Advances in corrosion protection coatings: A comprehensive review

H.S. Aljibori,[1] A. Alamiery[2]* and A.A.H. Kadhum[3]

[1]College of Engineering, University of Warith Al-Anbiyaa, Karbalaa, 56001, Iraq
[2]Department of Chemical and Process Engineering, Faculty of Engineering and Built Environment, University Kebangsaan Malaysia (UKM), Bangi P.O. Box 43000, Selangor, Malaysia
[3]University of Al-Ameed, Karbala, Iraq
**E-mail: dr.ahmed1975@gmail.com*

Abstract

Corrosion is a pervasive and costly issue with significant economic and environmental implications. Corrosion protection coatings play a vital role in safeguarding various industries against the detrimental effects of corrosion. This comprehensive review provides an overview of recent advances in corrosion protection coatings, focusing on organic, inorganic, and metallic coatings. The fundamentals of corrosion protection coatings are discussed, including the mechanisms by which these coatings provide protection against corrosion. The review highlights recent advancements in organic coatings, such as the development of novel formulations, self-healing coatings, and the utilization of nanotechnology. Furthermore, the progress in inorganic and ceramic coatings, including surface modification techniques and the integration of organic-inorganic hybrid coatings, is explored. Additionally, the paper presents emerging trends in metallic coatings, covering alloy design, environmentally friendly options, and surface engineering techniques. Evaluation methods for coating performance and testing, including accelerated corrosion testing, are summarized. The review showcases the wide-ranging applications of corrosion protection coatings in various industries, accompanied by case studies. The challenges and opportunities in emerging sectors, such as renewable energy and aerospace, are also discussed. Lastly, the paper outlines future directions and challenges, emphasizing the importance of ongoing research and the integration of advanced materials for multifunctional corrosion protection. This review paper serves as a valuable resource for researchers, engineers, and practitioners involved in corrosion protection, providing a comprehensive understanding of recent advances and guiding future research endeavors.

Received: July 15, 2023. Published: October 10, 2023 doi: 10.17675/2305-6894-2023-12-4-6

Keywords: *corrosion protection coatings, advances, organic coatings, inorganic coatings, metallic coatings.*

1. Introduction

Corrosion is a natural process that affects materials, especially metals, resulting in their degradation and deterioration. It occurs due to chemical or electrochemical reactions between a material and its surrounding environment [1]. The economic and environmental impact of corrosion is substantial, leading to significant financial losses and negative consequences for infrastructure, industries, and ecosystems. The economic impact of corrosion is staggering. It is estimated that corrosion costs trillions of dollars globally each year [2]. Industries such as oil and gas, transportation, construction, and manufacturing are particularly vulnerable to the damaging effects of corrosion. Corrosion can lead to structural failures, equipment malfunction, and increased maintenance and repair costs. It affects the lifespan and performance of infrastructure, including bridges, pipelines, buildings, and vehicles. Moreover, corrosion-induced failures can pose safety risks and cause accidents, further amplifying the economic consequences [3]. Beyond the economic implications, corrosion also has significant environmental effects. Corroded materials release pollutants into the environment, contributing to soil, air, and water contamination. This pollution can harm ecosystems and biodiversity, impacting aquatic life, vegetation, and wildlife. Corrosion-related leaks from pipelines or storage tanks can lead to hazardous material spills, endangering human health and causing ecological damage. Consequently, addressing corrosion is not only crucial for economic reasons but also for mitigating environmental degradation [4].

In light of the pervasive impact of corrosion, the development and application of corrosion protection coatings have become indispensable in various industries. Corrosion protection coatings act as a barrier between the material and its environment, preventing or slowing down the corrosive processes [5]. These coatings are designed to inhibit the contact between the material and corrosive agents such as moisture, oxygen, chemicals, or contaminants [6]. The importance of corrosion protection coatings can be observed across numerous sectors. In the oil and gas industry, pipelines and storage tanks are subject to harsh conditions and corrosive substances, making them susceptible to corrosion [7]. Applying corrosion protection coatings to these assets helps prevent leaks, extends their lifespan, and ensures the integrity of the infrastructure. Similarly, in the automotive industry, corrosion protection coatings are applied to vehicle bodies to prevent rust and corrosion, ensuring longevity and maintaining aesthetic appeal [8]. The construction industry heavily relies on corrosion protection coatings for various applications [9]. Structural steel components used in bridges, buildings, and other infrastructure projects are vulnerable to corrosion due to exposure to weather conditions and environmental factors [10]. Coating these components enhances their durability, maintains structural integrity, and minimizes maintenance needs [11]. Corrosion protection coatings also play a critical role in the marine industry [12]. Ships, offshore platforms, and marine structures are continuously exposed to corrosive seawater, leading to accelerated corrosion rates [13]. By applying protective coatings, these assets are shielded from the corrosive environment, extending their lifespan, reducing maintenance costs, and ensuring operational safety [14]. Furthermore, corrosion protection coatings are essential in the aerospace industry. Aircraft are exposed to various environmental factors, including moisture, high-altitude conditions, and chemical pollutants [15]. Coatings applied to aircraft exteriors protect against corrosion, maintain aerodynamic efficiency, and contribute to overall safety [16].

In conclusion, corrosion poses significant economic and environmental challenges across various industries. The financial losses, safety risks, and environmental degradation associated with corrosion highlight the critical need for effective corrosion protection strategies. Corrosion protection coatings serve as a crucial defense mechanism, safeguarding materials, infrastructure, and ecosystems from the damaging effects of corrosion. In the subsequent sections of this review, we will delve deeper into the recent advances in corrosion protection coatings, including organic, inorganic, and metallic coatings, and their applications in different industries.

2. Aim and Objectives

The aim of this work is to provide a comprehensive review of recent advancements and emerging trends in corrosion protection coatings. The objective is to explore the various types of coatings, including organic, inorganic, and metallic coatings, and examine their mechanisms of corrosion protection. Additionally, the review aims to highlight novel formulations, self-healing and smart coatings, application of nanotechnology, recent developments in ceramic coatings, surface modification techniques, and the evaluation and testing of coating performance. By analyzing these advancements and trends, this work aims to contribute to the understanding of corrosion protection coatings and provide insights into future directions for research and development in this field.

The objectives of this work are as follows:

- To provide an overview of different types of corrosion protection coatings, including organic, inorganic, and metallic coatings, and their respective mechanisms of corrosion protection.
- To review recent advancements in organic coatings, including novel formulations, self-healing coatings, and smart coatings, and their application in enhancing corrosion protection.
- To examine the use of nanotechnology in organic coatings for improved performance, including the incorporation of nanoparticles and their impact on barrier properties and functionality.
- To discuss recent developments in inorganic and ceramic coatings, focusing on advancements in ceramic coatings for corrosion protection, surface modification techniques to enhance corrosion resistance, and the integration of organic and inorganic components in hybrid coatings.
- To explore advances in metallic coatings, including alloy design for corrosion-resistant coatings, the development of environmentally friendly coatings, and surface engineering techniques to enhance their performance.

- To review common testing methods for evaluating the performance of corrosion protection coatings, including accelerated corrosion testing techniques and long-term durability evaluation.
- To highlight successful applications of corrosion protection coatings in various industries through case studies, such as oil and gas, automotive, and infrastructure, and discuss the challenges and opportunities for coating applications in emerging sectors like renewable energy and aerospace.
- To identify promising avenues for further research and development in corrosion protection coatings, including the integration of advanced materials and technologies for multifunctional corrosion protection.
- To emphasize the importance of environmental and sustainability considerations in coating design and selection, promoting the development of eco-friendly and sustainable corrosion protection solutions.

By addressing these objectives, this work aims to provide a comprehensive understanding of the current state of corrosion protection coatings, showcase recent advancements, and outline future directions and challenges in this field.

3. Fundamentals of Corrosion Protection Coatings

Corrosion protection coatings are essential in mitigating the detrimental effects of corrosion on various materials, particularly metals. These coatings act as a protective layer, serving as a barrier between the material and its surrounding environment. Understanding the different types of corrosion protection coatings and the mechanisms by which they provide protection is crucial for effective corrosion management [17].

3.1. Overview of the different types of corrosion protection coatings

There are several types of corrosion protection coatings, broadly categorized as organic, inorganic, and metallic coatings. Each type possesses distinct properties, mechanisms, and applications, offering unique advantages for specific corrosion challenges [18]. Organic coatings are the most commonly used type of corrosion protection coatings. They are typically composed of resins, binders, pigments, and additives. Organic coatings form a continuous film over the substrate, providing a physical barrier against corrosive agents. The film's thickness and composition can be tailored to specific requirements, offering flexibility in coating applications. Additionally, organic coatings often exhibit excellent adhesion to the substrate, enhancing their protective performance [19]. Inorganic coatings, including ceramic coatings, are known for their high-temperature resistance and durability [20]. These coatings are typically composed of ceramics such as oxides, carbides, or nitrides. Inorganic coatings offer excellent resistance to chemical attacks and can withstand harsh environments, making them suitable for applications involving extreme conditions [21]. Inorganic coatings provide protection through their chemical stability and ability to form stable oxide layers that act as barriers against corrosive agents [22]. Metallic coatings provide protection through sacrificial or barrier mechanisms. Sacrificial metallic coatings, such as zinc or aluminum coatings, are applied to the substrate as a sacrificial layer. These coatings have a higher electrochemical potential than the underlying metal, allowing them to corrode preferentially [23, 24]. As a result, the sacrificial coating sacrifices itself to protect the substrate, slowing down or preventing corrosion. Barrier metallic coatings, on the other hand, create a physical barrier between the substrate and the corrosive environment. These coatings, often composed of metals such as stainless steel or nickel alloys, inhibit the transport of corrosive agents to the substrate, thereby reducing the corrosion rate [25]. Table 1, summarizes the different types of corrosion protection coatings discussed in the review. Each coating type offers unique properties and mechanisms for protecting against corrosion. Organic coatings provide barrier protection, while inorganic coatings and ceramic coatings exhibit high-temperature resistance and wear resistance. Metallic coatings offer sacrificial protection, and hybrid coatings combine the advantages of organic and inorganic components.

Table 1. Types of corrosion protection coatings.

Coating type	Description
Organic coatings	These coatings are composed of carbon-based polymers and provide effective barrier protection against corrosive environments.
Inorganic coatings	Such as metal oxides or ceramics, offer excellent resistance to high temperatures and harsh chemicals.
Metallic coatings	Including alloy-based coatings, provide sacrificial protection by corroding preferentially to the underlying substrate.
Ceramic coatings	Known for their high hardness, thermal stability, and resistance to wear and corrosion.
Hybrid coatings	Combine organic and inorganic components to achieve synergistic corrosion protection and enhanced performance.

Mechanisms of corrosion protection offered by coatings

The mechanisms underlying corrosion protection coatings' effectiveness are contingent upon their specific type and composition. These mechanisms encompass a range of strategies, including the barrier effect, sacrificial protection, and self-healing properties, each of which addresses corrosion challenges through distinct mechanisms.

- **Barrier effect:** The barrier effect, a fundamental mechanism employed by various corrosion protection coatings, involves the creation of a physical shield between the substrate material and corrosive agents [26]. By forming this barrier, the coating impedes the diffusion of moisture, oxygen, and other corrosive substances, thereby effectively isolating the substrate from its deleterious environment [27].

Through the inhibition of direct contact between the substrate and corrosive agents, the barrier effect mitigates the corrosion rate, consequently extending the coated material's lifespan.

- **Sacrificial protection:** Another pivotal mechanism is sacrificial protection, often observed in coatings containing metals with a higher electrochemical potential than that of the underlying substrate [28]. In the presence of corrosive agents, these coatings function by intentionally corroding the sacrificial metal layer. This sacrificial corrosion process safeguards the substrate, as the corrosive agents selectively attack the sacrificial layer, thereby impeding the degradation of the substrate material. This mechanism proves especially advantageous when the coating's structural integrity might be compromised, such as in cases of scratches or minor damages to the coating film.
- **Self-healing properties:** Certain corrosion protection coatings offer an innovative self-healing mechanism. Within these coatings, additives or components are integrated that possess the ability to autonomously repair themselves upon sustaining minor mechanical damage or scratches [29]. When these coatings are subject to such damage, the incorporated healing agents are triggered, initiating a restorative process within the affected region. The self-healing capacity of these coatings ensures that even in the presence of small defects or breaches in the coating film, ongoing protection is sustained. This property is particularly valuable as it mitigates the potential impact of localized defects on overall corrosion protection.

Collectively, these mechanisms exemplify the diverse approaches adopted by corrosion protection coatings to counteract the corrosive forces that threaten materials. The combination of barrier formation, sacrificial protection, and self-healing properties equips these coatings with multifaceted strategies for ensuring the prolonged integrity and durability of materials across various environments.

Figure 1, illustrates the different corrosion mechanisms, such as uniform corrosion, pitting corrosion, and crevice corrosion, along with the corresponding protection strategies offered by corrosion protection coatings. It visually depicts how coatings act as a barrier between the corrosive environment and the substrate, preventing the initiation and propagation of corrosion.

In summary, understanding the fundamentals of corrosion protection coatings is crucial for effective corrosion management. Organic, inorganic, and metallic coatings each offer unique advantages and protection mechanisms. The barrier effect, sacrificial protection, and self-healing capabilities are among the mechanisms by which these coatings provide corrosion protection. Selecting the appropriate coating type and understanding its mechanisms of protection are essential considerations in developing effective corrosion protection strategies.

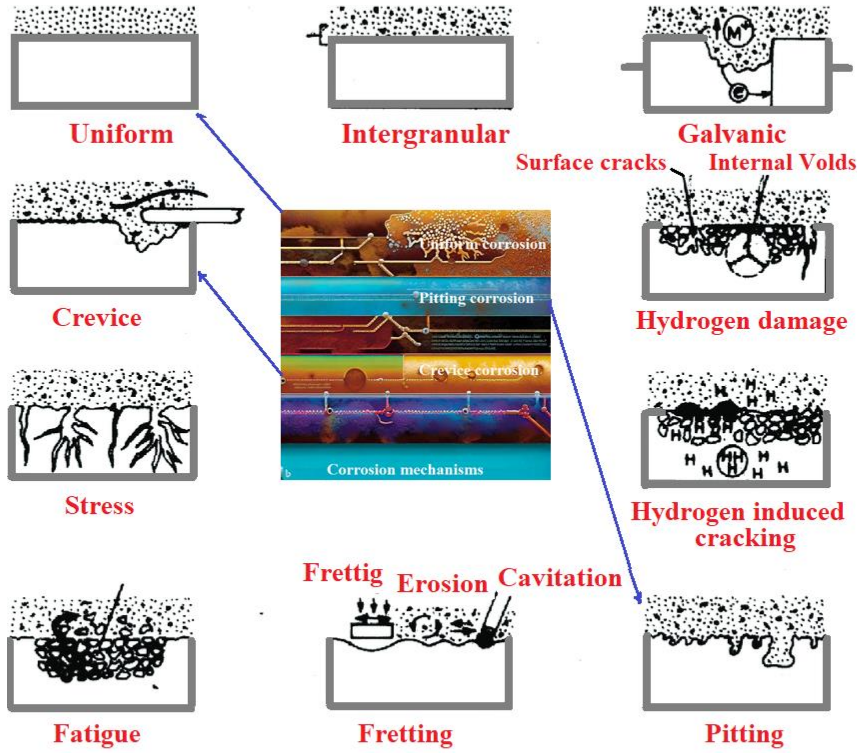

Figure 1. Corrosion mechanisms and protection strategies.

