Journal of Materials and Environmental Science
ISSN : 2028-2508
e-ISSN : 2737-890X
CODEN : JMESCN

University of Mohammed Premier
Oujda Morocco

J. Mater. Environ. Sci., 2026, Volume 17, Issue 6, Page 910-936

http://www.jmaterenvironsci.com

Industrial Applications of Metal–Organic Frameworks in Corrosion Protection Technologies

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Received *04 May 2026,*
Revised *08 June 2026,*
Accepted *10 June 2026*

Keywords:
- ✓ *Metal–Organic Frameworks;*
- ✓ *Corrosion protection;*
- ✓ *Multifunctional materials;*
- ✓ *Smart coatings;*
- ✓ *Nanocomposites;*
- ✓ *Electrochemical impedance spectroscopy.*

Citation: *Husaini M. (2026). Industrial Applications of Metal–Organic Frameworks in Corrosion Protection Technologies: J. Mater. Environ. Sci., 17(6), 910-936.*

Abstract: Corrosion remains a persistent challenge across major industrial sectors, leading to significant economic losses, safety risks, and material degradation. Conventional corrosion protection strategies, although widely used, often suffer from limitations such as environmental concerns, limited functionality, and reduced long-term effectiveness under harsh conditions. Metal–Organic Frameworks (MOFs) have recently emerged as promising advanced materials for corrosion protection due to their high surface area, tunable porosity, structural diversity, and ability to host functional species. This review presents a comprehensive overview of MOF-based corrosion protection systems, highlighting their roles in barrier coatings, inhibitor delivery, superhydrophobic surfaces, and multifunctional smart coatings. The industrial applications of MOFs across oil and gas, marine, automotive, aerospace, construction, and energy sectors are critically discussed. Furthermore, performance evaluation techniques such as electrochemical impedance spectroscopy, polarization studies, and accelerated corrosion testing are summarized. The review also addresses key challenges limiting commercialization, including scalability, cost, stability, and environmental concerns, while exploring emerging trends such as artificial intelligence-assisted design, green synthesis, nanocomposites, and digital corrosion monitoring systems. Finally, future perspectives are provided to guide the development of next-generation MOF-based corrosion protection technologies for industrial applications.

1. Introduction

Corrosion is a naturally occurring process that causes the deterioration of metallic materials through chemical or electrochemical interactions with their environment (Zhou *et al.,* 2025). As an electrochemical phenomenon, corrosion involves simultaneous anodic and cathodic reactions that convert metals into more stable compounds such as oxides and hydroxides (Pourbaix, 1974; Hammouti *et al.,* 1995; Bouri *et al.,* 2012; Zarrouk *et al.,* 2012; Khan *et al.,* 2025; Husaini, 2024a-c). The extent of corrosion depends on factors such as temperature, humidity, pH, and the presence of aggressive ions. Because metals are widely used in industrial infrastructure and engineering applications, corrosion remains a major challenge affecting structural integrity, operational efficiency, and service life (Husaini, 2026a-c). Corrosion also results in substantial economic losses through maintenance costs, equipment failure, production downtime, and the replacement of damaged components (Chakraborty *et al.,* 2025). In addition, corrosion-related failures can pose serious environmental and safety risks, particularly in industries such as oil and gas, marine transportation, construction, energy production, and chemical processing (Chen *et al.,* 2025).

To mitigate these effects, several corrosion protection strategies have been developed. Organic coatings are widely used to isolate metal surfaces from corrosive environments (Li *et al.,* 2025a), while corrosion inhibitors reduce degradation by suppressing electrochemical reactions. Cathodic protection techniques, including sacrificial anodes and impressed current systems, are commonly employed for pipelines, storage tanks, and marine structures (Husaini, 2025a-c). Surface modification methods such as anodization, electrodeposition, and conversion coatings have also been utilized to enhance corrosion resistance. However, many conventional approaches suffer from limitations including environmental concerns, limited durability, and high maintenance requirements. These challenges have stimulated the search for advanced materials capable of providing more effective and sustainable corrosion protection (Wang *et al.,* 2024).

Among the emerging materials attracting considerable attention are Metal–Organic Frameworks (MOFs), a class of crystalline porous materials composed of metal ions or clusters coordinated with organic ligands (Ramu *et al.,* 2024; Chaouiki *et al.,* 2026). MOFs possess exceptionally high surface areas, tunable pore structures, and versatile chemical functionalities, making them attractive for diverse applications (Zhang *et al.,* 2025a). Although initially developed for gas storage, separation, catalysis, and sensing, their potential in corrosion protection has gained significant interest in recent years. In corrosion-control systems, MOFs can function as corrosion inhibitors, nanocontainers for controlled inhibitor release, additives in protective coatings, and components of smart self-healing materials (Yang *et al.,* 2025). Their ability to combine passive barrier effects with active corrosion protection mechanisms offers significant advantages over conventional methods.

Given the growing interest in MOF-based anticorrosion systems, a comprehensive assessment of their industrial relevance is timely. This review discusses the fundamental properties of MOFs related to corrosion protection, their mechanisms of action, and their applications in protective coatings, inhibitor delivery systems, and advanced corrosion-resistant materials. Furthermore, the review highlights their industrial applications, addresses challenges associated with large-scale implementation, and outlines future research directions for developing sustainable and high-performance MOF-based corrosion protection technologies.

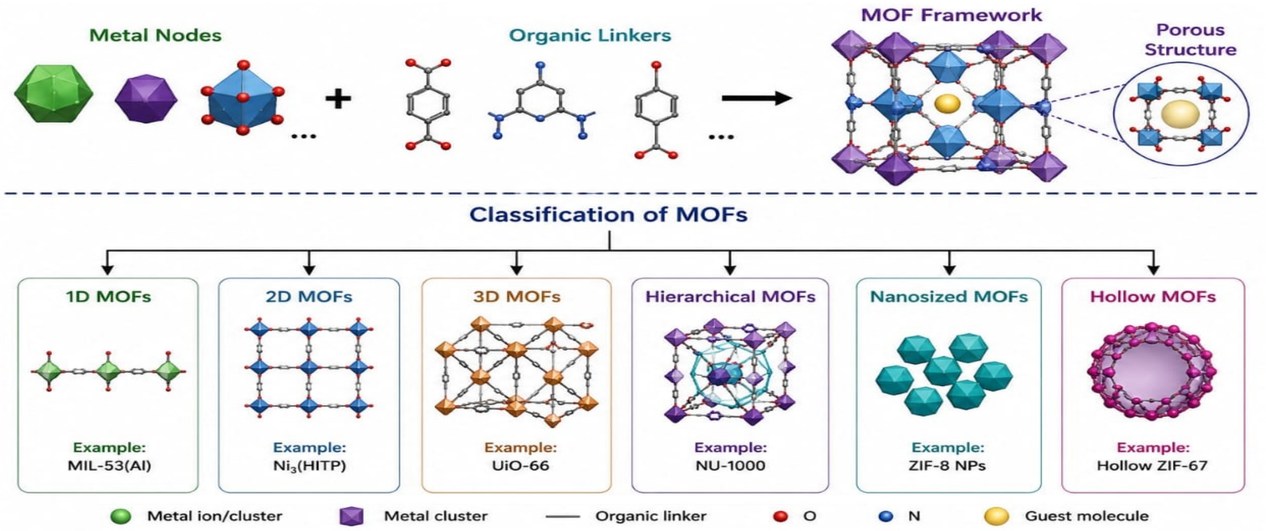

Figure 1: Structure and Classification of MOFs

2. Fundamentals of Metal–Organic Frameworks

Metal–Organic Frameworks (MOFs) are a class of crystalline porous materials formed through the coordination of metal-containing units with organic ligands to generate highly ordered three-dimensional networks (Li *et al.,* 2024). Since their emergence, MOFs have attracted significant attention due to their structural diversity, exceptionally high surface areas, and tunable physicochemical properties (Zhao *et al.,* 2024). The versatility of MOFs allows precise control over their composition, pore characteristics, and functionality, making them suitable for applications in gas storage, catalysis, sensing, drug delivery, environmental remediation, and corrosion protection (Wright *et al.,* 2025). Their unique combination of inorganic and organic building blocks provides opportunities for designing advanced materials tailored to specific industrial requirements.

