection Chemistry

Cathodic protection (CP) is an electrochemical corrosion control technique in which a metal structure is forced to act as the cathode of an electrochemical cell. By supplying electrons to the metal, the oxidation (corrosion) reaction is suppressed.

Principle and Chemistry of Cathodic Protection

Corrosion of iron or steel occurs when the metal loses electrons, which is an oxidation process. The reactions are as follows:

i. At the anode (Oxidation or Corrosion Reaction) as

$$Fe \rightarrow Fe^{2+} + 2e^- \quad (8)$$

This reaction dissolves the metal and causes corrosion. In cathodic protection, electrons are supplied externally to the metal surface, preventing iron from losing electrons and thus stopping corrosion.

ii. At the cathode (Reduction Reactions): The supplied electrons are consumed by reduction reactions occurring at the metal surface as follows:

   i. In an acidic environment, Hydrogen ions are reduced:

   $2H^+ + 2e^- \rightarrow H_2$ (9)

   ii. In a neutral or Alkaline Environment, Oxygen reduction is the dominant reaction as follows:

   $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$ (10)

   The formation of hydroxide ions increases the pH near the metal surface, providing additional protection. Steel or iron becomes cathodic and the metal dissolution is suppressed.

Sustainable and Emerging Corrosion Protection Technologies

Sustainable and emerging corrosion protection technologies are shifting corrosion management from reactive maintenance to predictive and environmentally responsible strategies. Green inhibitors, graphene coatings, nanotechnology, self-healing materials, smart monitoring systems, AI-driven analytics, and advanced cathodic protection are expected to dominate future corrosion control practices. These technologies not only extend asset lifespan but also support sustainability goals by reducing material losses, maintenance requirements, environmental pollution, and energy consumption. The recent studies, research and developments focus on environmentally friendly and smart corrosion control systems in specific areas as follows:

Green Technologies

Plant extract inhibitors, which contain flavonoids, alkaloids, tannins or polyphenols. The major examples plant extracts include Acalypha godseffiana, Acalypha wilkesiana and Cola nitida husk, Azadirachta indica (Neem), Bio-based coatings, environmentally friendly chemicals, AI corrosion prediction, Machine learning models, Digital twins and IoT corrosion monitoring

Nanotechnology

Nanotechnology involves Nanocomposite coatings, Nanoparticle inhibitors, Nano-engineered surfaces, Graphene coatings, Nano-silica coatings and Nanoceramic coatings

Smart Coatings

Smart coatings have features such as Self-healing properties, Stimuli-responsive coatings, damage sensor or detection and Controlled inhibitor release

Artificial Intelligence (AI) and Machine Learning (ML)

The applications of AI and ML include: Corrosion simulation and prediction, risk assessment, evaluation and management, predictive maintenance and digital twin corrosion management

Corrosion Monitoring Techniques

Corrosion monitoring techniques have evolved from simple weight-loss coupons to advanced electrochemical, sensor-based, IoT-enabled, and AI-driven systems. Modern corrosion management increasingly combines electrochemical monitoring, non-destructive testing, smart sensors, and predictive analytics to provide continuous, real-time assessment of asset integrity. These technologies help industries to reduce maintenance costs, improve safety, and achieve sustainable infrastructure management. Examples of corrosion monitoring techniques are Electrochemical Methods, Potentiodynamic polarization, Electrochemical impedance spectroscopy (EIS), Linear polarization resistance, Surface Characterization, Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDX), Atomic Force, Microscopy (AFM), X-ray Diffraction (XRD), Spectroscopic Techniques, Fourier Transform Infrared Spectroscopy (FTIR), UV-Visible Spectroscopy and Raman Spectroscopy. Table 2 provides a comparison between these techniques.

Table 2: A Comparison between Corrosion Monitoring Techniques

Technique	Real-Time	Destructive	Sensitivity	Typical Application
Weight Loss Coupon	No	Yes	Moderate	Pipelines
Electrical Resistance	Yes	No	Moderate	Pipelines
LPR	Yes	No	High	Water systems
EIS	Yes	No	Very High	Coatings
Ultrasonic Testing	Periodic	No	High	Storage tanks
MFL	Periodic	No	High	Pipelines
Fiber Optic Sensors	Yes	No	Very High	Offshore structures
IoT Monitoring	Yes	No	High	Smart infrastructure
AI-Based Systems	Yes	No	Very High	Predictive maintenance

CONCLUSION

Based on the findings, it can be concluded that corrosion is an inevitable natural process, but its impact can be significantly reduced through effective metal protection and corrosion prevention strategies and corrosion protection is a multidisciplinary field involving electrochemistry, materials science, surface engineering, and environmental chemistry. Traditional methods remain widely used, while modern developments focus on sustainable, smart, and nanotechnology-based solutions.

Recent publication trends in corrosion and prevention indicate increasing interest in green inhibitors, self-healing coatings, graphene materials, and AI-driven corrosion monitoring systems. Effective corrosion control combines appropriate material selection, protective coatings, cathodic protection, corrosion inhibitors, environmental management, and advanced monitoring techniques. Emerging research increasingly focuses on green inhibitors, nanotechnology, artificial intelligence, and smart protective systems, providing sustainable and efficient solutions for corrosion management across industrial sectors, while emerging technologies are transforming corrosion management and providing innovative solutions for future industrial challenges. Future corrosion protection research and strategies are expected to combine advanced materials, digital technologies, and environmentally sustainable approaches to improve asset integrity and reduce lifecycle costs.

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