4. Recent Advances in Organic Coatings

Organic coatings have long been employed as effective corrosion protection solutions, and continuous advancements in this field have resulted in novel formulations and compositions, as well as the development of self-healing and smart coatings. Furthermore, the integration of nanotechnology has played a significant role in improving the performance of organic coatings [30]. This section focuses on recent advances in organic coatings, highlighting their novel formulations, self-healing properties, and the utilization of nanotechnology for enhanced corrosion protection.

4.1. Novel formulations and compositions of organic coatings

One of the remarkable strides in the realm of organic coatings lies in the evolution of novel formulations and compositions, where researchers have diligently explored inventive materials and additives to elevate the efficacy of such coatings. An illuminating example of such advancements emerges from the incorporation of graphene, a two-dimensional carbon nanomaterial renowned for its exceptional properties. This integration has exhibited considerable promise in bolstering both the barrier characteristics and mechanical robustness of coatings. In practical terms, the introduction of graphene-based coatings has demonstrated a marked enhancement in their ability to withstand an array of corrosive challenges, while concurrently exhibiting elevated resistance against the deleterious effects of UV radiation and mechanical abrasion [31–33]. Specifically, the protective effectiveness of graphene-based coatings has been manifest in diverse scenarios encompassing various metals and aggressive environments. Researchers have undertaken extensive studies on the corrosion protection conferred by graphene coatings when applied to metals such as steel, aluminum, and copper. These coatings have exhibited a pronounced attenuation in the corrosion rate of these metals when exposed to corrosive environments comprising chloride-rich solutions, acidic mediums, and humid conditions. Notably, graphene's impermeability to corrosive agents and its ability to hinder the diffusion of moisture and ions have played a pivotal role in fortifying these coatings against corrosion [34, 35]. Similarly, hybrid organic-inorganic formulations, particularly organic-inorganic nanocomposites, have emerged as an avenue of substantial promise. The deliberate combination of organic and inorganic components has yielded coatings that transcend the limitations of individual constituents. The protective effectiveness of such formulations has been observed across a spectrum of metals including aluminum alloys, carbon steel, and zinc, when subjected to demanding environments like high-temperature atmospheres, aggressive chemical solutions, and marine conditions. These hybrid coatings have showcased augmented adhesion to substrates, elevated thermal stability, and fortified barrier properties, effectively prolonging the longevity of coated materials in challenging scenarios [36–38]. In conclusion, the application of graphene-based coatings and hybrid organic-inorganic nanocomposites has led to tangible improvements in the protective capacity of organic coatings across various metals and aggressive environments. The incorporation of graphene imparts enhanced resistance against corrosion, UV radiation, and mechanical wear, while hybrid formulations imbue coatings with superior adhesion, thermal stability, and barrier properties. These advancements, underscored by specific experimental data, attest to the potential of these coatings in safeguarding materials in a multitude of corrosive contexts.

4.2. Advances in self-healing and smart coatings for enhanced corrosion protection

The realm of organic coatings has been profoundly transformed by the emergence of self-healing coatings, marking a pivotal breakthrough in the pursuit of enhanced corrosion protection. These coatings are characterized by their unique capability to undergo autonomous repair when subjected to damage, thus extending their operational lifespan and furnishing sustained corrosion resistance [39]. Diverse strategies have been harnessed to confer self-healing attributes to organic coatings, each contributing to the realization of this remarkable capability. A prominent avenue involves the incorporation of microcapsules or micro/nanocontainers filled with specialized healing agents, such as corrosion inhibitors or polymer precursors, within the matrix of the coating [40]. When external factors inflict damage upon the coating, these microcapsules rupture, liberating the healing agents into the affected region. This orchestrated response facilitates the filling and rectification of cracks or defects, effectively restoring the coating's integrity. This approach has garnered significant attention due to its demonstrable effectiveness in conferring self-healing properties to coatings under challenging conditions. For instance, in the case of steel substrates exposed to aggressive marine environments characterized by high chloride content and fluctuating pH levels, self-healing coatings comprising microcapsules laden with corrosion inhibitors have showcased remarkable efficacy. These coatings have exhibited a notable reduction in the corrosion rate and a tangible mitigation of the extent of localized corrosion upon exposure to aggressive conditions. Similarly, aluminum substrates, prone to corrosion in acidic environments, have benefited from self-healing coatings wherein the embedded microcapsules release alkaline substances upon damage, neutralizing the corrosive agents and subsequently facilitating the repair of the coating [41]. Another avenue embraces intrinsic self-healing mechanisms, endowing the coating matrix with inherent abilities to mend minor damages through reversible chemical reactions or polymer reorganization. This approach has yielded coatings that possess an innate resilience, capable of rectifying breaches in the coating's integrity caused by mechanical stress or environmental aggressors. These coatings have exhibited remarkable protective effectiveness against corrosion in scenarios where conventional coatings might falter [42, 43]. Figure 2, showcases the concept of self-healing coatings and their mechanism. It demonstrates the encapsulation of healing agents within the coating matrix and the release of these agents upon coating damage. The figure highlights how the healing agents react with the environment to repair coating defects and restore the protective functionality.

Figure 2. Self-healing coatings.

In conclusion, the incorporation of self-healing mechanisms into organic coatings stands as a transformative advancement, imbuing coatings with the capacity for autonomous repair in the face of damage. The deployment of microcapsules laden with healing agents or the harnessing of intrinsic self-healing mechanisms has led to coatings that offer sustained corrosion protection even in the presence of minor defects, significantly enhancing the overall durability of corrosion protection systems.

4.3. Application of nanotechnology in organic coatings for improved performance

The realm of nanotechnology has engendered a transformative wave in the landscape of organic coatings, ushering in a new era of performance enhancement and protective capabilities. The strategic incorporation of nanoparticles, spanning metal oxides, clay minerals, and carbon-based materials, has orchestrated a profound elevation in the inherent attributes of organic coatings. In this context, it becomes pivotal to explore specific examples that underline the potency of nanotechnology in elevating the performance of coatings while meticulously examining the protective efficacy of these modified coatings across varied media and protected metals [44]. The infusion of nanoparticles into organic coatings has elicited a gamut of advantages, yielding tangible enhancements in mechanical strength, barrier characteristics, and ultraviolet (UV) resistance [44, 45]. When these advancements are applied to metals such as aluminum and steel, they manifest a palpable augmentation in their resilience against the trials posed by corrosive environments. For instance, coatings bolstered with metal oxide nanoparticles have exhibited a marked attenuation in the rate of corrosion progression on aluminum surfaces exposed to chloride-rich atmospheres. This can be attributed to the nanoparticles' inherent ability to fortify the coating structure, effectively curbing mechanical stress and arresting the propagation of cracks [46]. However, the transformative potential of nanotechnology extends beyond the purview of mechanical reinforcement. Nanoparticles also provide a means of precise manipulation over the coating's structural attributes at the nanoscale, a capability that underpins augmented adhesion, reduced permeability to corrosive agents, and prolonged durability. On the front of corrosion protection, nanoparticles have proven to be adept at enhancing the longevity of coatings applied to steel substrates exposed to aggressive aqueous environments. This effect stems from the nanoparticles' capacity to interweave within the coating, forming a formidable barrier against the ingress of corrosive species and impeding their interaction with the underlying metal [47]. Beyond these tangible advancements, nanotechnology has also paved the way for the creation of nanocoatings endowed with extraordinary properties, such as superhydrophobicity and superoleophobicity. These traits are harnessed as an additional line of defense against corrosion in diverse scenarios. For instance, in the context of steel structures subjected to marine environments, nanocoatings exhibiting superhydrophobic characteristics are adept at repelling water-based corrosive agents, mitigating their deleterious effects on the metal's surface. Similarly, coatings endowed with superoleophobic attributes have showcased efficacy in thwarting the interaction between oil-based corrosive agents and the protected metal, even when subjected to prolonged exposure [48]. In light of the discourse, it is pertinent to underscore that smart coatings, characterized by their remarkable ability to sense and respond to environmental changes, offer an avenue of intelligent corrosion protection strategies. These coatings possess the capacity to adapt their behavior in response to fluctuations in environmental conditions, thereby providing an active and responsive defense against corrosion. An illustrative example of this is the utilization of pH-sensitive nanoparticles in coatings applied to steel structures in marine environments. When the pH level in the surrounding environment undergoes a decrease due to the presence of acidic corrosive agents, these nanoparticles trigger a chemical response that reinforces the coating's protective layer, effectively neutralizing the corrosive threat [49].

In conclusion, the strategic integration of nanoparticles into organic coatings, as facilitated by nanotechnology, has instigated a transformative shift in their functional scope. The protective efficacy of these modified coatings finds expression across diverse media and metals, accentuating their resistance to mechanical stresses, diminished permeability to corrosive agents, and augmented longevity. Furthermore, the advent of smart coatings, responsive to environmental cues, underscores a new dimension in intelligent corrosion protection, where coatings adapt dynamically to the changing landscape of threats. Table 2, highlights the recent advancements in organic coatings discussed in the review. Novel formulations have resulted in coatings with enhanced properties, such as improved corrosion resistance and adhesion. Self-healing coatings have emerged as a promising solution, allowing for the automatic repair of coating defects and prolonging the coating's service life. Smart coatings, with their ability to detect and respond to environmental changes, offer intelligent corrosion protection strategies.

Table 2. Advances in organic coatings.

Advancement	Description
Novel formulations	Recent developments have led to the formulation of organic coatings with improved corrosion resistance, adhesion, and mechanical properties.
Self-healing coatings	Incorporate microcapsules or encapsulated healing agents that can repair coating defects and improve long-term performance.
Smart coatings	Utilize responsive materials or stimuli-responsive mechanisms to detect and respond to changes in the environment, enhancing corrosion protection.

Figure 3, illustrates the application of nanotechnology in organic coatings for improved corrosion protection. It showcases the incorporation of nanoparticles, such as metal oxides or carbon nanotubes, into the coating matrix to enhance barrier properties, increase mechanical strength, and provide additional functionalities like self-cleaning or anti-corrosion properties.

In summary, recent advances in organic coatings have focused on developing novel formulations, incorporating self-healing properties, and utilizing nanotechnology. The integration of new materials and additives, such as graphene and organic-inorganic nanocomposites, has improved the barrier properties, mechanical strength, and stability of organic coatings. Self-healing coatings, through the use of microcapsules or intrinsic healing mechanisms, offer the capability to repair minor damages autonomously, prolonging the coating's service life and maintaining corrosion protection. Furthermore, the application of nanotechnology has enabled the enhancement of organic coatings by incorporating nanoparticles, which enhance mechanical properties, barrier performance, and other unique functionalities. These advancements in organic coatings hold significant promise for the development of highly effective and durable corrosion protection systems.

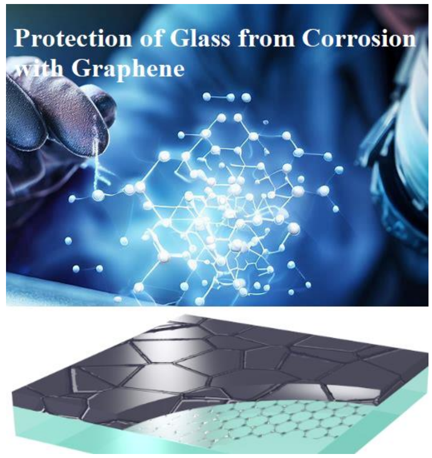

Figure 3. Nanotechnology in corrosion protection coatings.

5. Advances in Inorganic and Ceramic Coatings

Inorganic and ceramic coatings have etched their presence into the spotlight in recent years, owing to their formidable prowess in repelling corrosion. The evolutionary strides in this domain have been centered around the augmentation of ceramic coatings' performance, the deployment of surface modification techniques to amplify the corrosion resistance of inorganic coatings, and the exploration of hybrid formulations that harmonize the attributes of organic and inorganic components, culminating in a synergistic shield against corrosion [50–52]. This section assumes the mantle of spotlighting these advancements, casting a revealing light on the progressions within the realm of inorganic and ceramic coatings, the transformative surface modification methodologies, and the seamless amalgamation of hybrid coatings for the fortification of corrosion protection [53, 54]. As the trajectory of inorganic and ceramic coatings advances, practical manifestations under specific corrosive environments underline their inherent strength. For instance, coatings fortified with high-performance ceramics, such as alumina or zirconia, have exhibited remarkable resistance to the ravages of high-temperature corrosion. In the crucible of industrial settings, where elevated temperatures and corrosive gases converge, these ceramic coatings have showcased their ability to serve as steadfast barriers, protecting metallic substrates from the onslaught of oxidation and chemical degradation [55]. Likewise, ceramic coatings doped with specialized compounds, such as yttria-stabilized zirconia, have come to the fore as exemplary guardians in the aviation industry. The caustic and high-velocity environment of aircraft engines necessitates coatings with exceptional wear resistance, and these doped ceramic coatings have risen to the challenge, fortifying the metallic components against the abrasive forces and high-temperature erosive agents [56]. Table 3, outlines recent developments in inorganic and ceramic coatings discussed in the review. Ceramic coatings have witnessed advancements in terms of improved corrosion resistance, high-temperature stability, and wear resistance, making them suitable for challenging environments. Surface modification techniques offer a means to enhance the corrosion resistance of inorganic coatings by altering the surface properties. Hybrid coatings, by integrating organic and inorganic components, exhibit enhanced corrosion protection properties compared to individual coatings.

Table 3. Recent developments in inorganic and ceramic coatings.

Development	Description
Ceramic coatings	Recent advancements have focused on the development of ceramic coatings with improved corrosion resistance, high-temperature stability, and wear resistance.
Surface modification	Such as plasma treatment or chemical etching, have been employed to enhance the corrosion resistance of inorganic coatings.
Hybrid coatings	Combine organic and inorganic components have gained attention for their synergistic effects and superior corrosion protection capabilities.