2.1 Structure and Composition of MOFs

The fundamental structure of a MOF consists of two primary components: metal nodes and organic linkers. Metal nodes, which may be individual metal ions or metal-oxide clusters, serve as coordination centers that provide structural stability and determine many of the framework's chemical properties (Gao *et al.,* 2024a). Commonly used metals include zinc, copper, iron, zirconium, chromium, cobalt, and aluminum. These metallic centers are interconnected by organic linkers, typically polyfunctional molecules containing carboxylate, imidazolate, pyridyl, or phosphonate groups (Li *et al.,* 2024). The coordination between metal nodes and organic ligands results in the formation of extended networks with well-defined pore structures.

One of the distinguishing features of MOFs is their highly porous architecture. The arrangement of metal nodes and organic linkers creates interconnected channels and cavities that can accommodate guest molecules, ions, or corrosion inhibitors (Sun *et al.,* 2025). The size, shape, and distribution of these pores can be adjusted through rational design of the framework components, enabling the development of materials with specific adsorption, storage, and transport characteristics. This structural flexibility is particularly advantageous for corrosion protection applications where controlled release and adsorption processes are essential.

2.2 Classification of MOFs

MOFs can be classified according to their structural characteristics, chemical composition, and constituent building blocks (Zhao *et al.,* 2024). Among the most extensively studied groups are Zeolitic Imidazolate Frameworks (ZIFs), which are composed of transition metal ions coordinated with imidazolate ligands. ZIFs exhibit exceptional thermal and chemical stability, making them attractive candidates for protective coatings and inhibitor delivery systems (Chen *et al.,* 2022).

Another important family is the Materials Institute Lavoisier (MIL) series, which typically consists of iron, chromium, or aluminum metal centers linked by carboxylate-based ligands. MIL materials are known for their large pore volumes, high stability, and versatile functionalization capabilities. The University of Oslo (UiO) series, particularly zirconium-based UiO-66 and related structures, has gained considerable attention because of its outstanding mechanical strength, hydrothermal stability, and resistance to chemical degradation (Li *et al.,* 2024). Similarly, the Hong Kong University of Science and Technology (HKUST) series, especially HKUST-1, is recognized for its high surface area and well-defined porous structure, which are beneficial for adsorption and storage applications (Gao *et al.,* 2024b).

2.3 Synthesis Techniques The synthesis of MOFs can be achieved using a variety of techniques depending on the desired structural and functional characteristics. Hydrothermal synthesis is one of the most widely used methods and involves the reaction of metal precursors and organic ligands in aqueous media under elevated temperature and pressure conditions. Solvothermal synthesis follows a similar principle but employs organic solvents to facilitate crystal growth and framework formation

(Payam *et al.,* 2024). Microwave-assisted synthesis has emerged as an efficient alternative because it significantly reduces reaction times while maintaining high product quality. Electrochemical synthesis offers another attractive route in which metal ions are generated directly from sacrificial electrodes, allowing controlled MOF formation under relatively mild conditions. Mechanochemical synthesis, which relies on mechanical grinding or milling of reactants, has gained increasing attention as a sustainable and environmentally friendly approach because it minimizes solvent consumption and energy requirements (Gaillac *et al.,* 2017). The choice of synthesis method strongly influences crystal size, morphology, porosity, and overall material performance.

2.4 Properties Relevant to Corrosion Protection

Several intrinsic properties of MOFs make them highly promising materials for corrosion protection technologies. One of their most notable characteristics is their exceptionally high surface area, which enhances adsorption capacity and facilitates interactions with corrosive species or protective agents (Sun *et al.,* 2025). In addition, MOFs possess tunable porosity, allowing precise control over pore dimensions and internal environments. This feature enables the encapsulation and controlled release of corrosion inhibitors, thereby improving long-term protective performance (Ramu *et al.,* 2024).

Many MOFs also exhibit stimuli-responsive behavior, whereby external factors such as pH changes, temperature variations, or the presence of corrosive ions can trigger specific responses, including the release of encapsulated inhibitors (Cao *et al.,* 2025). Furthermore, MOFs can be readily functionalized through modification of either the metal nodes or organic linkers, enabling the incorporation of additional protective functionalities (Wright *et al.,* 2025). These characteristics collectively contribute to the growing interest in MOFs as advanced materials for smart coatings, inhibitor delivery systems, and next-generation corrosion protection technologies.

3. Corrosion Protection Mechanisms of Metal–Organic Frameworks

Metal–Organic Frameworks (MOFs) have emerged as promising materials for corrosion protection owing to their unique porous structures, tunable chemistry, and multifunctional characteristics (Zhou *et al.,* 2025). Unlike conventional corrosion-control materials that often rely on a single protective mechanism, MOFs can simultaneously provide passive and active protection through multiple pathways. Their high surface area, adjustable pore architecture, and ability to encapsulate functional agents enable them to act as corrosion inhibitors, nanocontainers, active coating additives, and stimuli-responsive delivery systems (Nwokolo *et al.,* 2025). As a result, MOF-based systems have attracted considerable attention for the development of advanced corrosion-resistant coatings and smart protective technologies.

3.1 Barrier Protection Mechanism

One of the primary corrosion protection mechanisms of MOFs is the formation of an effective physical barrier between the metallic substrate and the surrounding corrosive environment. When incorporated into protective coatings, MOF particles can reduce coating permeability by increasing the diffusion path of corrosive species such as water, oxygen, and chloride ions (Nwokolo *et al.,* 2025). The well-defined porous structure and uniform dispersion of MOFs within coating matrices enhance coating compactness and decrease the penetration rate of aggressive agents. Consequently, direct contact between the metal surface and corrosive media is significantly minimized, leading to improved corrosion resistance and prolonged service life (Zhou *et al.,* 2025).

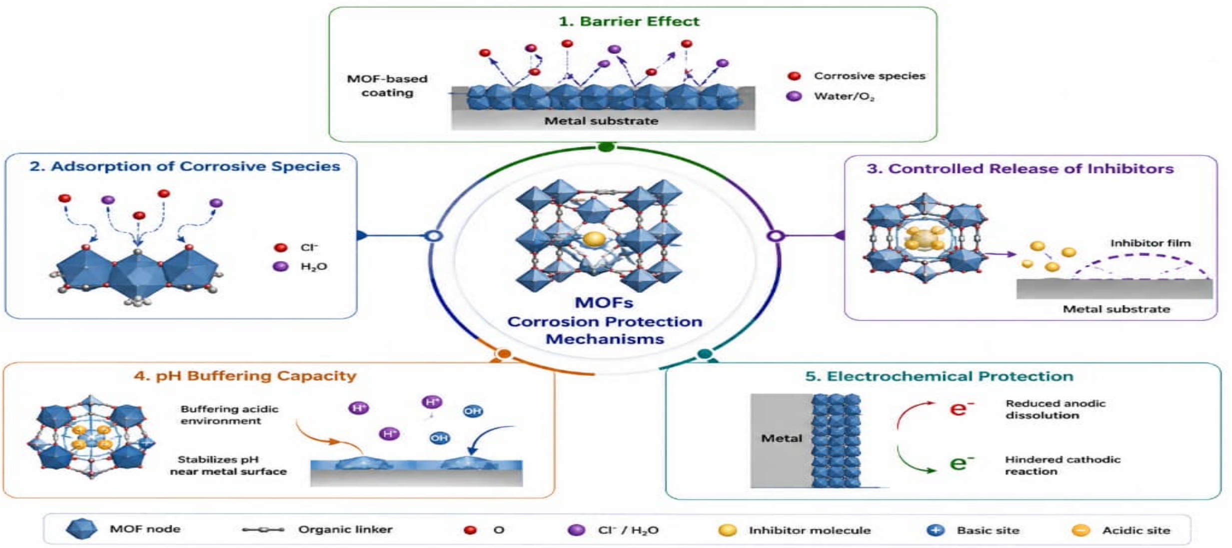

Figure 2: Corrosion Protection Mechanisms of MOFs

3.2 Adsorption-Based Corrosion Inhibition

MOFs can also protect metals through adsorption-mediated inhibition mechanisms. Functional groups present within the organic ligands and metal centers can interact strongly with metallic surfaces, resulting in the formation of a protective adsorbed layer (Cao *et al.,* 2025). This layer blocks active corrosion sites and suppresses both anodic metal dissolution and cathodic reduction reactions. The effectiveness of adsorption-based inhibition is influenced by factors such as framework composition, surface charge, pore structure, and the presence of heteroatoms that coordinate with metal surfaces. Through these interactions, MOFs can significantly reduce corrosion rates in aggressive environments (Ramu *et al.,* 2024).