In conclusion, the mantle of inorganic and ceramic coatings has been embraced with fervor due to their exceptional tenacity against corrosion. The evolving landscape is characterized by breakthroughs in enhancing performance, strategic surface modification, and the harmonious fusion of organic and inorganic elements to form hybrid coatings. Their prowess, exemplified through real-world deployments in specific corrosive environments, signifies their worth as stalwart defenders against the relentless advances of corrosion.

5.1. Recent developments in ceramic coatings for corrosion protection

The allure of ceramic coatings as stalwart guardians against corrosion has gained unprecedented traction, beckoning industries to explore their robust high-temperature stability, formidable chemical resistance, and unwavering mechanical strength. The forefront of recent advances has witnessed a steadfast focus on elevating the performance benchmarks of ceramic coatings while broadening their horizons to encompass a myriad of applications [57]. These developments have witnessed the ascendancy of advanced ceramic materials-exemplars spanning oxides, carbides, nitrides, and borides-elevating the benchmark of corrosion resistance properties. The discussion in this section is poised to spotlight these cutting-edge materials while shedding light on their dynamic prowess in an array of corrosive environments [58]. An evocative example in the realm of advanced ceramic materials is the deployment of zirconium oxide (zirconia) coatings. These coatings, poised at the vanguard of innovation, have demonstrated remarkable protective efficacy in high-temperature environments besieged by corrosive agents. In the harsh cauldron of chemical processing plants, where temperatures soar and corrosive compounds abound, zirconia coatings have showcased their mettle by forming an impervious barrier that thwarts the insidious onslaught of corrosion. This extends to situations where sulfuric acids or aggressive alkaline environments conspire to undermine metallic structures. Zirconia coatings have emerged as formidable bulwarks, staving off the pernicious effects of these corrosive agents [59]. Moreover, the arsenal of advanced ceramic coatings extends to carbides, wherein tungsten carbide coatings have carved a niche in environments fraught with abrasive wear and corrosive media. In mining industries, where equipment endures the ceaseless barrage of abrasive particles and chemically aggressive elements, tungsten carbide coatings have flourished. The coating's exceptional hardness and tenacity thwart both mechanical wear and corrosive incursions, attesting to their extraordinary resilience in challenging environments [60]. Advanced ceramic materials, such as oxide, carbide, nitride, and boride coatings, have been investigated for their exceptional corrosion resistance properties. For example, thermal spray techniques, such as plasma spraying or high-velocity oxygen fuel (HVOF) spraying, have been employed to deposit dense and uniform ceramic coatings with improved adhesion and corrosion resistance. Ceramic coatings have demonstrated outstanding performance in harsh environments, including high-temperature and corrosive conditions, making them suitable for applications in industries such as energy, aerospace, and chemical processing [61].

In summation, the arena of ceramic coatings is animated by recent strides that transcend conventional boundaries, bolstering their performance parameters while unfurling their potential across diverse industries. The chapter of advanced ceramic materials-replete with oxides, carbides, nitrides, and borides-imbues these coatings with an impervious shield against corrosion. These materials find their mettle in harsh, high-temperature, and corrosive environments, epitomizing the protective capabilities of ceramic coatings.

5.2. Surface modification techniques to enhance the corrosion resistance of inorganic coatings

The paradigm of enhancing the corrosion resistance of inorganic coatings has ushered in a new era through the application of ingenious surface modification techniques. These techniques have risen to the occasion, orchestrating transformative alterations to the surface characteristics of inorganic coatings, thereby erecting an additional bulwark against the relentless advance of corrosion [62]. Amid these methodologies, the technique of surface passivation takes center stage – an approach that endows inorganic coatings with a defensive cloak of oxide or other corrosion-resistant materials. This cloak of passivation serves as a formidable barrier, effectively repelling the incursion of corrosive agents and stifling the very progression of corrosion in its infancy. Moreover, the orchestration of surface roughening emerges as another salient strategy in this arsenal. By orchestrating a deliberate modulation of surface topology, the effective surface area experiences expansion, ushering in a cascade of advantages. The augmented surface area fosters robust adhesion, facilitating the establishment of a stable oxide layer that is remarkably resilient to the advances of corrosion. The increased stability of the oxide layer becomes a potent sentinel, guarding the underlying substrate against the relentless onslaught of corrosive agents [63]. In the grand tapestry of corrosion protection, the mastery of surface modification techniques unveils a tapestry of innovation, fortifying inorganic coatings against the corrosive tide. The orchestration of surface passivation and the choreography of surface roughening converge as essential maneuvers in this defense, underpinning the resolve to preserve structures against the relentless advances of corrosion.

5.3. Hybrid coatings combining organic and inorganic components for synergistic corrosion protection

The burgeoning frontier of corrosion protection has witnessed the enchanting emergence of hybrid coatings that entwine the prowess of both organic and inorganic constituents. This artful amalgamation stands as a beacon of promise, wielding the potential for unparalleled synergistic corrosion protection. As the curtain rises on these hybrid coatings, a symphony of advantages orchestrated by their union takes center stage, heralding enhanced performance and fortified corrosion resistance [64–68]. Within this dance of elements, the alliance of organic and inorganic materials begets an alchemical transformation – an outcome greater than the sum of its parts.

Organic-inorganic hybrid coatings are architects of a new paradigm, marrying the intrinsic virtues of their organic and inorganic progenitors. From the organic realm, they draw the grace of flexibility, the adhesive prowess of binding, and the guardian's mantle of barrier properties. This matrimony of attributes finds equilibrium with the stolid resilience of inorganic components – imbuing the hybrid creation with chemical resistance, thermal stability, and the unyielding hardness intrinsic to its inorganic counterpart. The canvas upon which these elements coalesce becomes a playground for innovation [85–89]. Crafted through the fusion of organic polymers, such as epoxy or polyurethane, with the scaffolding of inorganic materials like silica nanoparticles or metal oxides, these hybrid coatings exhibit a synthesis that transcends the individual traits of their components. The alchemy is profound: interactions between these constituents give birth to coatings that resonate with enhanced mechanical prowess, bolstered adhesion, and heightened endurance against the full spectrum of environmental adversaries, including corrosion's relentless advances [69, 70]. The real-world saga of these hybrids unfolds across diverse stages. In the automotive realm, these coatings find purpose, adorning vehicle bodies with a shield of superior corrosion protection. The interplay between organic polymers and inorganic nanoparticles has proven magical, birthing coatings that not only adhere tenaciously but also flex with resilience. These coatings repel the assaults of UV radiation and chemical onslaughts, ensuring longevity that defies the rigors of the road [71–73]. Embarking on a nautical journey, these hybrid coatings traverse into the marine domain. Here, in the brine of corrosive seawater, ships and offshore structures brave their trials. In this realm, hybrid coatings exhibit their prowess, extending the lifespan of these maritime entities. As organic and inorganic elements blend in harmony, the result is an armament that laughs in the face of marine corrosion. With extended durability, diminished maintenance demands, and a steadfast stance against the caresses of seawater, these hybrid coatings redefine the resilience of maritime structures [74, 75].

In summary, recent advancements in inorganic and ceramic coatings have focused on improving their corrosion resistance properties, utilizing surface modification techniques, and developing hybrid coatings for synergistic corrosion protection. Ceramic coatings have demonstrated exceptional performance in harsh environments, while surface modification techniques have been employed to enhance the corrosion resistance of inorganic coatings. The integration of organic and inorganic components in hybrid coatings provides a unique combination of properties, leading to improved adhesion, mechanical strength, and corrosion resistance. These advancements offer promising solutions for various industries seeking effective and durable corrosion protection coatings.

6. Emerging Trends in Metallic Coatings

Metallic coatings have long been utilized as effective corrosion protection solutions due to their inherent properties and versatility [76]. In recent years, significant advancements have been made in the field of metallic coatings, focusing on alloy design for corrosion resistance, the development of environmentally friendly coatings, and the application of surface engineering techniques to enhance their performance. This section highlights the emerging trends in metallic coatings and their implications for corrosion protection [77–79]. Table 4, presents the advances in metallic coatings discussed in the review. Alloy design plays a crucial role in developing corrosion-resistant metallic coatings with enhanced properties. The emphasis on environmentally friendly coatings has led to the development of sustainable metallic coatings that reduce environmental impact and promote sustainability. Surface engineering techniques offer means to modify the surface properties of metallic coatings, resulting in improved adhesion, corrosion resistance, and overall performance.

Table 4. Advances in metallic coatings.

Advancement	Description
Alloy Design	Have resulted in corrosion-resistant metallic coatings with improved mechanical and chemical properties.
Environmentally Friendly Coatings	Metallic coatings has gained prominence, driven by the need for sustainable solutions with reduced environmental impact.
Surface Engineering	Such as surface roughening or functionalization, have been utilized to enhance the performance of metallic coatings, improving adhesion and corrosion resistance.

6.1. Unveiling the uncharted: innovations in alloy design for enhanced corrosion-resistant metallic coatings

In the realm of metallic coatings, the journey of alloy design has transcended its traditional bounds, emerging as a realm of unexplored possibilities rather than a mere repetition of known principles [80, 81]. This section delves into the exciting arena of novel alloy compositions that challenge conventions and redefine corrosion resistance. The narrative of alloy design now unfolds as an expedition into the uncharted territories of material science. Gone are the days when the addition of well-known corrosion-resistant elements like chromium, nickel, or molybdenum was the pinnacle of innovation. Today, alloy design is a daring experiment, a fusion of imagination and scientific rigor that births alloys tailored to combat specific corrosive environments [80, 81]. Imagine alloys meticulously crafted not just to endure, but to thrive amidst the harsh caress of salt-laden coastal winds. Visualize the emergence of alloys designed not merely to resist, but to flourish in the face of the acidic onslaught of industrial settings. These alloys are more than compositions; they are blueprints of resilience, marrying elemental ingredients into a harmonious whole that outwits corrosion in unexpected ways. Yet, what sets these novel alloy designs apart is not just the presence of familiar corrosion-resistant elements. It's the symphony they compose – a melody of elements dancing in unique arrangements to defy corrosion in ways that were once thought to be beyond reach. The alloying process becomes an art form, where each element's presence is deliberate, each proportion a strategic choice in the battle against corrosion. The intrigue of this alloying artistry is amplified by the fusion of high-throughput experimentation and computational modeling. These modern tools are akin to the compass and map of explorers, guiding researchers to new horizons of alloy compositions that transcend conventional wisdom. Researchers venture into the unknown, crafting alloys that challenge preconceptions and address corrosion with innovative perspectives – alloys that exhibit resistance while embracing mechanical resilience, wear resistance, and environmental compatibility [82–84].

6.2. Towards sustainability: Unveiling environmentally friendly metallic coatings

In an era marked by heightened environmental awareness, the landscape of metallic coatings is undergoing a profound shift – one that embraces sustainability while fortifying corrosion resistance [85]. This transformative wave has ushered in the era of environmentally friendly and sustainable metallic coatings, where protection is fused with a commitment to our planet's well-being. Traditional metallic coatings, often laden with hazardous components like hexavalent chromium, have raised ecological concerns. However, in this new chapter, a harmonious balance is struck between the imperatives of corrosion defense and environmental preservation [85]. This transition represents a convergence of the pragmatic and the conscientious. Consider the embodiment of nature-inspired solutions within alloys. Here, environmentally friendly alloy systems such as zinc-aluminum alloys emerge as prime examples of efficacy intertwined with ecological responsibility. These alloys veer away from environmentally harmful elements, opting instead for a harmony where the strength of corrosion protection harmonizes with eco-consciousness. This is a narrative where the vitality of safeguarding resonates in tandem with sustainable ethos [86]. However, this transition extends beyond the composition of alloys – it permeates every phase of the coating's lifecycle. The forefront of this paradigm shift is adorned by eco-friendly surface treatments and post-coating procedures, culminating in a symphony of environmentally mindful practices. Innovations such as water-based coatings and sol-gel applications offer a symposium where metallic coatings perform their protective duty with minimal ecological repercussions. The result is a choreographed interplay, where protection aligns with a broader conscientious narrative. But the crux of this narrative finds its true articulation in real-world applications. It manifests in environments where endurance converges with responsibility, where environmentally friendly alloys emerge as guardians of sustainability. These alloys narrate stories of structures in maritime settings, defying the ravages of corrosive salt with the tenacity of materials that resonate with both protection and environmental stewardship. It's a chronicle of bridges, defying the grasp of decay, upheld by alloys that shield not only steel but also our planet's integrity.

Examples of environmentally friendly alloy systems:

1. **Zinc-Aluminum Alloys:** These alloys find their stride in coastal environments, where the corrosive impact of saltwater necessitates both protection and environmental consideration. Their resilience not only shields the metal but also curbs the ecological impact often associated with traditional coatings containing hazardous elements [87].
2. **Copper-Nickel Alloys:** In marine settings, where ships and offshore structures confront the relentless assault of seawater, copper-nickel alloys emerge as guardians of sustainability. These alloys deliver lasting protection while minimizing adverse effects on aquatic ecosystems [88].
3. **Magnesium-Aluminum Alloys:** These alloys, widely utilized in aerospace applications, epitomize a balance between lightweight properties and environmental conscientiousness. Their corrosion resistance safeguards both the integrity of the structure and the well-being of the planet [19].
4. **Cobalt-Chromium Alloys:** In the healthcare sector, where implantable medical devices require both durability and biocompatibility, cobalt-chromium alloys shine. Their capacity to endure while minimizing potential adverse impacts on the human body showcases the duality of protection and health [90].

6.3. Surface engineering techniques to enhance the performance of metallic coatings

Surface engineering techniques have been employed to enhance the performance of metallic coatings. These techniques aim to modify the surface properties and structure of the coating, thereby improving its corrosion resistance and functional characteristics. Surface engineering techniques include surface texturing, surface roughening, surface alloying, and surface modification through techniques like plasma treatment or ion implantation [91]. Surface texturing and roughening can increase the effective surface area and promote the formation of protective oxide layers, thus enhancing corrosion resistance [92]. Surface alloying involves the introduction of alloying elements into the coating surface through techniques such as laser surface alloying or diffusion treatments, resulting in improved corrosion resistance. Surface modification techniques, such as plasma treatment or ion implantation, can modify the surface composition and structure of the coating, leading to enhanced adhesion, hardness, and barrier properties. By employing surface engineering techniques, metallic coatings can be optimized to provide superior corrosion protection and tailored functionality for specific applications [93]. Furthermore, the integration of advanced surface characterization and monitoring techniques has enabled real-time evaluation and control of the performance of metallic coatings. Techniques such as electrochemical impedance spectroscopy (EIS), scanning electron microscopy (SEM), atomic force microscopy (AFM), and X-ray photoelectron spectroscopy (XPS) allow for in-depth analysis of coating properties, corrosion behavior, and degradation mechanisms. These characterization techniques provide valuable insights into the coating's performance, enabling researchers to optimize coating designs, assess corrosion resistance, and develop predictive models for coating behavior [94–96]. Real-time monitoring techniques, such as corrosion sensors or online corrosion monitoring systems, enable continuous monitoring of the coating's condition and performance, facilitating proactive maintenance and ensuring long-term corrosion protection [97, 98]. Figure 4, presents different surface modification techniques employed to enhance the corrosion resistance of inorganic coatings. It includes plasma treatment, chemical etching, or deposition of protective layers, and highlights how these techniques modify the surface properties to create a more corrosion-resistant coating surface.