3.3 Controlled Release of Corrosion Inhibitors

A distinctive feature of MOFs is their ability to serve as nanocontainers for corrosion inhibitors. Their porous frameworks can encapsulate various protective compounds and release them in a controlled manner when exposed to corrosive conditions (Sanyal *et al.,* 2024). Triggered release may occur in response to environmental stimuli such as pH changes, ion concentration variations, moisture ingress, or coating damage. This controlled delivery approach ensures that inhibitors are supplied only when needed, thereby enhancing protection efficiency while reducing unnecessary consumption of active agents. Such behavior contributes to the long-term durability of protective systems (Zhou *et al.,* 2025).

3.4 Self-Healing Mechanisms

Self-healing corrosion protection represents one of the most advanced applications of MOFs. In MOF-based coatings, encapsulated corrosion inhibitors can be released automatically when coating defects, scratches, or microcracks develop (Chen *et al.,* 2025). Upon release, the active species migrate to damaged regions and form protective layers that restore the barrier properties of the coating. This autonomous repair capability helps prevent localized corrosion and delays coating failure. As a result, self-healing MOF systems offer an effective strategy for extending the lifespan of metallic structures operating in harsh environments (Sanyal *et al.,* 2024).

3.5 Hydrophobic and Superhydrophobic Protection

Surface wettability plays a critical role in corrosion processes. MOFs can be engineered to produce hydrophobic or superhydrophobic surfaces that significantly reduce contact between water and metallic substrates (Paul *et al.,* 2024). By incorporating low-surface-energy functional groups or combining MOFs with suitable surface modifiers, highly water-repellent coatings can be obtained. These surfaces limit moisture adsorption, decrease electrolyte accumulation, and hinder the transport of corrosive species to the metal surface. Consequently, hydrophobic and superhydrophobic MOF-based coatings provide an additional level of protection against environmental degradation (Yadav *et al.,* 2025).

3.6 Multifunctional Smart Protection

The most significant advantage of MOFs lies in their ability to integrate multiple protection mechanisms within a single material system. MOF-based coatings can simultaneously function as physical barriers, corrosion inhibitor reservoirs, self-healing agents, and stimuli-responsive protective materials (Nwokolo *et al.,* 2025). Their responsiveness to environmental changes enables adaptive protection strategies that activate only under corrosive conditions. Furthermore, MOFs can be functionalized with additional active components to impart sensing, antimicrobial, catalytic, or anti-fouling properties alongside corrosion resistance. This multifunctionality positions MOFs as key materials for next-generation smart corrosion protection technologies (Yadav *et al.,* 2025).

Recent research has demonstrated that MOFs can operate as corrosion inhibitors, nanocontainers, active fillers, and intelligent release reservoirs, providing both passive and active protection mechanisms. By combining barrier effects, inhibitor delivery, self-healing capabilities, and environmental responsiveness, MOF-based systems offer a versatile and highly effective approach for mitigating corrosion across a wide range of industrial applications (Zhou *et al.,* 2025).

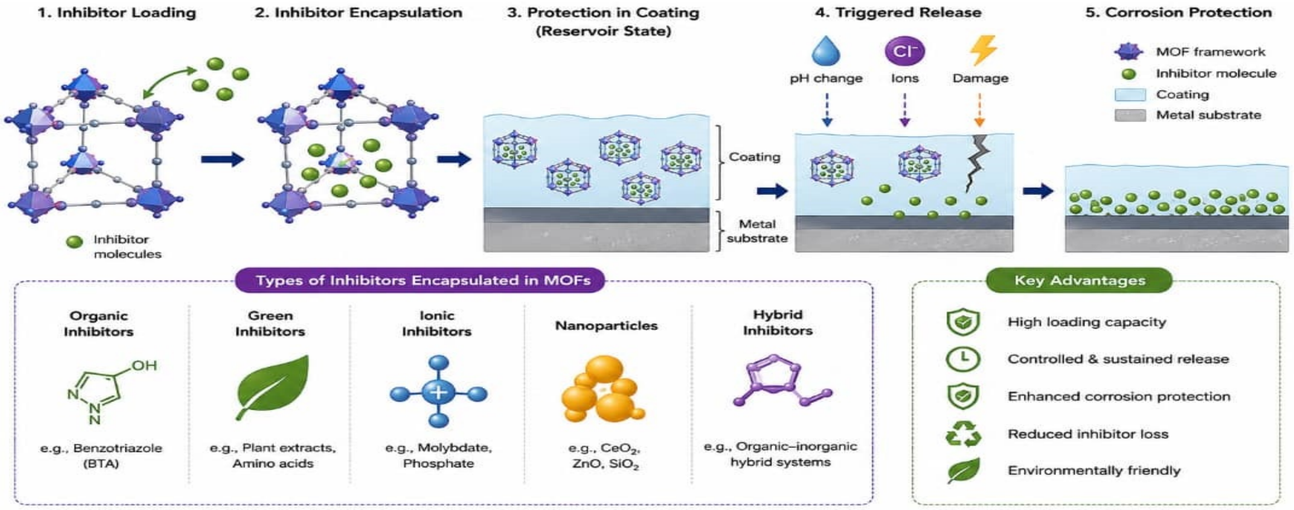

Figure 3: MOFs as Corrosion Inhibitors and Nanocontainers

4. Industrial Applications of MOFs in Corrosion Protection Technologies

Metal–organic frameworks (MOFs) have attracted significant attention in corrosion protection technologies due to their high porosity, tunable structures, large surface area, and ability to encapsulate active corrosion-inhibiting agents (Zhao *et al.,* 2024). These unique physicochemical properties enable MOFs to function as effective corrosion inhibitors, smart coating additives, and controlled-release carriers for protective compounds. In industrial environments, MOFs improve the durability and stability of metallic materials by reducing electrochemical reactions responsible for corrosion processes (Sun *et al.,* 2024). Their applications have been widely investigated for different engineering metals and alloys exposed to aggressive acidic and saline environments.

4.1 MOFs as Corrosion Inhibitors

Metal–Organic Frameworks (MOFs) have attracted considerable attention as advanced corrosion inhibitors due to their unique structural characteristics, including high surface area, tunable porosity, and abundant active adsorption sites (Li *et al.,* 2024). Unlike conventional inhibitors that often rely solely on adsorption, MOFs can provide multiple protection mechanisms through surface coverage, inhibitor release, and interaction with corrosive species. The presence of heteroatoms such as nitrogen, oxygen, sulfur, and phosphorus within MOF structures enhances their affinity for metallic surfaces, resulting in the formation of stable protective films (Huang *et al.,* 2025). Furthermore, the adjustable composition of MOFs allows researchers to tailor their anticorrosion performance for specific metals and corrosive environments. These advantages have encouraged extensive investigations into the application of MOFs as standalone inhibitors and as active components in corrosion protection systems (Zhao *et al.,* 2024).