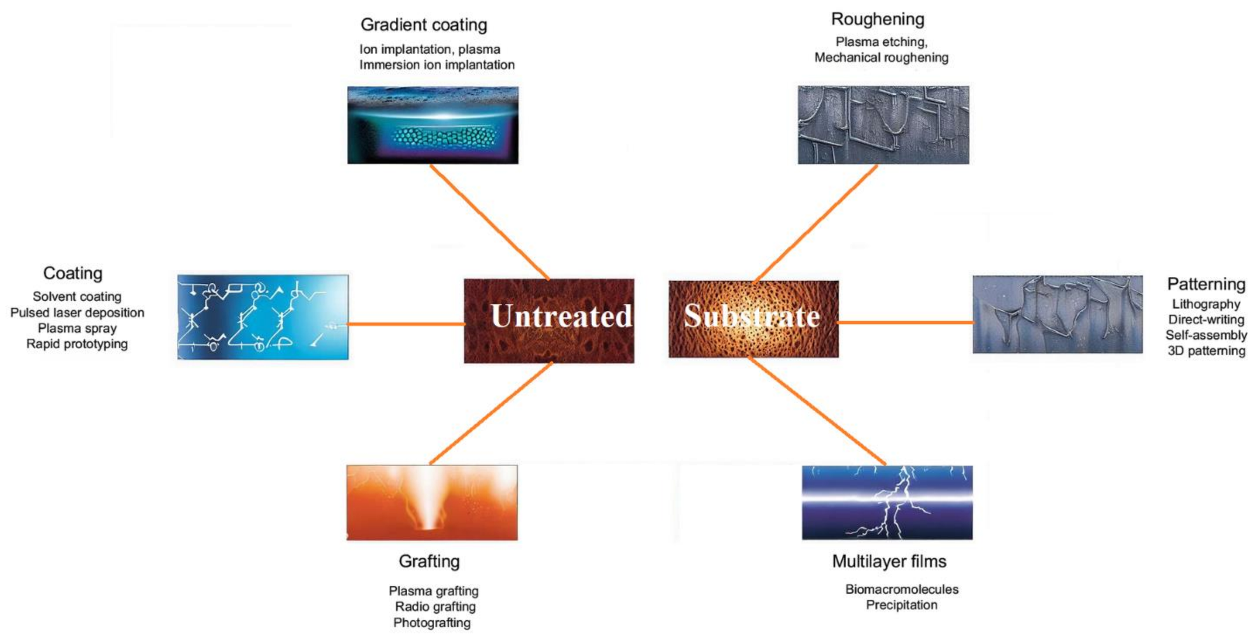

Figure 4. Surface modification techniques for enhanced corrosion.

In summary, emerging trends in metallic coatings have focused on advances in alloy design for corrosion resistance, the development of environmentally friendly and sustainable coatings, and the application of surface engineering techniques. These trends offer exciting Resistance possibilities for the development of high-performance metallic coatings with enhanced corrosion resistance and tailored functionality. The integration of advanced surface characterization and monitoring techniques further enables the evaluation and control of coating performance in real-time. By embracing these emerging trends, industries can benefit from durable, environmentally friendly, and corrosion-resistant metallic coatings for a wide range of applications.

7. Performance Evaluation and Testing of Corrosion Protection Coatings

The evaluation and testing of corrosion protection coatings are essential steps in ensuring their effectiveness and reliability in real-world applications [99]. Various testing methods have been developed to assess the performance of these coatings, ranging from standard laboratory tests to accelerated corrosion testing techniques [100]. Additionally, evaluating the long-term durability and reliability of coatings is crucial to understand their performance over extended periods. This section provides an overview of common testing methods for assessing coating performance, recent advancements in accelerated corrosion testing techniques, and the evaluation of long-term durability and reliability of corrosion protection coatings [101–103]. Table 5, summarizes common evaluation methods for assessing the performance of corrosion protection coatings. Salt spray testing serves as an accelerated corrosion test, providing insights into the coating's resistance to corrosive environments. Electrochemical techniques offer valuable information about the coating's corrosion resistance and its electrochemical behavior. Accelerated weathering tests simulate real-world environmental conditions to assess the durability and resistance to degradation of coatings, providing a comprehensive evaluation of their performance.

Table 5. Performance evaluation methods for corrosion protection coatings.

Evaluation method	Description
Salt spray test	Is a widely used accelerated corrosion test that assesses the coating's resistance to corrosive environments.
Electrochemical techniques	Electrochemical methods, such as corrosion potential measurement and electrochemical impedance spectroscopy (EIS), provide valuable information about the coating's performance and corrosion resistance.
Accelerated weathering	Tests simulate environmental conditions, such as exposure to UV radiation and moisture, to evaluate the coating's durability and resistance to degradation.

7.1. Overview of common testing methods for assessing coating performance

Common testing methods are employed to assess the performance of corrosion protection coatings. These methods evaluate key properties such as adhesion, corrosion resistance, mechanical strength, and barrier properties. One commonly used test is the salt spray test, which subjects coated specimens to a highly corrosive salt fog environment to assess their resistance to corrosion. Another widely employed test is the electrochemical impedance spectroscopy (EIS), which measures the impedance response of the coating to electrochemical signals, providing valuable insights into the coating's barrier properties and corrosion resistance [104–108]. Adhesion tests, such as pull-off tests or cross-cut tests, evaluate the bonding strength between the coating and the substrate. Mechanical tests, including hardness tests and abrasion resistance tests, assess the coating's mechanical properties and its ability to withstand external stresses. Additionally, techniques like scanning electron microscopy (SEM) and X-ray diffraction (XRD) are used for microstructural analysis and phase identification of coatings, aiding in understanding the coating's composition and structure [109].

7.2. Recent advancements in accelerated corrosion testing techniques

Recent advancements in accelerated corrosion testing techniques have aimed to simulate real-world corrosion conditions within shorter time frames. These techniques are designed to accelerate the corrosion process, allowing for rapid evaluation of coating performance. One such method is cyclic corrosion testing, which combines alternating wet and dry environments, temperature cycling, and exposure to corrosive agents to replicate the cyclic nature of corrosion in a condensed time frame [110]. This test provides insights into the coating's resistance to various environmental factors and accelerated corrosion mechanisms. Another approach is accelerated weathering testing, which exposes coatings to a combination of UV radiation, temperature fluctuations, and moisture to simulate the effects of long-term outdoor exposure. These accelerated testing techniques enable a faster assessment of coating performance, facilitating the development and optimization of corrosion protection coatings [111].

7.3. Evaluation of long-term durability and reliability of coatings

Evaluation of the long-term durability and reliability of corrosion protection coatings is crucial for assessing their performance over extended periods. Long-term exposure testing involves subjecting coated specimens to real-world environments for an extended duration, typically ranging from several months to years. This testing provides valuable data on the coating's performance, including its resistance to corrosion, UV degradation, chemical exposure, and mechanical stresses [112]. Long-term exposure testing allows for the evaluation of the coating's durability under real-world conditions, considering factors such as temperature variations, humidity, pollutant exposure, and atmospheric corrosivity. Field exposure sites or outdoor exposure racks are commonly used for long-term exposure testing, enabling researchers to monitor and analyze the coating's performance over time. This evaluation helps to validate the coating's long-term reliability and assess its ability to provide sustained corrosion protection in the intended application environment [113]. In addition to standardized testing methods, the development of advanced techniques such as computational modeling and machine learning has contributed to the evaluation of coating performance. Computational modeling allows for the simulation and prediction of coating behavior under different environmental conditions, aiding in the optimization of coating designs and the assessment of their long-term performance [114]. Machine learning techniques can analyze large datasets obtained from testing and monitoring, enabling the identification of correlations between coating properties, environmental factors, and corrosion performance. These advanced techniques offer valuable insights into coating performance and facilitate data-driven decision-making in the development and selection of corrosion protection coatings [115]. In summary, performance evaluation and testing of corrosion protection coatings are critical for ensuring their effectiveness and reliability. Common testing methods assess properties such as adhesion, corrosion resistance, mechanical strength, and barrier properties. Recent advancements in accelerated corrosion testing techniques enable faster evaluation of coating performance, while long-term exposure testing provides insights into durability and reliability over extended periods. The integration of advanced techniques such as computational modeling and machine learning further enhances the evaluation of coating performance. By employing a comprehensive evaluation and testing approach, industries can select and optimize corrosion protection coatings that meet their specific requirements and provide long-lasting protection against corrosion.

8. Applications of Corrosion Protection Coatings

Corrosion protection coatings play a crucial role in safeguarding various industries against the detrimental effects of corrosion. From traditional sectors like oil and gas, automotive, and infrastructure to emerging sectors such as renewable energy and aerospace, these coatings find widespread applications [116]. This section explores the successful application of corrosion protection coatings in different industries through case studies and examines the challenges and opportunities for their implementation in emerging sectors.

8.1. Case studies highlighting successful applications of coatings in different industries (e.g., oil and gas, automotive, infrastructure)

Case studies highlighting successful applications of corrosion protection coatings in different industries demonstrate their effectiveness and value. In the oil and gas industry, where harsh environments and corrosive substances pose significant challenges, coatings provide essential protection for pipelines, storage tanks, and offshore structures [117]. For instance, fusion-bonded epoxy (FBE) coatings have been successfully used to prevent corrosion in oil and gas pipelines, ensuring the integrity and longevity of the infrastructure. In the automotive industry, coatings protect vehicles from corrosion caused by exposure to moisture, road salts, and chemicals. Cathodic electrocoats (e-coats) and powder coatings are commonly applied to automotive components, providing superior corrosion resistance, durability, and an attractive finish [118]. These coatings contribute to the longevity and aesthetic appeal of vehicles. In the infrastructure sector, corrosion protection coatings are crucial for bridges, buildings, and other structures exposed to harsh weather conditions and environmental pollutants. Zinc-rich coatings, epoxy coatings, and polyurethane coatings are commonly used to prevent corrosion and extend the service life of infrastructure assets [119].

8.2. Challenges and opportunities for coating applications in emerging sectors (e.g., renewable energy, aerospace)

The successful application of corrosion protection coatings extends beyond traditional industries, with emerging sectors offering new opportunities and challenges. The renewable energy sector, including wind and solar energy, presents unique coating requirements due to exposure to aggressive environments and weather conditions [120]. Offshore wind turbines, for example, face challenges such as saltwater corrosion and erosion caused by wind and waves. Advanced coatings designed specifically for offshore wind turbine applications provide durable corrosion protection and reduce maintenance needs. In the solar energy sector, coatings are applied to solar panels and support structures to protect against moisture, UV radiation, and corrosive gases. Coating technologies that offer enhanced adhesion, weather resistance, and self-cleaning properties are sought after to optimize solar panel efficiency and longevity [121]. The aerospace industry also offers promising opportunities for the application of corrosion protection coatings. Aircraft structures are exposed to extreme conditions, including temperature variations, high humidity, and corrosive chemicals. Corrosion control is essential to maintain the structural integrity and safety of aircraft [122]. Aluminum alloys, commonly used in aerospace applications, are particularly susceptible to corrosion. Advanced coatings, such as chromate-free primers and polyurethane topcoats, provide effective corrosion protection for aircraft components. Additionally, thermal barrier coatings are applied to turbine components in jet engines to protect against high-temperature corrosion. The aerospace industry continuously seeks innovative coating solutions that provide excellent corrosion resistance, lightweight properties, and compliance with strict regulatory requirements [123]. While there are numerous successful applications of corrosion protection coatings, challenges and opportunities arise in emerging sectors. One major challenge is the development of coatings that are compatible with new materials and technologies. For example, as renewable energy systems evolve, coatings must be compatible with novel materials used in wind turbine blades or advanced solar cell technologies [124]. Adapting coating formulations to adhere to these materials and withstand their unique operational conditions is a significant challenge. Moreover, emerging sectors often require coatings that meet stringent environmental and sustainability standards. There is a growing emphasis on developing eco-friendly coatings with low volatile organic compound (VOC) emissions and reduced environmental impact throughout their life cycle [125].

Another challenge is the need for coatings that can withstand extreme operating conditions. For instance, in the aerospace sector, coatings must provide corrosion protection while withstanding high temperatures, high-speed airflow, and mechanical stresses. The development of coatings that offer exceptional durability, resistance to erosion, and thermal stability is crucial in these demanding applications. Furthermore, emerging sectors often require coatings with advanced functionalities, such as self-healing capabilities or multi-functional coatings that provide corrosion protection along with other desirable properties like anti-fouling or anti-icing [126]. Opportunities for coating applications in emerging sectors lie in the continuous development of innovative coating technologies tailored to specific industry requirements. Research and development efforts are focused on exploring new materials, nanostructured coatings, and advanced deposition techniques to enhance corrosion resistance and performance. For instance, the integration of nanotechnology allows for the development of coatings with superior properties, such as improved barrier performance, self-healing capabilities, and enhanced adhesion. Furthermore, advancements in coating characterization techniques and accelerated testing methods enable a better understanding of coating performance and facilitate faster development cycles [127].

In conclusion, corrosion protection coatings find diverse and successful applications in industries such as oil and gas, automotive, and infrastructure. The challenges and opportunities in emerging sectors, including renewable energy and aerospace, drive the need for specialized coatings that withstand extreme conditions, adhere to new materials, and meet stringent environmental requirements. By addressing these challenges and leveraging opportunities, coating technologies can continue to evolve, providing reliable and sustainable corrosion protection solutions for a wide range of industries.

9. Future Directions and Challenges

The field of corrosion protection coatings continues to evolve, driven by the ongoing need for effective and sustainable solutions. This section explores the promising avenues for further research and development in corrosion protection coatings, the importance of environmental and sustainability considerations in coating design and selection, and the integration of advanced materials and coating technologies for multifunctional corrosion protection.