4.1.1 Mild Steel Protection

Mild steel is extensively used in industrial equipment, pipelines, storage tanks, and structural components because of its low cost and favorable mechanical properties. However, its susceptibility to corrosion in acidic environments remains a significant challenge. MOFs have demonstrated excellent inhibition performance for mild steel by adsorbing onto the metal surface and creating a protective barrier that suppresses anodic and cathodic reactions (Huang *et al.,* 2025). Their porous structure facilitates strong interactions with metallic substrates while limiting the penetration of aggressive ions. Additionally, the incorporation of corrosion-inhibiting functional groups within MOFs enhances their adsorption efficiency and stability. As a result, MOF-based inhibitors have emerged as promising alternatives to conventional organic and inorganic inhibitors (Ma *et al.,* 2023).

HCl Media

Hydrochloric acid is widely used in industrial operations such as acid pickling, descaling, and oil-well acidization, where severe corrosion of mild steel often occurs. Numerous studies have reported high inhibition efficiencies for MOFs in HCl solutions due to their strong adsorption on steel surfaces (Huang *et al.,* 2025). The interaction between MOF ligands and iron atoms forms a compact protective film that decreases metal dissolution and charge-transfer processes. Furthermore, MOFs can trap chloride ions within their porous structures, reducing their aggressive attack on the substrate. The ability of MOFs to provide sustained protection under highly acidic conditions makes them attractive for industrial acid-treatment applications (Li *et al.,* 2024).

H_2SO_4 Media

Sulfuric acid is another highly aggressive medium encountered in fertilizer production, petroleum refining, and chemical manufacturing industries. Corrosion of mild steel in sulfuric acid is generally more severe because of the high concentration of sulfate ions and increased electrochemical activity. MOFs have demonstrated significant inhibition performance in H_2SO_4 environments by reducing both anodic metal dissolution and cathodic hydrogen evolution reactions (Huang *et al.,* 2025). Their adsorption on the metal surface creates a physical and chemical barrier that limits contact between the substrate and corrosive species. In addition, MOFs can serve as reservoirs for active inhibitors that are gradually released under corrosive conditions, contributing to long-term protection (Ma *et al.,* 2023).

4.1.2 Stainless Steel Protection

Stainless steel is valued for its excellent corrosion resistance, which is primarily attributed to the formation of a passive chromium-rich oxide film. Nevertheless, exposure to chloride-containing environments, acidic solutions, or elevated temperatures can lead to localized corrosion such as pitting and crevice corrosion. MOFs have shown considerable potential in enhancing the corrosion resistance of stainless steel through stabilization of passive films and suppression of localized attack (Roushani *et al.,* 2025). Their adsorption on the surface can reinforce protective oxide layers and reduce the diffusion of aggressive ions toward vulnerable regions. In addition, MOFs incorporated into coatings can provide supplementary barrier protection and inhibitor release capabilities (Li *et al.,* 2024).

4.1.3 Aluminum Alloy Protection

Aluminum alloys are widely employed in aerospace, automotive, transportation, and construction sectors because of their low density and high strength-to-weight ratio. Despite their natural oxide film, aluminum alloys remain susceptible to pitting corrosion in chloride-rich environments (Husaini, 2023a&b). MOFs can improve corrosion resistance by enhancing barrier properties, inhibiting electrochemical reactions, and facilitating controlled release of protective species (Ma *et al.,* 2023). Their porous structure allows storage of corrosion inhibitors that can be released when coating damage occurs. Furthermore, MOFs can be integrated into conversion coatings and hybrid protective systems to improve adhesion and durability (Zhao *et al.,* 2024).

4.1.4 Magnesium Alloy Protection

Magnesium alloys are among the lightest structural materials and are widely used in aerospace, automotive, and biomedical applications. However, their high chemical reactivity leads to rapid corrosion in aqueous and chloride-containing environments. MOF-based corrosion protection systems have emerged as effective solutions for mitigating this challenge (Gaillac *et al.,* 2017). By acting as barrier materials and inhibitor carriers, MOFs reduce electrolyte penetration and limit corrosion reactions at the metal surface. Their porous architecture also enables incorporation of active corrosion inhibitors for controlled release during service. Additionally, MOFs can be integrated with micro-arc oxidation and conversion coatings to enhance overall protection performance (Roh *et al.,* 2024).

4.2 MOFs in Protective Coating Systems

Protective coatings represent one of the most practical and commercially attractive applications of Metal–Organic Frameworks (MOFs) in corrosion protection technologies. Traditional coating systems primarily function as passive barriers that isolate metallic substrates from aggressive environments. However, coating defects, microcracks, and prolonged environmental exposure often lead to coating degradation and eventual corrosion failure. The incorporation of MOFs into coating matrices has emerged as an effective strategy for enhancing both passive and active protection mechanisms. Owing to their high surface area, tunable pore structure, and ability to encapsulate corrosion inhibitors, MOFs can improve coating integrity, mechanical properties, and long-term durability (Nwokolo *et al.,* 2025). Furthermore, MOF-containing coatings can respond to environmental stimuli by releasing active corrosion inhibitors when needed, thereby providing intelligent corrosion protection (Zhang *et al.,* 2026). These characteristics have stimulated extensive research into the integration of MOFs within various coating systems.

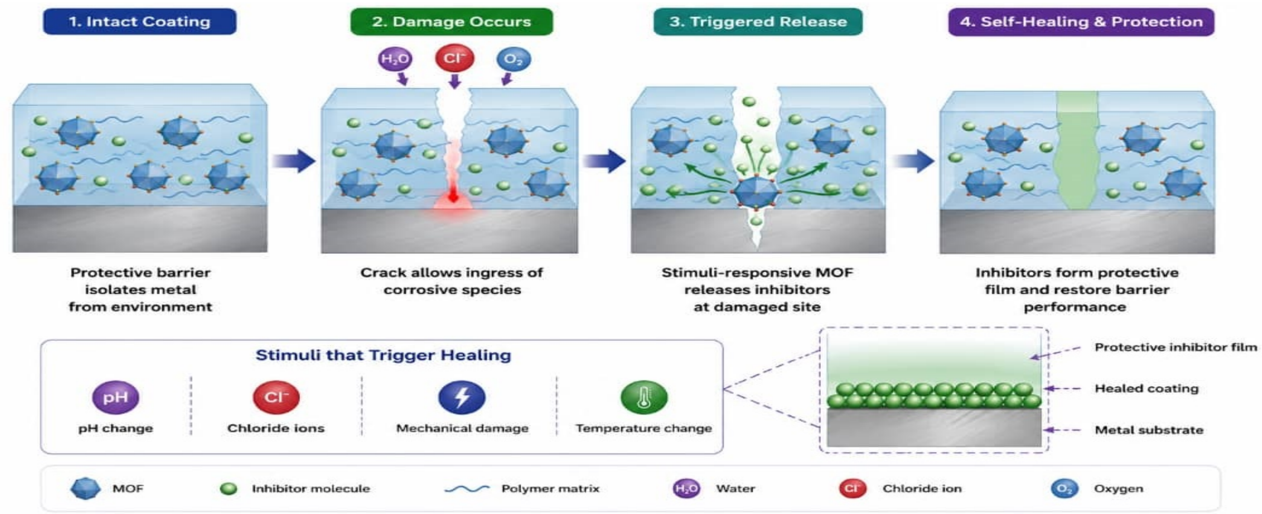

Figure 4: MOF-based Smart Self-healing Coating System

4.2.1 Epoxy Coatings

Epoxy coatings are among the most widely used protective coatings because of their excellent adhesion, chemical resistance, and mechanical strength. Despite these advantages, conventional epoxy coatings may develop pores and microdefects that allow the penetration of corrosive species during long-term exposure. The incorporation of MOFs into epoxy matrices significantly enhances coating performance by increasing barrier effectiveness and reducing permeability (Seidi *et al.,* 2020). MOF particles create more complex diffusion pathways that hinder the transport of water, oxygen, and chloride ions toward the metal substrate. In addition, their porous structures can store corrosion inhibitors that are released when coating damage occurs (Mao *et al.,* 2025). The strong interaction between MOFs and epoxy polymers also improves coating cohesion and adhesion to the substrate. Consequently, MOF-modified epoxy coatings exhibit superior corrosion resistance and extended service life compared with conventional epoxy systems (Liu *et al.,* 2024).