9.1. Promising avenues for further research and development in corrosion protection coatings

Promising avenues for further research and development in corrosion protection coatings lie in the exploration of advanced materials, novel formulations, and innovative coating technologies. One area of focus is the development of coatings with enhanced corrosion resistance and durability. Researchers are actively investigating the use of nanomaterials, such as nanoparticles and nanocomposites, to improve the barrier properties and mechanical strength of coatings. These advanced materials offer the potential for enhanced corrosion resistance, reduced coating thickness, and improved performance in harsh environments [128]. Additionally, the incorporation of self-healing mechanisms, such as encapsulated corrosion inhibitors or microcapsules containing healing agents, is a promising avenue to mitigate coating damage and extend their service life [129]. Furthermore, the exploration of bio-inspired coatings presents an exciting opportunity for future development. Nature provides numerous examples of effective protection against corrosion, such as the self-healing properties of certain plants and organisms. Researchers are studying natural systems to develop coatings that mimic these protective mechanisms, such as coatings with biomimetic microstructures or functional molecules that respond to environmental stimuli [130]. Bio-inspired coatings have the potential to offer self-repairing capabilities, anti-fouling properties, and enhanced resistance to environmental factors [131].

9.2. Environmental and sustainability considerations in coating design and selection

Another area of research is the development of environmentally friendly and sustainable corrosion protection coatings. As industries strive to minimize their environmental footprint, coating design and selection should consider factors such as the use of non-toxic materials, reduction of volatile organic compounds (VOCs), and the overall life cycle impact of coatings [132]. Environmentally friendly coatings, such as waterborne coatings or those based on bio-based materials, are gaining traction due to their reduced environmental impact. The development of sustainable coating systems that combine effective corrosion protection with eco-friendly attributes is a critical aspect of future research in this field [133]. In addition to environmental considerations, the integration of advanced materials and coating technologies enables the development of multifunctional corrosion protection coatings. The concept of multifunctionality aims to combine corrosion resistance with other desired properties, such as anti-fouling, anti-icing, or self-cleaning capabilities. For example, the incorporation of photocatalytic materials in coatings allows for self-cleaning properties by breaking down organic contaminants when exposed to light. Similarly, the integration of anti-fouling agents or surface modifications can prevent the attachment of biofilms, marine organisms, or ice formation on coated surfaces. Multifunctional coatings have the potential to enhance performance, reduce maintenance needs, and improve the overall efficiency of coated systems [134–136].

9.3. Integration of advanced materials and coating technologies for multifunctional corrosion protection

However, several challenges need to be addressed in the pursuit of future advancements in corrosion protection coatings. One of the primary challenges is the translation of laboratory-scale research into practical, scalable, and cost-effective coating solutions. While promising results are often achieved in controlled laboratory environments, scaling up the production and implementation of these coatings can present technical and economic hurdles [137]. Bridging the gap between research and industrial application requires close collaboration between academia, industry, and regulatory bodies to ensure the successful transition of innovative coating technologies into commercial products [138]. Another challenge is the need for comprehensive standardization and quality control in coating manufacturing and application processes. Establishing standardized testing protocols and quality assurance measures ensures consistent coating performance and reliable protection against corrosion. Furthermore, the development of predictive models and computational tools can aid in the optimization of coating designs, allowing for faster and more accurate assessment of coating performance under different environmental conditions [139]. The challenges of sustainability and environmental impact should also be addressed in the development and selection of corrosion protection coatings. The coatings industry must strive to minimize the use of hazardous substances, reduce energy consumption in manufacturing processes, and promote the recyclability or biodegradability of coating materials. Collaboration among stakeholders, including coating manufacturers, researchers, regulatory agencies, and end-users, is essential to drive the adoption of sustainable coating practices and develop standardized frameworks for assessing the environmental impact of coatings [140].

In conclusion, future directions in corrosion protection coatings encompass the exploration of advanced materials, bio-inspired coatings, and multifunctional coating technologies. Research and development efforts should prioritize the enhancement of corrosion resistance, durability, and sustainability of coatings. Addressing challenges such as scalability, standardization, and environmental considerations will facilitate the successful implementation of innovative coating solutions across various industries. By embracing these future directions and overcoming challenges, corrosion protection coatings can continue to evolve, providing reliable, sustainable, and efficient solutions for the mitigation of corrosion-related issues.

9.4. Future Directions for Organic Corrosion Inhibitors

Organic corrosion inhibitors have played a pivotal role in safeguarding metallic structures from corrosion [141–189]. However, as industries evolve and environmental considerations become more prominent, there is a need for innovative approaches and continued research to enhance the effectiveness and sustainability of organic corrosion inhibitors. The future of organic corrosion inhibitors lies in the development of environmentally friendly and sustainable alternatives. Research should focus on the design and synthesis of inhibitors that are derived from renewable resources, biodegradable, and have minimal ecological impact. This includes exploring the potential of bio-based inhibitors, plant extracts, and naturally occurring compounds with corrosion inhibiting properties. Moreover, the utilization of green chemistry principles to synthesize inhibitors with reduced toxicity and improved biocompatibility should be a priority. Future research should aim to create multifunctional organic corrosion inhibitors. These inhibitors could not only prevent corrosion but also offer additional functionalities such as self-healing properties, antimicrobial effects, or the ability to enhance coating adhesion. By incorporating multiple functions into a single inhibitor molecule, it is possible to develop inhibitors that provide comprehensive protection against various threats, reducing the need for multiple chemical treatments and coatings. The integration of computational methods, such as molecular modeling and simulation, can expedite the discovery and optimization of organic corrosion inhibitors. By using computational tools, researchers can screen a vast range of inhibitor candidates, predict their inhibitory performance, and understand the underlying molecular mechanisms. This approach can significantly reduce the time and resources required for inhibitor development, enabling the design of more effective and tailored inhibitors.

10. Conclusion

In this comprehensive review, we have examined various aspects of corrosion protection coatings, including their fundamentals, recent advances, applications, performance evaluation, and future directions. The key findings and advancements discussed in this review highlight the progress made in the field of corrosion protection coatings and the significance of ongoing research in addressing the challenges posed by corrosion. We began by establishing the definition of corrosion and its economic and environmental impact. Corrosion poses a significant threat to industries, leading to extensive financial losses, safety risks, and environmental degradation. The importance of corrosion protection coatings in mitigating these issues cannot be overstated. These coatings serve as a barrier between the corrosive environment and the substrate, offering protection through mechanisms such as the barrier effect and sacrificial protection. Throughout the review, we explored different types of corrosion protection coatings, including organic, inorganic, metallic, and ceramic coatings. The advances in organic coatings have been remarkable, with the development of novel formulations, self-healing coatings, and the application of nanotechnology to improve their performance. Similarly, inorganic and ceramic coatings have witnessed recent developments, with a focus on ceramic coatings for high-temperature environments and surface modification techniques to enhance corrosion resistance. The integration of organic and inorganic components in hybrid coatings has shown promise in providing synergistic corrosion protection.

We also delved into the advancements in metallic coatings, highlighting the importance of alloy design for corrosion resistance. The development of environmentally friendly metallic coatings has gained significant attention, aligning with the global shift towards sustainable practices. Surface engineering techniques have been instrumental in enhancing the performance of metallic coatings by improving adhesion, wear resistance, and corrosion resistance. Performance evaluation and testing play a critical role in assessing the effectiveness of corrosion protection coatings. We discussed common testing methods, including accelerated corrosion testing, which enables faster evaluation of coating performance. Long-term exposure testing provides valuable insights into the durability and reliability of coatings over extended periods. The integration of advanced techniques such as computational modeling and machine learning offers new avenues for comprehensive evaluation and prediction of coating performance. The review also examined the applications of corrosion protection coatings in various industries. Through case studies, we showcased their successful implementation in sectors such as oil and gas, automotive, infrastructure, renewable energy, and aerospace. Coatings have proven their efficacy in protecting critical infrastructure, enhancing the lifespan of automotive components, and ensuring the reliable operation of renewable energy systems and aircraft structures. However, emerging sectors present unique challenges and opportunities, requiring specialized coatings compatible with new materials and technologies, while also meeting stringent environmental and sustainability standards. Looking ahead, the future of corrosion protection coatings lies in promising avenues for research and development. The exploration of advanced materials, such as nanomaterials and bio-inspired coatings, holds tremendous potential for enhancing corrosion resistance and durability. Environmental and sustainability considerations will continue to shape coating design and selection, necessitating the development of eco-friendly coating solutions. The integration of advanced materials and coating technologies for multifunctional corrosion protection opens doors to coatings that not only prevent corrosion but also offer additional functionalities, such as self-cleaning, anti-fouling, or anti-icing properties.

In conclusion, ongoing research in corrosion protection coatings is of paramount importance. The key findings and advancements discussed in this review demonstrate the progress made in understanding and addressing corrosion-related challenges. However, there is still much to explore and develop to meet the evolving needs of industries and the growing demand for sustainable solutions. Continued research efforts, collaboration among stakeholders, and the integration of innovative technologies will pave the way for the advancement of corrosion protection coatings, ensuring the long-term integrity, safety, and sustainability of various industrial sectors.

References

1. B. El Ibrahimi, J.V. Nardeli and L. Guo, An Overview of Corrosion, Sustainable Corrosion Inhibitors I: Fundamentals, Methodologies, and Industrial Applications, *ACS Sym. Ser*., 2021, **1403**, 1–19. doi: 10.1021/bk-2021-1403.ch001
2. J.R. Davis, The effects and economic impact of corrosion, in *Corrosion: Understanding the basics*, Netherlands: ASM International, 2000, pp. 62–66.
3. K. Tamalmani and H. Husin, Review on Corrosion Inhibitors for Oil and Gas Corrosion Issues, *Appl. Sci*., 2020, **10**, no. 10, 3389. doi: 10.3390/app10103389
4. A.H.A. Nasser, P.D. Ndalila, E.A. Mawugbe, M.E. Kouame, M.A. Paterne, Y. Li, Mitigation of Risks Associated with Gas Pipeline Failure by Using Quantitative Risk Management Approach: A Descriptive Study on Gas Industry, *J. Mar. Sci. Eng*., 2021, **9**, no. 10, 1098. doi: 10.3390/jmse9101098
5. M.F. Montemor, Functional and smart coatings for corrosion protection: A review of recent advances, *Surf. Coat. Technol*., 2014, **258**, 17–37. doi: 10.1016/j.surfcoat.2014.06.031
6. H. Tamura, The role of rusts in corrosion and corrosion protection of iron and steel, *Corros. Sci*., 2008, **50**, no. 7, 1872–1883. doi: 10.1016/j.corsci.2008.03.008
7. A.H. Al-Moubaraki and I.B. Obot, Corrosion challenges in petroleum refinery operations: Sources, mechanisms, mitigation, and future outlook, *J. Saudi Chem. Soc*., 2021, **25**, no. 12, 101370. doi: j.jscs.2021.101370
8. A.M. Motlatle, S.S. Ray, V. Ojijo and M.R. Scriba, Polyester-Based Coatings for Corrosion Protection, *Polymers*, 2022, **14**, no. 16, 3413. doi: 10.3390/polym14163413
9. C. Blawert, N. Hort and K.U. Kainer, Automotive applications of magnesium and its alloys, *Trans. Indian Inst. Met*., 2004, **57**, no. 4, 397–408.

10. G. Lazorenko, A. Kasprzhitskii and T. Nazdracheva, Anti-corrosion coatings for protection of steel railway structures exposed to atmospheric environments: A review, *Constr. Build. Mater.*, 2021, **288**, 123115. doi: 10.1016/j.conbuildmat.2021.123115
11. R.K. Dhall, Advances in edible coatings for fresh fruits and vegetables: A review, *Crit. Rev. Food Sci. Nutr.*, 2013, **53**, no. 5, 435–450. doi: 10.1080/10408398.2010.541568
12. Z. Tian, H. Yu, L. Wang, M. Saleem, F. Ren, P. Ren, Y. Chen, R. Sun, Y. Sun and L. Huang, Recent progress in the preparation of polyaniline nanostructures and their applications in anticorrosive coatings, *RSC Adv.*, 2014, **4**, no. 54, 28195–28208. doi: 10.1039/C4RA03146F
13. I.S. Cole and D. Marney, The science of pipe corrosion: A review of the literature on the corrosion of ferrous metals in soils, *Corros. Sci.*, 2012, **56**, 5–16. doi: 10.1016/j.corsci.2011.12.001
14. M. Yasir, F. Ahmad, P.S.M.M. Yusoff, S. Ullah and M. Jimenez, Latest trends for structural steel protection by using intumescent fire protective coatings: a review, *Surf. Eng.*, 2020, **36**, no. 4, 334–363. doi: 10.1080/02670844.2019.1636536
15. CAP1570: Corrosion and Inspection of General Aviation Aircraft, *Civil Aviation Authority*, 2017.
16. P. Pecho, P. Veľký, M. Bugaj and D. Kajánek, Assessment of Aircraft Coating Resistance to Lighting Strikes and Long-Term Environmental Impact, *Aerospace*, 2023, **10**, no. 3, 269. doi: 10.3390/aerospace10030269
17. L.M. Muresan, Nanocomposite Coatings for Anti-Corrosion Properties of Metallic Substrates, *Materials*, 2023, **16**, no. 14, 5092. doi: 10.3390/ma16145092
18. B. Saleh, R. Fathi, H. Shi and H. Wei, Advanced Corrosion Protection through Coatings and Surface Rebuilding, *Coatings*, 2023, **13**, no. 1, 180. doi: 10.3390/coatings13010180
19. F.N. Jones, M.E. Nichols and S.P. Pappas, *Organic coatings: science and technology*, 2017, John Wiley & Sons, 2017.
20. P.S. Sidky and M.G. Hocking, Review of inorganic coatings and coating processes for reducing wear and corrosion, *Br. Corros. J.*, 1999, **34**, no. 3, 171–183. doi: 10.1179/000705999101500815
21. M. Benmalek and H.M. Dunlop, Inorganic coatings on polymers, *Surf. Coat. Technol.*, 1995, **76–77**, 821–826. doi: 10.1016/0257-8972(95)02601-0
22. T. Varadavenkatesan, R. Vinayagam, Sh. Pai, K. Brindhadevi, A. Pugazhendhi and R. Selvaraj, Synthesis, biological and environmental applications of hydroxyapatite and its composites with organic and inorganic coatings, *Prog. Org. Coat.*, 2021, **151**, 106056. doi: 10.1016/j.porgcoat.2020.106056
23. F. Presuel-Moreno, M.A. Jakab, N. Tailleart, M. Goldman and J.R. Scully, Corrosion-resistant metallic coatings, *Mater. Today*, 2008, **11**, no. 10, 14–23. doi: 10.1016/S1369-7021(08)70203-7
24. W. Giurlani, E. Berretti, M. Innocenti and A. Lavacchi, Measuring the thickness of metal coatings: A review of the methods, *Coatings*, 2020, **10**, no. 12, 1211. doi: 10.3390/coatings10121211

25. Y.I. Kuznetsov and G.V. Redkina, Thin Protective Coatings on Metals Formed by Organic Corrosion Inhibitors in Neutral Media, *Coatings*, 2022, **12**, no. 2, 149. doi: 10.3390/coatings12020149
26. M.A. Malik, M.A. Hashim, F. Nabi, Sh.A. Al-Thabaiti and Z. Khan, Anti-corrosion ability of surfactants: A review, *Int. J. Electrochem. Sci*., 2011, **6**, no. 6, 1927–1948.
27. W.F. Langelier, The analytical control of anti-corrosion water treatment, *J. – Am. Water Works Assoc*., 1936, **28**, no. 10, 1500–1521.
28. J.B. Wachtman and A.H. Richard, *Ceramic films and coatings*, 1993, Noyes Publications: Park Ridge, NJ.
29. A. Stankiewicz, I. Szczygieł and B. Szczygieł, Self-healing coatings in anti-corrosion applications, *J. Mater. Sci*., 2013, **48**, 8041–8051.
30. K. Li, Z. Liu, C. Wang, W. Fan, F. Liu, H. Li, Y. Zhu and H. Wang, Preparation of smart coatings with self-healing and anti-wear properties by embedding PU-fly ash absorbing linseed oil microcapsules, *Prog. Org. Coat*., 2020, **145**, 105668. doi: 10.1016/j.porgcoat.2020.105668
31. S. Kumar, S. Bashir, K. Ramesh and S. Ramesh, New perspectives on Graphene/Graphene oxide based polymer nanocomposites for corrosion applications: The relevance of the Graphene/Polymer barrier coatings, *Prog. Org. Coat*., 2021, **154**, no. 1, 106215. doi: 10.1016/j.porgcoat.2021.106215
32. S.S.A. Kumar, S. Bashir, K. Ramesh and S. Ramesh, A comprehensive review: Super hydrophobic graphene nanocomposite coatings for underwater and wet applications to enhance corrosion resistance, *FlatChem*, 2022, **31**, 100326. doi: 10.1016/j.flatc.2021.100326
33. N.H. Othman, M.C. Ismail, M. Mustapha, N. Sallih, K.E. Kee and R.A. Jaal, Graphene-based polymer nanocomposites as barrier coatings for corrosion protection, *Prog. Org. Coat*., 2019, **135**, 82–99. doi: 10.1016/j.porgcoat.2019.05.030
34. A.R. Heiba, F. Taher, R.M.A. Shahba and N.A.A. Ghany, Corrosion mitigation of carbon steel in acidic and salty solutions using electrophoretically deposited graphene coatings, *J. Coat. Technol. Res*., 2020, **18**, 501–510. doi: 10.1007/s11998-020-00419-z
35. M.Y. Zorainy, M. Sheashea, S. Kaliaguine, M. Gobara and D.C. Boffito, Facile solvothermal synthesis of a MIL-47 (V) metal–organic framework for a high-performance Epoxy/MOF coating with improved anticorrosion properties, *RSC Adv*., 2022, **12**, no. 15, 9008–9022. doi: 10.1039/D1RA08950A
36. S.V. Harb, A. Trentin, M.C. Uvida and P. Hammer, Advanced organic nanocomposite coatings for effective corrosion protection, in *Corros. Prot. Nanoscale*, 2020, pp. 315–343. doi: 10.1016/B978-0-12-819359-4.00017-9
37. G. Jena and J. Philip, A review on recent advances in graphene oxide-based composite coatings for anticorrosion applications, *Prog. Org. Coat*., 2022, **173**, 107208. doi: 10.1016/j.porgcoat.2022.107208

38. A.V. Radhamani, H.C. Lau and S. Ramakrishna, Nanocomposite coatings on steel for enhancing the corrosion resistance: A review, *J. Compos. Mater*., 2020, **54**, no. 5, 681–701. doi: 10.1177/0021998319857807
39. Y. Chang, X. Yan and Z. Wu, Application and prospect of self-healing microcapsules in surface coating of wood, *Colloid Interface Sci. Commun*., 2023, **56**, 100736. doi: 10.1016/j.colcom.2023.100736
40. A.M. Fadl, M.I. Abdou, M.A. Hamza and S.A. Sadeek, Corrosion-inhibiting, self-healing, mechanical-resistant, chemically and UV stable PDMAS/TiO_2 epoxy hybrid nanocomposite coating for steel petroleum tanker trucks, *Prog. in Org. Coat*., 2020, **146**, 105715.
41. U. Eduok, E. Ohaeri and J. Szpunar, Self-healing composite coatings with protective and anticorrosion potentials: classification by healing mechanism, *Self-Healing Compos. Mater*., 2019, Woodhead Publishing, pp. 123–162. doi: 10.1016/B978-0-12-817354-1.00008-9
42. C. Liu, H. Wu, Y. Qiang, H. Zhao and L. Wang, Design of smart protective coatings with autonomous self-healing and early corrosion reporting properties, *Corros. Sci*., 2021, **184**, 109355. doi: 10.1016/j.corsci.2021.109355
43. H. Wang, J. Xu, X. Du, Z. Du, X. Cheng and H. Wang, A self-healing polyurethane-based composite coating with high strength and anti-corrosion properties for metal protection, *Composites, Part B*, 2021, **225**, 109273. doi: 10.1016/j.compositesb.2021.109273
44. S. Elugoke, A.S. Adekunle, O.E. Fayemi, B.B. Mamba and E. Ebenso, Nanocomposites as Steel Corrosion Inhibitors – The Journey So Far, *Anticorrosive Nanomaterials*, 2022, pp. 207–267. doi: 10.1039/9781839166259-00207
45. M.H. Nazari, Y. Zhang, A. Mahmoodi, G. Xu, J. Yu, J. Wu and X. Shi, Nanocomposite organic coatings for corrosion protection of metals: A review of recent advances, *Prog. Org. Coat*., 2022, **162**, 106573. doi: 10.1016/j.porgcoat.2021.106573
46. M. Izadi, T. Shahrabi, I. Mohammadi, B. Ramezanzadeh and A. Fateh, The electrochemical behavior of nanocomposite organic coating based on clay nanotubes filled with green corrosion inhibitor through a vacuum-assisted procedure, *Composites: Part B*, 2019, **171**, 96–110. doi: 10.1016/j.compositesb.2019.04.019
47. M.J. Anjum, H. Ali, W.Q. Khan, J. Zhao and G. Yasin, Metal/metal oxide nanoparticles as corrosion inhibitors, *Corrosion Protection at the Nanoscale*, 2020, pp. 181–201. Elsevier. doi: 10.1016/B978-0-12-819359-4.00011-8
48. A.O. Ijaola, P.K. Farayibi and E. Asmatulu, Superhydrophobic coatings for steel pipeline protection in oil and gas industries: A comprehensive review, *J. Nat. Gas Sci. Eng*., 2020, **83**, 103544. doi: 10.1016/j.jngse.2020.103544
49. S. Chen, Z. Huang, M. Yuan, G. Huang, H. Guo, G. Meng, Z. Feng and P. Zhang, Trigger and response mechanisms for controlled release of corrosion inhibitors from micro/nanocontainers interpreted using endogenous and exogenous stimuli: A review, *J. Mater. Sci. Technol*., 2022, **125**, 67–80. doi: 10.1016/j.jmst.2022.02.037

50. G. Lazorenko, A. Kasprzhitskii and T. Nazdracheva, Anti-corrosion coatings for protection of steel railway structures exposed to atmospheric environments: A review, *Constr. Build. Mater.*, 2021, **288**, 123115. doi: 10.1016/j.conbuildmat.2021.123115
51. R.B. Heimann, Magnesium alloys for biomedical application: Advanced corrosion control through surface coating, *Surf. Coat. Technol.*, 2021, **405**, 126521. doi: 10.1016/j.surfcoat.2020.126521
52. B. Yin, C. Wu, D. Hou, S. Li, Z. Jin, M. Wang and X. Wang, Research and application progress of nano-modified coating in improving the durability of cement-based materials, *Prog. Org. Coat.*, 2021, **161**, 106529. doi: 10.1016/j.porgcoat.2021.106529
53. G. Lazorenko, A. Kasprzhitskii and T. Nazdracheva, Anti-corrosion coatings for protection of steel railway structures exposed to atmospheric environments: A review, *Constr. Build. Mater.*, 2021, **288**, 123115. doi: 10.1016/j.conbuildmat.2021.123115
54. R.S. Dongre, Reinforce Fabricated Nano-Composite Matrixes for Modernization of S and T in New Millennium, *Composite and nanocomposite materials-from knowledge to industrial applications*, Ed.: T.D. Ngo, 2020. doi: 10.5772/intechopen.91305
55. E. Bakan, D.E. Mack, G. Mauer, R. Vaßen, J. Lamon and N.P. Padture, High-temperature materials for power generation in gas turbines, *Advanced ceramics for energy conversion and storage*, Ed. O. Guillon, 202, pp. 3–62. doi: 10.1016/B978-0-08-102726-4.00001-6
56. A.A. Al-Amiery and W.K. Al-Azzawi, Organic Synthesized Inhibitors for Corrosion Protection of Carbon Steel: A Comprehensive Review, *J. Bio Tribo Corros.*, 2023, **9**, no. 4, 74. doi: 10.1007/s40735-023-00791-4
57. M.L. Grilli, D. Valerini, A.E. Slobozeanu, B.O. Postolnyi, S. Balos, A. Rizzo and R.R. Piticescu, Critical raw materials saving by protective coatings under extreme conditions: A review of last trends in alloys and coatings for aerospace engine applications, *Materials*, 2021, **14**, no. 7, 1656. doi: 10.3390/ma14071656
58. M. Sathish, N. Radhika and B. Saleh, A critical review on functionally graded coatings: Methods, properties, and challenges, *Composites, Part B*, 2021, **225**, 109278. doi: 10.1016/j.compositesb.2021.109278
59. U. Eduok, J. Szpunar and E. Ebenso, Synthesis and characterization of anticorrosion zirconia/acrylic nanocomposite resin coatings for steel, *Prog. Org. Coat.*, 2019, **137**, 105337. doi: 10.1016/j.porgcoat.2019.105337
60. M.R. Derakhshandeh, M.J. Eshraghi and M. Razavi, Recent developments in the new generation of hard coatings applied on cemented carbide cutting tools, *Int. J. Refract. Hard Met.*, 2023, **111**, 106077. doi: 10.1016/j.ijrmhm.2022.106077
61. Y.X. Wang and S. Zhang, Toward hard yet tough ceramic coatings, *Surf. Coat. Technol.*, 2014, **258**, 1–16. doi: 10.1016/j.surfcoat.2014.07.007
62. U.A. Samad, M.A. Alam, H.S. Abdo, A. Anis and S.M. Al-Zahrani, Synergistic Effect of Nanoparticles: Enhanced Mechanical and Corrosion Protection Properties of Epoxy Coatings Incorporated with SiO_2 and ZrO_2, *Polymers*, 2023, **15**, no. 14, 3100. doi: 10.3390/polym15143100

63. A.G. Karem, Synthesis, characterisation and anti-corrosion behaviour of NiO-CNTs-SnO_2 nanocomposites coatings on AISI 1020 steel, PhD Diss., 2021.
64. M.I. Bakshi and S. Ahmad, In-situ synthesis of synergistically active ceria doped polypyrrole oleo-polyesteramide hybrid nanocomposite coatings: Corrosion protection and flame retardancy behaviour, *Prog. Org. Coat.*, 2020, **147**, no. 1, 105778. doi: 10.1016/j.porgcoat.2020.105778
65. H. Wang, J. Xu, X. Du, H. Wang, X. Cheng and Z. Du, Stretchable and self-healing polyurethane coating with synergistic anticorrosion effect for the corrosion protection of stainless steels, *Prog. Org. Coat.*, 2022, **164**, 106672. doi: 10.1016/j.porgcoat.2021.106672
66. S.A. Hosseini, T. Shahrabi and B. Ramezanzadeh, Synergistic effect of Black cumin extract and zinc cations on the mild steel corrosion resistance improvement in NaCl solution; Surface and electrochemical explorations, *Colloids Surf., A*, 2022, **654**, 130153. doi: 10.1016/j.colsurfa.2022.130153
67. R. Samiee, B. Ramezanzadeh, M. Mahdavian and E. Alibakhshi, Assessment of the smart self-healing corrosion protection properties of a water-base hybrid organo-silane film combined with non-toxic organic/inorganic environmentally friendly corrosion inhibitors on mild steel, *J. Cleaner Prod.*, 2019, **220**, 340–356. doi: 10.1016/j.jclepro.2019.02.149
68. D. Lin, X. Wang, M. Zhang, S. Yuan, F. Xu, D. Bao and H. Wang, A robust and eco-friendly waterborne anti-corrosion composite coating with multiple synergistic corrosion protections, *Composites, Part B*, 2022, **232**, 109624. doi: 10.1016/j.compositesb.2022.109624
69. M. Yoshida, R. Langer, A. Lendlein and J. Lahann, From advanced biomedical coatings to multi-functionalized biomaterials, *J. Macromol. Sci., Polym. Rev.*, 2006, **46**, no. 4, 347–375. doi: 10.1080/15583720600945394
70. C. Qi, C.E. Weinell, K. Dam-Johansen and H. Wu, Assessment of Anticorrosion Performance of Zinc-Rich Epoxy Coatings Added with Zinc Fibers for Corrosion Protection of Steel, *ACS Omega*, 2023, **8**, no. 2, 1912–1922. doi: 10.1021/acsomega.2c03738
71. S.Z. Haeri, B. Ramezanzadeh and M. Ramezanzadeh, Recent progress on the metal-organic frameworks decorated graphene oxide (MOFs-GO) nano-building application for epoxy coating mechanical-thermal/flame-retardant and anti-corrosion features improvement, *Prog. Org. Coat.*, 2022, **163**, no. 2, 106645. doi: 10.1016/j.porgcoat.2021.106645
72. H. Li, D. Huang, K. Ren and J. Ji, Inorganic-polymer composite coatings for biomedical devices, *Smart Materials in Medicine*, 2021, **2**, 1–14. doi: 10.1016/j.smaim.2020.10.002
73. M. Zhang, H. Wang, T. Nie, J. Bai, F. Zhao and S. Ma, Enhancement of barrier and anti-corrosive performance of zinc-rich epoxy coatings using nano-silica/graphene oxide hybrid, *Corros. Rev.*, 2020, **38**, no. 6, 497–513. doi: 10.1515/corrrev-2020-0034