4.2.2 Polyurethane Coatings

Polyurethane coatings are widely utilized in industrial and marine environments due to their flexibility, abrasion resistance, and weathering stability. However, prolonged exposure to harsh conditions can compromise their protective performance. The incorporation of MOFs into polyurethane coatings enhances their barrier properties while maintaining desirable mechanical characteristics (Li *et al.,* 2025). MOFs can improve coating density and reduce the formation of microchannels that facilitate corrosive species transport. Furthermore, their porous frameworks can act as reservoirs for corrosion inhibitors, enabling active corrosion protection through controlled release mechanisms. The synergistic interaction between MOFs and polyurethane matrices often results in improved coating durability and resistance to environmental degradation. These benefits make MOF-modified polyurethane coatings attractive for offshore structures, pipelines, storage tanks, and transportation equipment exposed to aggressive service conditions (Zhang *et al.,* 2026).

4.2.3 Sol–Gel Coatings

Sol–gel coatings have gained significant attention as environmentally friendly alternatives to conventional chromate-based protective coatings. These coatings are produced through hydrolysis and condensation reactions that form dense inorganic or hybrid networks capable of protecting metallic surfaces. The incorporation of MOFs into sol–gel systems further enhances their corrosion protection performance by increasing structural integrity and providing active corrosion-control functions (Nwokolo *et al.,* 2025). MOFs can improve coating compactness while reducing crack formation during curing and service. Their porous architecture also facilitates the encapsulation and controlled release of corrosion inhibitors. Additionally, MOFs contribute to improved adhesion between the coating and substrate, thereby reducing the likelihood of coating delamination. These combined effects make MOF-modified sol–gel coatings promising candidates for aerospace, automotive, and marine applications (Zhang *et al.,* 2026).

4.2.4 Hybrid Organic–Inorganic Coatings

Hybrid organic–inorganic coatings combine the flexibility and processability of organic polymers with the durability and stability of inorganic materials (Husaini *et al.,* 2025). The incorporation of MOFs into these systems creates multifunctional coatings capable of delivering enhanced corrosion protection through several complementary mechanisms. MOFs improve coating barrier properties by increasing tortuosity and restricting the movement of corrosive species (Nwokolo *et al.,* 2025). At the same time, they provide active protection through inhibitor storage and controlled release capabilities. Their compatibility with both organic and inorganic components facilitates uniform dispersion throughout the coating matrix, contributing to improved mechanical performance and coating stability. Furthermore, MOFs can introduce additional functionalities such as self-healing, hydrophobicity, and corrosion sensing (Ramu, Yang *et al.,* 2024). As a result, hybrid organic–inorganic coatings containing MOFs are increasingly regarded as advanced materials for long-term corrosion protection in demanding industrial environments (Zhang *et al.,* 2026).

Overall, the integration of MOFs into epoxy, polyurethane, sol–gel, and hybrid coating systems has significantly expanded the capabilities of modern corrosion protection technologies. By enhancing coating barrier properties, mechanical strength, inhibitor storage capacity, and intelligent response behavior, MOFs provide both passive and active protection mechanisms (Nwokolo *et al.,* 2025). These advantages position MOF-based coating systems as promising solutions for improving the durability, reliability, and sustainability of metallic structures operating in aggressive environments (Zhang *et al.,* 2026).

4.3 Metal–Organic Frameworks as Nanocontainers for Smart Corrosion Protection

Metal–Organic Frameworks (MOFs) have attracted significant attention as intelligent nanocontainers for advanced corrosion protection systems due to their high porosity, structural tunability, and ability to host functional species within their frameworks (Wang *et al.,* 2024). In corrosion control applications, MOFs act as reservoir materials capable of storing corrosion inhibitors and releasing them in a controlled and stimuli-responsive manner when triggered by specific environmental conditions. This smart delivery capability enables both passive barrier protection and active corrosion inhibition, making MOF-based systems highly effective for long-term material protection (Chen *et al.,* 2025).

4.3.1 Encapsulation of Corrosion Inhibitors

One of the most important functions of MOFs in anticorrosion systems is their ability to encapsulate corrosion inhibitors within their porous structures. The large internal surface area and adjustable pore size of MOFs allow efficient loading of inhibitor molecules. These inhibitors can be physically trapped or chemically coordinated within the framework, depending on the MOF structure and functional groups. Once incorporated into protective coatings, MOFs serve as storage sites that prevent premature depletion of inhibitors while maintaining stability under normal conditions (Li *et al.,* 2025b).

4.3.2 pH-Responsive Release Systems

MOF-based nanocontainers can be engineered to respond to changes in local pH, which is a common indicator of corrosion activity. During corrosion processes, localized acidification occurs at anodic sites due to metal dissolution. MOFs designed with pH-sensitive coordination bonds can degrade or open their pores under acidic conditions, releasing encapsulated inhibitors directly at the corrosion site. This targeted release ensures efficient delivery precisely where it is needed, minimizing waste and improving protection performance (Ansari *et al.,* 2025).

4.3.3 Chloride-Triggered Release Systems

Chloride ions are among the most aggressive species responsible for accelerating corrosion, particularly in marine environments. MOFs can be tailored to respond to chloride-rich conditions, enabling chloride-triggered release of corrosion inhibitors. In such systems, chloride ions may induce ligand exchange or disrupt coordination bonds within the framework, leading to structural changes that facilitate inhibitor release. This selective response allows MOF-based coatings to activate only under highly corrosive conditions, providing adaptive protection in chloride-prone environments (Zhang *et al.,* 2025b).

4.3.4 Long-Term Protection Performance

The use of MOFs as nanocontainers significantly improves long-term corrosion resistance by enabling sustained and controlled inhibitor release over extended periods. Unlike conventional coatings that suffer from rapid depletion of active agents, MOF-based systems maintain functionality through gradual and stimuli-driven release mechanisms. Additionally, their structural stability under service conditions ensures prolonged protective performance in harsh environments. The combination of reservoir capacity and smart responsiveness makes MOFs highly suitable for durable industrial corrosion protection applications (Zhou *et al.,* 2025).

4.4 Metal–Organic Framework-Based Self-Healing Coatings

Self-healing coatings represent an advanced class of protective materials designed to automatically repair damage induced during service exposure. In corrosion protection, these coatings are particularly valuable because mechanical defects such as cracks or scratches often serve as initiation sites for localized corrosion. Metal–Organic Frameworks (MOFs) and related nanocontainers have emerged as promising functional components in self-healing systems due to their porous architecture, high loading capacity, and ability to store and release active healing agents in a controlled manner (Xu *et al.,* 2024). By integrating MOFs into coating matrices, it becomes possible to achieve both preventive and restorative protection mechanisms within a single material system.

4.4.1 Autonomous Healing Systems

Autonomous self-healing systems operate without external intervention once damage occurs. In such systems, MOF-based or hybrid nanocontainers are embedded within polymer coatings and loaded with corrosion inhibitors or healing agents. When the coating is damaged, these encapsulated species are released into the affected region, where they help restore barrier integrity and suppress further corrosion activity (Zhang *et al.,* 2024). This release is often triggered by environmental changes such as moisture ingress or local electrochemical variations, ensuring that healing agents remain inactive until needed.

4.4.2 Stimuli-Responsive Healing

Stimuli-responsive self-healing coatings provide a more advanced protection strategy by enabling controlled activation in response to specific environmental triggers. MOF-based systems can be engineered to respond to stimuli such as pH changes, chloride ions, or humidity variations. For example, in corrosive environments, localized acidification or ionic changes can destabilize the nanocontainer structure, leading to the release of corrosion inhibitors directly at damaged sites (He *et al.,* 2026). This targeted response improves efficiency and reduces unnecessary consumption of active materials, making the system more sustainable and adaptive.

4.4.3 Industrial Potential of Self-Healing Coatings

The integration of MOF-based and hybrid nanocontainer systems into self-healing coatings offers significant industrial potential, particularly in environments where long-term durability is essential. Sectors such as marine engineering, oil and gas infrastructure, transportation, and chemical processing can benefit from coatings that autonomously repair damage and maintain corrosion resistance under harsh conditions (Li *et al.,* 2025a). Compared to conventional coatings, these systems provide extended service life, reduced maintenance frequency, and improved operational safety. However, challenges such as large-scale manufacturing, cost optimization, and long-term environmental stability must still be addressed for full industrial deployment.

4.5 MOF-Derived Superhydrophobic Coatings

Metal–Organic Framework (MOF)-derived superhydrophobic coatings have gained increasing attention in corrosion protection because they combine surface engineering with chemical functionality and barrier performance in a single system. Plasma electrolytic oxidation (PEO)-based coatings modified with functional components and MOF-related structures have been shown to enhance water repellency and improve long-term stability in corrosive environments (Cao *et al.,* 2025). These systems are particularly effective because their surface architecture can be engineered to manipulate wettability while maintaining mechanical robustness.

4.5.1 Surface Wettability Control

Surface wettability strongly influences corrosion behavior since it governs the extent of contact between electrolytes and metallic substrates (Qi *et al.,* 2024). MOF-derived coatings enable precise tuning of surface energy through the formation of hierarchical micro- and nanoscale structures that trap air and reduce effective liquid–solid interaction. This structural effect is often combined with chemical modification using low-surface-energy groups, which further enhances hydrophobic performance. As a result, water contact angles can be significantly increased, reducing the ability of corrosive ions to adhere and penetrate the surface. In addition, such wettability control helps stabilize the coating interface under varying environmental conditions, improving resistance to wetting and prolonging service life (Yang *et al.,* 2026).

4.5.2 Water Repellency Mechanisms

The water repellency of MOF-based superhydrophobic coatings is mainly explained by the Cassie–Baxter wetting state, where trapped air pockets within surface roughness reduce the actual solid–liquid contact area (Rahimipour *et al.,* 2026). This air cushion acts as a physical barrier that limits electrolyte penetration and reduces the transport of aggressive species such as chloride ions toward the metal surface. In addition, the presence of hydrophobic organic ligands or surface modifiers decreases surface free energy, which helps maintain the non-wetting state even under mechanical or chemical stress. The combination of structural trapping of air and chemical hydrophobicity enhances droplet mobility and contributes to self-cleaning behavior, which further supports long-term corrosion resistance. Plasma and hybrid-modified systems also improve the stability of this mechanism under prolonged exposure conditions (Adeleke and Caldona, 2025).

4.5.3 Marine and Offshore Applications

MOF-derived superhydrophobic coatings are particularly important in marine and offshore applications where materials are exposed to continuous seawater contact, chloride attack, and biological fouling (Qi *et al.,* 2024). In such environments, water-repellent surfaces reduce direct interaction between the metal substrate and corrosive media, thereby slowing down corrosion processes. These coatings also help minimize salt deposition and surface contamination, which are major contributors to accelerated degradation in marine systems. Furthermore, hydrothermal and functionalized MOF-based coatings have shown improved durability under prolonged saline exposure, making them suitable for ship hulls, offshore platforms, and subsea pipelines (Rahimipour *et al.,* 2026). Their combined anti-wetting and protective properties also reduce maintenance requirements and extend the operational lifespan of marine infrastructure.

4.6 MOFs in Multifunctional Corrosion Protection Systems

Metal–Organic Frameworks (MOFs) have emerged as highly versatile materials for multifunctional corrosion protection due to their high porosity, tunable pore structure, and ability to incorporate functional species within their frameworks. These features allow MOF-based systems to go beyond conventional barrier coatings and integrate multiple protective roles such as self-cleaning, anti-fouling, anti-icing, and corrosion sensing within a single smart architecture. Recent advances in intelligent coating design emphasize their growing importance in next-generation corrosion mitigation strategies (Zhao *et al.,* 2025).

4.6.1 Anti-Corrosion and Self-Cleaning Coatings

MOF-based coatings provide dual functionality by combining corrosion resistance with self-cleaning behavior through engineered surface morphology and chemical modification. The intrinsic porous structure of MOFs enables the development of hierarchical micro- and nanoscale roughness (Huang *et al.,* 2024), which reduces the real contact area between water droplets and the surface, promoting easy roll-off behavior. This mechanism allows contaminants such as dust, salts, and atmospheric pollutants to be continuously removed from the surface, thereby minimizing corrosion initiation sites. In addition, chemical functionalization with low-surface-energy groups enhances water repellency and improves coating stability under cyclic exposure to wet and dry conditions. The synergy between surface texture and chemistry ensures long-term durability and maintains self-cleaning efficiency even under harsh environmental conditions.

4.6.2 Anti-Corrosion and Anti-Fouling Systems

In marine environments, biofouling is a critical factor that accelerates corrosion by promoting microbial adhesion and the formation of biofilms that alter local electrochemical conditions. MOF-based coatings mitigate this challenge through a combination of anti-adhesive surface properties and controlled release of functional species from their porous networks (Gao *et al.,* 2024a). These released agents inhibit bacterial growth and reduce the development of biofilms on submerged metallic surfaces, while surface chemistry further limits organism attachment. This dual-action mechanism is particularly beneficial for long-term applications such as offshore platforms, subsea pipelines, and ship hulls, where biological activity significantly contributes to material degradation. The ability of MOFs to sustain functionality over time makes them highly suitable for dynamic marine environments.

4.6.3 Anti-Corrosion and Anti-Icing Coatings

MOF-derived coatings also exhibit strong potential in anti-icing applications, which are essential for structures exposed to low-temperature and high-humidity environments. Ice formation can compromise coating integrity and accelerate corrosion through repeated freeze–thaw cycles. MOF-based systems reduce ice nucleation by lowering surface energy and introducing porous architectures that trap air (Wang *et al.,* 2025). This trapped air layer acts as a thermal barrier, reducing heat transfer between the environment and the metal surface, thereby delaying ice formation. Furthermore, reduced ice adhesion allows easier removal under external forces such as wind or mechanical vibration. These combined effects improve operational reliability in cold-region infrastructure such as wind turbines, aircraft systems, and outdoor industrial installations.

4.6.4 Corrosion Monitoring and Sensing Applications

Beyond protective functions, MOFs also play a significant role in corrosion monitoring due to their tunable optical, electrochemical, and luminescent properties. Functional MOF-based sensors can respond to environmental changes such as pH fluctuations, ion concentration variations, and redox activity associated with early-stage corrosion processes (Sun *et al.,* 2025). These responses enable real-time detection of corrosion initiation, allowing timely intervention before severe material degradation occurs. In addition, hybrid MOF–polymer systems provide enhanced mechanical stability and multi-stimuli responsiveness, improving sensing accuracy and durability in harsh operational environments (Liu *et al.,* 2025). Such smart sensing systems are increasingly important for predictive maintenance and structural health monitoring in critical engineering applications.

5. Sector-Specific Industrial Applications

Metal–Organic Framework (MOF)-based corrosion protection systems are increasingly being explored across multiple industrial sectors due to their tunable structure, high surface area, and multifunctional behavior. Their ability to provide barrier protection, controlled inhibitor release, and smart responsive functionality makes them suitable for demanding engineering environments where conventional coatings often suffer from degradation under long-term exposure. Recent advances in porous and functional coating materials highlight their growing relevance in improving durability, safety, and lifecycle performance of industrial assets (Patel *et al.,* 2024).