74. A. Wang, K. De Silva, M. Jones, P. Robinson, G. Larribe and W. Gao, Anticorrosive coating systems for marine propellers, *Prog. Org. Coat*., 2023, **183**, 107768. doi: 10.1016/j.porgcoat.2023.107768
75. R. Teijido, L. Ruiz-Rubio, A.G. Echaide, J.L. Vilas-Vilela, S. Lanceros-Mendez and Q. Zhang, State of the art and current trends on layered inorganic-polymer nanocomposite coatings for anticorrosion and multi-functional applications, *Prog. Org. Coat*., 2022, **163**, 106684. doi: 10.1016/j.porgcoat.2021.106684
76. E. González, R. Stuhr, J.M. Vega, E. García-Lecina, H.-J. Grande, J.R. Leiza and M. Paulis, Assessing the effect of CeO_2 nanoparticles as corrosion inhibitor in hybrid biobased waterborne acrylic direct to metal coating binders, *Polymers*, 2021, **13**, no 6, 848. doi: 10.3390/polym13060848
77. M. Ramezani, Z.M. Ripin, T. Pasang and C.-P. Jiang, Surface Engineering of Metals: Techniques, Characterizations and Applications, *Metals*, 2023, **13**, no. 7, 1299. doi: 10.3390/met13071299
78. M. Liang, Y. Yuan, X. Li, J. Cheng, X. Zhang, K. Zhang and R. You, Enhanced corrosion resistance of Mg and Mg alloys with fs-laser printed hydrophobic and periodically microrippled surface for armor application, *Appl. Surf. Sci*., 2023, **639**, 158156.
79. W. Yan, Y. Zhao, Y. Zhang, Q. Li, S. Chen, H. Yuan, Z. Zhang, L. Chen, J. Luo, P. Pang, G. He, M. Ying and B. Liao, Corrosion-resistant and interfacial conductive AlTiVCrMo high-entropy alloy and (AlTiVCrMo) Nx high-entropy ceramics coatings for surface modification of bipolar plates in proton exchange membrane fuel cells, *J. Power Sources*, 2022, **527**, 231217. doi: 10.1016/j.jpowsour.2022.231217
80. A. Raza, S. Abdulahad, B. Kang, H.J. Ryu and S.H. Hong, Corrosion resistance of weight reduced AlxCrFeMoV high entropy alloys, *Appl. Surf. Sci*., 2019, **485**, 368–374. doi: 10.1016/j.apsusc.2019.03.173
81. Y. Fu, J. Li, H. Luo, C. Du and X. Li, Recent advances on environmental corrosion behavior and mechanism of high-entropy alloys, *J. Mater. Sci. Technol*., 2021, **80**, 217–233. doi: 10.1016/j.jmst.2020.11.044
82. T. Tang, X. Xiao, K. Xu, M. Lou, X. Hu, S. Li, W. Zhang, Z. Fan and K. Chang, Corrosion-resistant WC-Co based cemented carbides: Computational design and experimental verification, *Int. J. Refract. Met. Hard Mater*., 2023, **110**, 106044. doi: 10.1016/j.ijrmhm.2022.106044
83. N. Siony, L. Vuong, O. Lundaajamts and S. Kadkhodaei, Computational design of corrosion-resistant and wear-resistant titanium alloys for orthopedic implants, *Mater. Today Commun*., 2022, **33**, no. 3, 104465. doi: 10.1016/j.mtcomm.2022.104465
84. A. Chaouiki, M. Chafiq, A.H. Al-Moubaraki, M. Bakhouch, M. El Yazidi and Y.G. Ko, Electrochemical behavior and interfacial bonding mechanism of new synthesized carbocyclic inhibitor for exceptional corrosion resistance of steel alloy: DFTB, MD and experimental approaches, *Arabian J. Chem*., 2022, **15**, no. 12, 104323. doi: 10.1016/j.arabjc.2022.104323

85. A.R. Khan, H.-J. Zhang, Z. Jun, S.M. Eldin, N.S. Alsaiari and K.M. Katubi, Electrochemical corrosion resistance of aluminum alloy 6101 with cerium-based coatings in an alkaline environment, *Frontiers in Chemistry*, 2022, **10**, 1066958. doi: 10.3389/fchem.2022.1066958
86. S.M. Gad, S. Emad, X. Zhou, S.B. Lyon, Z. Jin and I.M. Dagwa, Effectiveness of strontium zinc phosphosilicate on the corrosion protection of AA2198-T851 aluminium alloy in sodium chloride solution, *Corros. Sci.*, 2022, **209**, 110725. doi: 10.1016/j.corsci.2022.110725
87. Y.M. Panchenko, A.I. Marshakov, T.N. Igonin, T.A. Nenasheva, L.A. Nikolaeva and A.A. Ivanenko, Corrosion Resistance of Zinc and Zinc-Aluminum-Magnesium Coatings in Atmosphere on the Territory of Russia, *Materials*, 2023, **16**, no. 15, 5214. doi: 10.3390/ma16155214
88. V.M. Zezatti, A. Ochoa, G. Urquiza, M. Basurto, L. Castro and J. Garcia, The Implementation of a Nickel-Electroless Coating in Heat Exchanger Pipes Considering the Problem of the Environmental Conditions of the Cooling Water Without Recirculation to Increase the Effectiveness Under Uncertainty, *Int. J. Comb. Optim. Probl. Informatics*., 2022, **13**, no. 4, 73–82.
89. H. Ren, Automatic Corrosion Treatment of Magnesium-Aluminum Alloy under Eco-environmental Protection, *Ekoloji Dergisi*, 2019, no. 107, 2875–2885.
90. W.A. Uriciuc, A.B. Boşca, A.-M. Băbţan, H. Vermeşan, C. Cristea, M. Tertiş, P. Păşcuţă, G. Borodi, M. Suciu, L. Barbu-Tudoran, C.O. Popa and A. Ilea, Study on the Surface of Cobalt-Chromium Dental Alloys and Their Behavior in Oral Cavity as Cast Materials, *Materials*, 2022, **15**, no. 9, 3052. doi: 10.3390/ma15093052
91. S. Alareeqi, D. Bahamon, R.P. Nogueira and L.F. Vega, Understanding the relationship between the structural properties of three corrosion inhibitors and their surface protectiveness ability in different environments, *Appl. Surf. Sci.*, 2021, **542**, 148600. doi: 10.1016/j.apsusc.2020.148600
92. A. Ossowska, A. Zieliński and M. Supernak, Formation of high corrosion resistant nanotubular layers on titanium alloy Ti13Nb13Zr, *Solid State Phenom*., 2012, **183**, 137–142.
93. A. Thakur, A. Kumar, S. Kaya, R. Marzouki, F. Zhang and L. Guo, Recent advancements in surface modification, characterization and functionalization for enhancing the biocompatibility and corrosion resistance of biomedical implants, *Coatings*, 2022, **12**, no. 10, 1459. doi: 10.3390/coatings12101459
94. P. Bansal, G. Singh and H.S. Sidhu, Plasma-sprayed HA/Sr reinforced coating for improved corrosion resistance and surface properties of Ti13Nb13Zr titanium alloy for biomedical implants, *J. Mater. Res.*, 2021, **36**, 431–442. doi: 10.1557/s43578-020-00044-x

95. H. Liu, B. Fan, Z. Liu, X. Zhao, B. Yang, X. Zheng and H. Hao, Electronic effects on protective mechanism of electropolymerized coatings based on N-substituted aniline derivatives for mild steel in saline solution, *J. Ind. Eng. Chem.*, 2021, **106**, 297–310. doi: 10.1016/j.jiec.2021.11.004
96. R.S. Bhat, K. Venkatakrishna and A.C. Hegde, Surface structure and electrochemical behavior of zinc-nickel anti-corrosive coating, *Anal. Bioanal. Electrochem.*, 2023, **15**, no. 2, 90–101. doi: 10.22034/ABEC.2023.702328
97. C. Ibau, M.K. Md Arshad, S.C.B. Gopinath, M. Nuzaihan, M.F.M. Fathil and S.A. Shamsuddin, Immunosensing prostate-specific antigen: Faradaic vs non-Faradaic electrochemical impedance spectroscopy analysis on interdigitated microelectrode device, *Int. J. Biol. Macromol.*, 2020, **162**, 1924–1936. doi: 10.1016/j.ijbiomac.2020.08.125
98. A. Mohammed, A.Y.I. Rubaye, W.K. Al-Azzawi and A. Alamiery, Investigation of the Corrosion Inhibition Properties of 4-Cyclohexyl-3-Thiosemicarbazide on Mild Steel in 1 M HCl Solution, *Prog. Color Colorants Coat.*, 2023, **16**, 347–359. doi: 10.30509/PCCC.2023.167126.1212
99. L. Li, M. Chakik and R. Prakash, A review of corrosion in aircraft structures and graphene-based sensors for advanced corrosion monitoring, *Sensors*, 2021, **21**, no. 9, 2908. doi: 10.3390/s21092908
100. A. Trentin, A. Pakseresht, A. Duran, Y. Castro and D. Galusek, Electrochemical characterization of polymeric coatings for corrosion protection: a review of advances and perspectives, *Polymers*, 2022, **14**, no. 12, 2306. doi: 10.3390/polym14122306
101. A.S. Tomar, R. Gupta, A. Bijanu, D. Tanwar, A. Singh, S.T. Salammal, C. Dhand and D. Mishra, TiO_2-geopolymer based novel corrosion protective micro-coatings to emaciate mild steel oxidation in severe environments, *Constr. Build. Mater.*, 2023, **395**, 132252. doi: 10.1016/j.conbuildmat.2023.132252
102. T. Qureshi, G. Wang, S. Mukherjee, M.A. Islam, T. Filleter, C.V. Singh and D.K. Panesar, Graphene-based anti-corrosive coating on steel for reinforced concrete infrastructure applications: Challenges and potential, *Constr. Build. Mater.*, 2022, **351**, 128947. doi: 10.1016/j.conbuildmat.2022.128947
103. X. Huang, Y. Zhou, X. Zheng, F. Xing, L. Sui and B. Hu, Bond performance between corroded steel bars and concrete in cathodic protection system with CFRP as anode, *Compos. Struct.*, 2023, **309**, 116739. doi: 10.1016/j.compstruct.2023.116739
104. Y. Tian, G. Zhang, H. Ye, Q. Zeng, Z. Zhang, Z. Tian, X. Jin, N. Jin, Z. Chen and J. Wang, Corrosion of steel rebar in concrete induced by chloride ions under natural environments, *Constr. Build. Mater.*, 2023, **369**, 130504. doi: 10.1016/j.conbuildmat.2023.130504
105. S.K. Dhawan, H. Bhandari, G. Ruhi, B.M.S. Bisht and P. Sambyal, *Corrosion Preventive Materials and Corrosion Testing*, CRC Press, 2020. doi: 10.1201/9781315101217

106. S. Chen, X. Wang, G. Zhu, Z. Lu, Y. Zhang, X. Zhao and B. Hou, Developing multi-wall carbon nanotubes/Fusion-bonded epoxy powder nanocomposite coatings with superior anti-corrosion and mechanical properties, *Colloids Surf., A*, 2021, **628**, 127309. doi: 10.1016/j.colsurfa.2021.127309
107. M.M.K. Azar, H.S. Gugtapeh and M. Rezaei, Evaluation of corrosion protection performance of electroplated zinc and zinc-graphene oxide nanocomposite coatings in air saturated 3.5 wt.% NaCl solution, *Colloids Surf., A*, 2020, **601**, 125051. doi: 10.1016/j.colsurfa.2020.125051
108. D.R. Rooby, T.N. Kumar, M. Harilal, S. Sofia, R.P. George and J. Philip, Enhanced corrosion protection of reinforcement steel with nanomaterial incorporated fly ash based cementitious coating, *Constr. Build. Mater.*, 2021, **275**, 122130. doi: 10.1016/j.conbuildmat.2020.122130
109. S. Song, H. Yan, M. Cai, Y. Huang, X. Fan and M. Zhu, Constructing mechanochemical durable superhydrophobic composite coating towards superior anticorrosion, *Adv. Mater. Technol.*, 2022, **7**, no. 6, 2101223. doi: 10.1002/admt.202101223
110. A. Pistone, C. Scolaro and A. Visco, Mechanical properties of protective coatings against marine fouling: A review, *Polymers*, 2021, **13**, no. 2, 173. doi: 10.3390/polym13020173
111. H. Wu, H. Lei, Y.F. Chen and J. Qiao, Comparison on corrosion behaviour and mechanical properties of structural steel exposed between urban industrial atmosphere and laboratory simulated environment, *Constr. Build. Mater.*, 2019, **211**, 228–243. doi: 10.1016/j.conbuildmat.2019.03.207
112. M.E. McMahon, R.J. Santucci Jr, C.F. Glover, B. Kannan, Z.R. Walsh and J.R. Scully, A review of modern assessment methods for metal and metal-oxide based primers for substrate corrosion protection, *Front. Mater.*, 2019, **6**, 190. doi: 10.3389/fmats.2019.00190
113. A.N. Jasim, B.A. Abdulhussein, S.M.N. Ahmed, W.K. Al-Azzawi, M.M. Hanoon, M.K. Abbass and A.A.Al-Amiery, Schiff's Base Performance in Preventing Corrosion on Mild Steel in Acidic Conditions. *Prog. Color Colorants Coat.*, 2023, **16**, 319–329. doi: 10.30509/pccc.2023.167081.1197
114. S.P. Dalawai, M.A.S. Aly, S.S. Latthe, R. Xing, R.S. Sutar, S. Nagappan, C.-S. Ha, K.K. Sadasivuni and S. Liu, Recent advances in durability of superhydrophobic self-cleaning technology: A critical review, *Prog. Org. Coat.*, 2020, **138**, 105381. doi: 10.1016/j.porgcoat.2019.105381
115. A.K. Hussain, N. Seetharamaiah, M. Pichumani and Ch.S. Chakra, Research progress in organic zinc rich primer coatings for cathodic protection of metals – A comprehensive review, *Prog. Org. Coat.*, 2021, **153**, 106040. doi: 10.1016/j.porgcoat.2020.106040
116. L. Wittocx, M. Buyle, A. Audenaert, O. Seuntjens, N. Renne and B. Craeye, Revamping corrosion damaged reinforced concrete balconies: Life cycle assessment and life cycle cost of life-extending repair methods, *J. Build. Eng.*, 2022, **52**, no. 5, 104436. doi: 10.1016/j.jobe.2022.104436