5.1 Oil and Gas Industry

In the oil and gas industry, corrosion is a persistent issue due to exposure to CO_2, H_2S, chlorides, water, and variable pressure–temperature conditions. Advanced porous functional materials have shown strong potential in enhancing corrosion resistance in pipelines and storage systems by improving barrier efficiency and enabling more controlled mitigation of aggressive species (Zhang *et al.,* 2025a). In pipelines, these materials help reduce internal corrosion caused by multiphase flow conditions, while in storage tanks they limit degradation arising from fuel impurities and water accumulation. Offshore platforms also benefit from such systems, where continuous seawater exposure and mechanical stress require coatings with high chemical stability and long-term durability.

5.2 Marine Industry

Marine environments are among the most aggressive corrosion settings due to constant seawater immersion, dissolved oxygen, chloride ions, and biological fouling. Functional nanostructured coatings have been reported to significantly enhance the durability of marine and offshore infrastructure by reducing chloride penetration and slowing electrochemical degradation (Kim *et al.,* 2024). In ships, these coatings improve hull longevity by minimizing rust formation and surface deterioration, while in harbors they reduce corrosion caused by tidal cycles and salt spray. Offshore structures such as platforms and subsea installations benefit from improved resistance to both mechanical erosion and biofouling-related corrosion acceleration.

5.3 Automotive Industry

In the automotive sector, corrosion protection plays a vital role in ensuring structural integrity, safety, and aesthetic quality. Smart anticorrosion coatings developed for lightweight alloys enhance resistance to road salts, humidity, and temperature fluctuations commonly encountered during vehicle operation (Ahmed *et al.,* 2025). These coatings are particularly important for body panels, chassis components, and engine parts exposed to thermal cycling and chemical attack. Additionally, their compatibility with lightweight materials supports fuel efficiency and emission reduction goals by minimizing the need for heavy protective layers while maintaining high corrosion resistance.

5.4 Aerospace Industry

Aerospace materials, especially aluminum and magnesium alloys, require exceptional corrosion resistance due to exposure to extreme atmospheric, thermal, and mechanical conditions. Advanced corrosion-resistant coating systems provide protection against oxidation, pitting, and moisture-induced degradation in aircraft structures (Martínez *et al.,* 2026; Husaini, 2020a&b). These coatings are engineered to maintain stability under high-altitude radiation, temperature variations, and cyclic loading conditions (Husaini, 2021). Furthermore, their lightweight nature is critical in aerospace applications, where even small weight increases can significantly impact fuel efficiency and performance.

5.5 Construction and Infrastructure

In civil engineering, corrosion of reinforced concrete and steel structures remains a major challenge affecting long-term durability and maintenance costs. Multifunctional coating systems have been developed to reduce chloride ingress, moisture penetration, and carbonation effects in reinforced concrete structures (Singh *et al.,* 2025). Steel bridges benefit from improved resistance to de-icing salts and atmospheric corrosion, while industrial buildings experience reduced degradation from chemical exposure and humidity. These improvements contribute to extended service life, reduced repair frequency, and improved structural reliability in infrastructure systems.

5.6 Energy Sector

The energy sector includes systems that operate under highly aggressive environmental and operational conditions, making corrosion protection essential for reliability and safety. Wind turbine structures require advanced coatings capable of resisting moisture, dust, salt deposition, and cyclic mechanical loading, thereby improving operational efficiency and lifespan (Wang *et al.,* 2024). Solar energy systems also benefit from protective coatings that reduce degradation of metallic supports and conductive components exposed to outdoor conditions. In nuclear facilities, corrosion-resistant functional coatings help mitigate material degradation caused by radiation exposure, high temperature, and chemically aggressive environments, ensuring long-term structural integrity and operational safety (Zhou *et al.,* 2025).

Figure 5: Industrial Applications of MOFs across Major Sectors

6. Industrial Performance Evaluation of MOF-Based Corrosion Protection Systems

The evaluation of Metal–Organic Framework (MOF)-based corrosion protection systems requires a combination of electrochemical techniques, accelerated environmental exposure tests, and advanced surface characterization methods. These approaches collectively provide insight into coating integrity, degradation behavior, and long-term performance under industrial conditions. Recent developments in electrochemical analysis and corrosion testing emphasize the importance of integrated evaluation strategies for reliable performance prediction (Zhang *et al.,* 2025b).

6.1 Electrochemical Impedance Spectroscopy (EIS)

Electrochemical Impedance Spectroscopy (EIS) is widely used to assess the barrier properties and electrochemical stability of MOF-based coatings by analyzing the response of the metal–electrolyte interface over a range of frequencies. It provides information on charge transfer resistance, coating capacitance, and diffusion-controlled processes. High impedance values generally indicate effective suppression of ionic transport and strong coating integrity, while time-dependent changes in impedance reflect coating degradation and electrolyte penetration pathways. Advanced studies also highlight improved interpretation methods and modeling approaches for corrosion systems using EIS data (Zhang *et al.,* 2025a; Zhang *et al.,* 2024).

6.2 Potentiodynamic Polarization

Potentiodynamic polarization is used to quantify corrosion kinetics by measuring corrosion potential, corrosion current density, and polarization resistance. It provides direct evaluation of the thermodynamic tendency and electrochemical rate of corrosion. In MOF-based systems, a reduction in corrosion current density indicates improved inhibition efficiency, while a positive shift in corrosion potential reflects enhanced electrochemical stability. Recent studies on nanostructured coatings have demonstrated the usefulness of polarization techniques in comparing protective performance under different environmental conditions (Kumar *et al.,* 2024).

6.3 Salt Spray Testing

Salt spray testing is an accelerated corrosion method used to simulate marine and industrial chloride-rich environments under controlled laboratory conditions. Coated samples are exposed to continuous saline fog to evaluate resistance to rust formation, blistering, and coating delamination. The test is particularly useful for assessing long-term durability of MOF-based coatings in aggressive environments. Comparative studies have shown strong correlations between salt spray exposure results and electrochemical impedance behavior, making it a widely accepted industrial standard for coating evaluation (Liu *et al.,* 2025; Zhang *et al.,* 2023).

6.4 Immersion Testing

Immersion testing involves exposing coated metal substrates to corrosive media such as NaCl solutions, acidic environments, or simulated seawater for extended periods. This method provides realistic information on long-term coating stability, inhibitor release behavior, and degradation kinetics. Monitoring parameters such as mass loss, pH variation, and surface morphology evolution helps in understanding corrosion progression mechanisms. Recent research highlights the importance of long-duration immersion studies in evaluating smart coating systems under practical service conditions (Salim *et al.,* 2024; Zriouel *et al.,* 2025; Hassan *et al.,* 2026).

6.5 Surface Characterization Techniques

Surface characterization techniques are essential for analyzing the structural, morphological, and chemical evolution of MOF-based coatings before and after corrosion exposure. Scanning Electron Microscopy (SEM) is used to observe surface damage such as cracks, pits, and corrosion products.

Transmission Electron Microscopy (TEM) provides nanoscale insight into MOF dispersion and structural integrity within composite coatings. Atomic Force Microscopy (AFM) evaluates surface roughness and nanoscale topography, which influence wettability and adhesion behavior.

X-ray Photoelectron Spectroscopy (XPS) is used to determine elemental composition and chemical states at the coating surface, providing information on corrosion products and interfacial reactions. Fourier Transform Infrared Spectroscopy (FTIR) identifies functional groups and bonding interactions within MOFs and polymer matrices. Recent advances in multi-technique surface analysis emphasize the importance of combining SEM, TEM, AFM, XPS, and FTIR for comprehensive corrosion performance evaluation (Chen *et al.,* 2025).

7. Challenges Limiting Industrial Commercialization

Despite the rapid development of Metal–Organic Framework (MOF)-based corrosion protection systems, their large-scale industrial deployment is still limited by a combination of economic, technical, environmental, and regulatory challenges. These limitations hinder the transition from laboratory-scale demonstrations to reliable, cost-effective industrial applications in harsh service environments (Wang *et al.,* 2025).

7.1 High Production Costs

A major limitation is the high cost associated with MOF synthesis, which depends on expensive metal precursors, organic linkers, and tightly controlled reaction conditions. Many MOF fabrication routes also involve solvent-intensive processes and prolonged synthesis times, which increase energy consumption and production expenses. In addition, post-synthetic modifications required to improve stability, dispersion, or functionality further raise overall costs. As a result, MOF-based coatings are currently less economically viable compared to conventional industrial corrosion protection systems such as epoxy coatings, zinc-rich paints, and metallic plating technologies (Patel *et al.,* 2025).

7.2 Scale-Up Difficulties

The transition from laboratory-scale synthesis to industrial-scale production remains challenging due to difficulties in controlling nucleation, crystal growth, and phase uniformity. Variations in temperature, mixing efficiency, and reaction kinetics in large reactors often lead to inconsistencies in particle size and structural integrity. Furthermore, achieving uniform dispersion of MOFs within polymer or coating matrices is difficult at large scale, especially for applications requiring large surface coverage such as pipelines, offshore structures, and industrial tanks. These scale-up limitations significantly reduce reproducibility and industrial reliability (Khan *et al.,* 2024).

7.3 Long-Term Stability Issues

Although MOFs perform well under controlled laboratory conditions, their long-term stability under real environmental exposure remains a key concern. Many MOF structures are sensitive to humidity, acidic or alkaline media, and high chloride concentrations, which can lead to partial framework degradation or structural collapse over time. This instability directly affects corrosion protection efficiency, particularly in marine, offshore, and chemical processing environments where continuous exposure to aggressive media is unavoidable (Zhou *et al.,* 2024).

7.4 Mechanical Durability

Mechanical durability is another critical challenge limiting industrial application. MOF structures are often inherently brittle and may crack or fracture under mechanical stress such as abrasion, erosion, or impact loading. In real-world service conditions, coatings must withstand cyclic mechanical forces, vibration, and surface wear, which can compromise integrity and lead to premature failure. Poor interfacial adhesion between MOF-based coatings and metallic substrates further increases the risk of delamination, reducing long-term protection efficiency (Singh *et al.,* 2024; Ogunleye *et al.,* 2025).

7.5 Environmental and Toxicological Concerns

Environmental safety and toxicological impacts remain important considerations for large-scale MOF deployment. Some MOFs contain metal ions and organic ligands that may pose ecological risks if released during degradation, corrosion failure, or disposal processes. Additionally, the environmental fate of MOF nanoparticles in aquatic and soil systems is not yet fully understood, particularly regarding long-term bioaccumulation and toxicity. Life-cycle assessments emphasize the need for greener synthesis routes and environmentally benign MOF materials for sustainable industrial use (Patel *et al.,* 2025).

7.6 Standardization and Regulatory Issues

The absence of standardized protocols for synthesis, characterization, and corrosion performance evaluation remains a significant barrier to commercialization. Variability in experimental methods and reporting formats makes it difficult to compare results across different studies and research groups. In addition, regulatory approval processes for nanostructured materials are often complex, lengthy, and region-dependent, slowing down industrial adoption. Establishing harmonized standards and clear regulatory frameworks is essential to support consistent evaluation and accelerate the commercialization of MOF-based corrosion protection technologies (Brown *et al.,* 2025; Martínez *et al.,* 2026).

8. Emerging Trends and Future Perspectives

Recent advancements in Metal–Organic Framework (MOF)-based corrosion protection systems are increasingly driven by the need for smarter, greener, and more scalable technologies. The focus is gradually shifting from conventional passive protection toward intelligent, adaptive, and digitally integrated corrosion control systems suitable for next-generation industrial applications (Chen *et al.,* 2024).

8.1 AI-Assisted MOF Design

Artificial intelligence (AI) and machine learning are transforming the design of MOF-based materials by enabling rapid prediction of structure–property relationships. Instead of relying solely on trial-and-error synthesis, AI models can screen large chemical spaces to identify optimal metal nodes, linkers, and pore architectures for corrosion resistance and functional stability. This accelerates material discovery while improving performance prediction accuracy. Recent studies highlight that AI-driven frameworks significantly reduce experimental time and enhance design efficiency for advanced functional materials (Liang *et al.,* 2025).

8.2 Green and Sustainable MOFs

Sustainability has become a key priority in MOF development, leading to increased interest in environmentally friendly synthesis routes. Green MOFs are being developed using less toxic metal sources, biodegradable organic ligands, and water-based or solvent-free synthesis methods. These approaches reduce environmental impact while maintaining structural performance and corrosion resistance. In addition, sustainable MOF production supports compliance with tightening environmental regulations and industrial decarbonization goals (Gupta *et al.,* 2024).

8.3 3D-Printed Protective Coatings

Additive manufacturing and 3D printing are emerging as powerful tools for fabricating customized corrosion protection systems. These technologies allow precise control over coating thickness, geometry, and material distribution, enabling tailored protection for complex industrial components. Incorporating MOFs into printable inks or composite matrices further enhances functionality and allows on-demand fabrication of smart coatings. Recent developments show that 3D printing is increasingly being used to design advanced functional protective layers for industrial applications (Morales *et al.,* 2025).

8.4 MOF Nanocomposites

MOF-based nanocomposites are gaining attention as a strategy to overcome limitations such as brittleness and limited mechanical stability. By combining MOFs with polymers, graphene, ceramics, or other nanofillers, hybrid materials can be engineered with improved adhesion, toughness, and barrier performance. These nanocomposites also enable multifunctionality, including self-healing, anti-fouling, and stimulus-responsive behavior, making them highly suitable for harsh operational environments (Park *et al.,* 2026).

8.5 Digital Corrosion Monitoring Systems

The integration of digital technologies is revolutionizing corrosion monitoring through real-time data acquisition and predictive analytics. MOF-based sensors can be combined with IoT-enabled systems to continuously monitor environmental and electrochemical changes associated with corrosion processes. This allows early detection of material degradation and supports predictive maintenance strategies, reducing downtime and repair costs in industrial systems. Recent advances emphasize the importance of smart sensing materials integrated into digital corrosion monitoring platforms (Almeida *et al.,* 2025).

8.6 Industrial Scale-Up Strategies

Scaling MOF-based technologies from laboratory research to industrial production remains a critical challenge. Continuous-flow synthesis, cost reduction strategies, and process optimization are being explored to improve scalability and reproducibility. In addition, hybrid fabrication approaches that integrate MOFs with conventional coating systems are gaining attention as practical solutions for industrial deployment. These developments aim to ensure consistent performance, reduced production costs, and reliable large-scale manufacturing of MOF-based corrosion protection systems (Chen *et al.,* 2024).

Conclusion

Metal–Organic Frameworks (MOFs) represent a promising class of advanced materials for corrosion protection due to their high porosity, structural tunability, and multifunctional capabilities that go beyond conventional passive barrier coatings. Their ability to enable controlled inhibitor release, surface wettability modification, and sensing functions makes them highly suitable for demanding industrial environments across sectors such as oil and gas, marine, automotive, aerospace, construction, and energy. Despite these advantages, challenges such as high production costs, scalability limitations, long-term stability concerns, mechanical durability issues, and lack of standardized regulations still restrict large-scale commercialization. Ongoing research is increasingly focused on overcoming these limitations through sustainable synthesis approaches, AI-assisted material design, nanocomposite development, and integration with digital monitoring systems. Addressing these challenges will be essential for enabling the practical deployment of MOF-based corrosion protection technologies in real industrial applications.

Disclosure statement: *Conflict of Interest:* The authors declare that there are no conflicts of interest.
Compliance with Ethical Standards: This article does not contain any studies involving human or animal subjects.

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(2026) ; http://www.jmaterenvironsci.com