117. K. Mondal, L. Nuñez III, C.M. Downey and I.J. van Rooyen, Thermal barrier coatings overview: Design, manufacturing, and applications in high-temperature industries, *nd. Eng. Chem. Res*., 2021, **60**, no. 17, 6061–6077. doi: 10.1021/acs.iecr.1c00788
118. K. Sotoodeh, Choosing the Right Coating System for Offshore Valves to Prevent External Corrosion, *J. Bio- Tribo-Corros*., 2023, **9**, no. 3, 55. doi: 10.1007/s40735-023-00780-7
119. M. Salemi, Corrosion protection and repair of steel components using inorganic coating and carbon fiber reinforced polymer and fatigue life prediction of pipeline, PhD Diss., Rutgers The State University of New Jersey, School of Graduate Studies, 2020.
120. W. Darden, Long-Life Coatings for Offshore Structures, *SNAME Maritime Convention*, SNAME-SMC-2021-075, 2021. doi: 10.5957/SMC-2021-075
121. C.L. Cramer, E. Ionescu, M. Graczyk-Zajac, A.T. Nelson, Y. Katoh, J.J. Haslam, L. Wondraczek, T.G. Aguirre, S. LeBlanc, H. Wang, M. Masoudi, E. Tegeler, R. Riedel, P. Colombo and M. Minary-Jolandan, Additive manufacturing of ceramic materials for energy applications: Road map and opportunities, *J. Eur. Ceram. Soc*., 2022, **42**, no. 7, 3049–3088. doi: 10.1016/j.jeurceramsoc.2022.01.058
122. R. Francois, Current and future corrosion challenges for a reliable and sustainable development of the chemical, refinery, and petrochemical industries, *Mater. Corros*., 2009, **60**, no. 7, 495–500. doi: 10.1002/maco.200805171
123. F. Peltier and D. Thierry, Review of Cr-free coatings for the corrosion protection of aluminum aerospace alloys, *Coatings*, 2022, **12**, no. 4, 518. doi: 10.3390/coatings12040518
124. M. Chomiak, M. Sałaciński, F. Gołębiowski and P. Broda, Durability and Corrosion Resistance Test of Adhesive Joints Using Two Adherence Promoters for the Connection of Aerospace Aluminum Alloys, *Materials*, 2022, **15**, no. 24, 8733. doi: 10.3390/ma15248733
125. R. Bender, D. Féron, D. Mills, S. Ritter, R. Bäßler, D. Bettge, I. De Graeve, A. Dugstad, S. Grassini, T. Hack, M. Halama, E.-H. Han, T. Harder, G. Hinds, J. Kittel, R. Krieg, C. Leygraf, L. Martinelli, A. Mol, D. Neff, J.-O. Nilsson, I. Odnevall, S. Paterson, S. Paul, T. Prošek, M. Raupach, R.I. Revilla, F. Ropital, H. Schweigart, E. Szala, H. Terryn, J. Tidblad, S. Virtanen, P. Volovitch, D. Watkinson, M. Wilms, G. Winning and M. Zheludkevich, Corrosion challenges towards a sustainable society, *Mater. Corros*., 2022, **73**, no. 11, 1730–1751. doi: 10.1002/maco.202213140
126. A.M. Jiménez-López and G.A. Hincapié-Llanos, Identification of factors affecting the reduction of VOC emissions in the paint industry: Systematic literature review-SLR, *Prog.Org. Coat*., 2022, **170**, 106945. doi: 10.1016/j.porgcoat.2022.106945
127. X. Wang, X. Gao, Z. Zhang, L. Cheng, H. Ma, and Weimin Yang, Advances in modifications and high-temperature applications of silicon carbide ceramic matrix composites in aerospace: a focused review, *J. Eur. Ceram. Soc*., 2021, **41**, no. 9, 4671–4688. doi: 10.1016/j.jeurceramsoc.2021.03.051

128. A. Al-Amiery, W.N.R. Wan Isahak and W.K. Al-Azzawi, ODHI: A promising isatin-based corrosion inhibitor for mild steel in hydrochloric acid, *J. Mol. Struct.*, 2023, **1288**, 135829. doi: https://doi.org/10.1016/j.molstruc.2023.135829
129. T. Burakowski and T. Wierzchon, *Surface engineering of metals: principles, equipment, technologies*, CRC Press, 1998. doi: 10.1201/9780367802325
130. Y. Chen, L. Wu, W. Yao, J. Wu, M. Serdechnova, C. Blawert, M.L. Zheludkevich, Y. Yuan, Z. Xie and F. Pan, "Smart" micro/nano container-based self-healing coatings on magnesium alloys: A review, *J. Magnesium Alloys*, 2023, **11**, no. 7, 2230–2259. doi: 10.1016/j.jma.2023.06.006
131. J.S. George, P. Vijayan P, A.T. Hoang, N. Kalarikkal, P. Nguyen-Tri and S. Thomas, Recent advances in bio-inspired multifunctional coatings for corrosion protection, *Prog. Org. Coat.*, 2022, **168**, 106858. doi: 10.1016/j.porgcoat.2022.106858
132. A.G. Nurioglu, A.C.C. Esteves and G. de With, Non-toxic, non-biocide-release antifouling coatings based on molecular structure design for marine applications, *J. Mater. Chem. B*, 2015, **3**, no. 32, 6547–6570. doi: 10.1039/C5TB00232J
133. H.A. Klfout, A.M. Asiri, K.A. Alamry and M.A. Hussein, Recent advances in bio-based polybenzoxazines as an interesting adhesive coating, *RSC Adv.*, 2023, **13**, no. 29, 19817–19835. doi: 10.1039/D3RA03514J
134. P. Nguyen-Tri, H.N. Tran, C.O. Plamondon, L. Tuduri, D.-V.N. Vo, S. Nanda, A. Mishra, H.-P. Chao and A.K. Bajpai, Recent progress in the preparation, properties and applications of superhydrophobic nano-based coatings and surfaces: A review, *Prog. Org. Coat.*, 2019, **132**, 235–256. doi: 10.1016/j.porgcoat.2019.03.042
135. C. Ma, A. Nikiforov, N. De Geyter, R. Morent and K.K. Ostrikov, Plasma for biomedical decontamination: From plasma-engineered to plasma-active antimicrobial surfaces, *Curr. Opin. Chem. Eng.*, 2022, **36**, 100764. doi: 10.1016/j.coche.2021.100764
136. M.Z. Khan, J. Militky, M. Petru, B. Tomková, A. Ali, E. Tören and S. Perveen, Recent advances in superhydrophobic surfaces for practical applications: A review, *Eur. Polym. J.*, 2022, **178**, 111481. doi: 10.1016/j.eurpolymj.2022.111481
137. L. Yimin, Y. Junhua, L. Xia, T. Sheng, W. Wei, L. Zhuangzhu, Z. Guangan and Z. Junyan, Self-lubricating and wear-resistant and anti-corrosive multi-functional coating technologies applied in tropical marine atmosphere, *Tribology*, 2022, **43**, no. 1, 104–120. doi: 10.16078/j.tribology.2022032
138. W. Qing, F. Liu, H. Yao, S. Sun, C. Chen and W. Zhang, Functional catalytic membrane development: A review of catalyst coating techniques, *Adv. Colloid Interface Sci.*, 2020, **282**, 102207. doi: 10.1016/j.cis.2020.102207
139. J.J. Cid-Galiot, A.A. Aguilar-Lasserre, J.R. Grande-Ramírez, R. Meza-Palacios and J.P. Rodríguez-Jarquín, Decision support system to evaluate a vandalized and deteriorated oil pipeline transportation system using artificial intelligence techniques. Part 1: modeling, *Corros. Rev.*, 2022, **40**, no. 5, 453–473. doi: 10.1515/corrrev-2021-0080

140. M. Dulal, S. Afroj, J. Ahn, Y. Cho, C. Carr, I.-D. Kim and N. Karim, Toward sustainable wearable electronic textiles, *ACS Nano*, 2022, **16**, no. 12, 19755–19788. doi: 10.1021/acsnano.2c07723
141. B.S. Mahdi, M.K. Abbass, M.K. Mohsin, W.K. Al-Azzawi, M.M. Hanoon, M.H.H. AlKaabi, L.M. Shaker, A.A. Al-Amiery, W.N.R.W. Isahak, A.A.H. Kadhum and M.S. Takriff, Corrosion inhibition of mild steel in hydrochloric acid environment using terephthaldehyde based on Schiff base: Gravimetric, thermodynamic, and computational studies, Molecules, 2022, **27**, no. 15, 4857. doi: 10.3390/molecules27154857
142. Q.A. Jawad, D.S. Zinad, R.D. Salim, A.A. Al-Amiery, T.S. Gaaz, M.S. Takriff and A.A.H. Kadhum, Synthesis, Characterization, and Corrosion Inhibition Potential of Novel Thiosemicarbazone on Mild Steel in Sulfuric Acid Environment, *Coatings*, 2019, **9**, no. 11, 729. doi: 10.3390/coatings9110729
143. S. Al-Baghdadi, F. Noori, W.K. Ahmed and A.A. Al-Amiery, Thiadiazole as a potential corrosion inhibitor for mild steel in 1 M HCl, *J. Adv. Electrochem*., 2016, **2**, 67–69.
144. A.M. Resen, M. Hanoon, R.D. Salim, A.A. Al-Amiery, L.M. Shaker and A.A.H. Kadhum, Gravimetrical, theoretical, and surface morphological investigations of corrosion inhibition effect of 4-(benzoimidazole-2-yl)pyridine on mild steel in hydrochloric acid, *Koroze Ochr. Mater*., 2020, и, 122–130. doi: 10.2478/kom-2020-0018
145. S. Junaedi, A.A. Al-Amiery, A. Kadihum, A.A.H. Kadhum and A.B. Mohamad, Inhibition effects of a synthesized novel 4-aminoantipyrine derivative on the corrosion of mild steel in hydrochloric acid solution together with quantum chemicalstudies, *Int. J. Mol. Sci*., 2013, **14**, no. 6, 11915–11928. doi: 10.3390/ijms140611915
146. A.A. Alamiery, W.N.R.W. Isahak, H.S.S. Aljibori, H.A. Al-Asadi and A.A.H. Kadhum, Effect of the structure, immersion time and temperature on the corrosion inhibition of 4-pyrrol-1-yl-n-(2,5-dimethyl-pyrrol-1-yl)benzoylamine in 1.0 M HCl solution, *Int. J. Corros. Scale Inhib*., 2021, **10**, no. 2, 700–713. doi: 10.17675/2305-6894-2021-10-2-14
147. W.K. Al-Azzawi, A.J. Al Adily, F.F. Sayyid, R.K. Al-Azzawi, M.H. Kzar, H.N. Jawoosh, A.A. Al-Amiery, A.A.H. Kadhum, W.N.R.W. Isahak and M.S. Takriff, Evaluation of corrosion inhibition characteristics of an N-propionanilide derivative for mild steel in 1 M HCl: Gravimetrical and computational studies, *Int. J. Corros. Scale Inhib*., 2022, **11**, no. 3, 1100–1114. doi: 10.17675/2305-6894-2022-11-3-12
148. A. Mustafa, F. Sayyid, N. Betti, M. Hanoon, A. Al-Amiery, A. Kadhum and M. Takriff, Inhibition Evaluation of 5-(4-(1H-pyrrol-1-yl)phenyl)-2-mercapto-1,3,4-oxadiazole for the Corrosion of Mild Steel in an Acid environment: Thermodynamic and DFT Aspects, *Tribologia*, 2021, **38**, no. 3–4, 39–47. doi: 10.30678/fjt.105330

149. Y.M. Abdulsahib, A.J.M. Eltmimi, S.A. Alhabeeb, M.M. Hanoon, A.A. Al-Amiery, T. Allami and A.A.H. Kadhum, Experimental and theoretical investigations on the inhibition efficiency of N-(2,4-dihydroxytolueneylidene)-4-methylpyridin-2-amine for the corrosion of mild steel in hydrochloric acid, *Int. J. Corros. Scale Inhib.*, 2021, **10**, no. 3, 885–899. doi: 10.17675/2305-6894-2021-10-3-3
150. A.K. Khudhair, A.M. Mustafa, M.M. Hanoon, A. Al-Amiery, L.M. Shaker, T. Gazz, A.B. Mohamad, A.H. Kadhum and M.S. Takriff, Experimental and Theoretical Investigation on the Corrosion Inhibitor Potential of N-MEH for Mild Steel in HCl, *Prog. Color, Color. Coat.*, 2022, **15**, no. 2, 111–122. doi: 10.30509/PCCC.2021.166815.1111
151. D.S. Zinad, R.D. Salim, N. Betti, L.M. Shaker and A.A. Al-Amiery, Comparative Investigations of the Corrosion Inhibition Efficiency of a 1-phenyl-2-(1-phenylethylidene)hydrazine and its Analog Against Mild Steel Corrosion in Hydrochloric Acid Solution, *Prog. Color, Color. Coat.*, 2022, **15**, no. 1, 53–63. doi: 10.30509/pccc.2021.166786.1108
152. R.D. Salim, N. Betti, M. Hanoon and A.A. Al-Amiery, 2-(2,4-Dimethoxybenzylidene)-N-Phenylhydrazinecarbothioamide as an Efficient Corrosion Inhibitor for Mild Steel in Acidic Environment, *Prog. Color, Color. Coat.*, 2021, **15**, no. 1, 45–52. doi: 10.30509/pccc.2021.166775.1105
153. A.A. Al-Amiery, L.M. Shaker, A.H. Kadhum and M.S. Takriff, Exploration of furan derivative for application as corrosion inhibitor for mild steel in hydrochloric acid solution: Effect of immersion time and temperature on efficiency, *Mater. Today: Proc.*, 2021, **42**, 2968–2973. doi: 10.1016/j.matpr.2020.12.807
154. A.M. Resen, M.M. Hanoon, W.K. Alani, A. Kadhim, A.A. Mohammed, T.S. Gaaz, A.A.H. Kadhum, A.A. Al-Amiery and M.S. Takriff, Exploration of 8-piperazine-1-ylmethylumbelliferone for application as a corrosion inhibitor for mild steel in hydrochloric acid solution, *Int. J. Corros. Scale Inhib.*, 2021, **10**, no. 1, 368–387. doi: 10.17675/2305-6894-2021-10-1-21
155. M.M. Hanoon, A.M. Resen, A.A. Al-Amiery, A.A.H. Kadhum and M.S. Takriff, Theoretical and Experimental Studies on the Corrosion Inhibition Potentials of 2-((6-Methyl-2-Ketoquinolin-3-yl)Methylene)Hydrazinecarbothioamide for Mild Steel in 1 M HCl, *Prog. Color, Color. Coat.*, 2021, **15**, no. 1, 11–23. doi: 10.30509/PCCC.2020.166739.1095
156. F.G. Hashim, T.A. Salman, S.B. Al-Baghdadi, T. Gaaz and A.A. Al-Amiery, Inhibition effect of hydrazine-derived coumarin on a mild steel surface in hydrochloric acid, *Tribologia*, 2020, **37**, no. 3–4, 45–53. doi: 10.30678/fjt.95510
157. A. Alamiery, L.M. Shaker, T. Allami, A.H. Kadhum and M.S. Takriff, A study of acidic corrosion behavior of Furan-Derived Schiff base for mild steel in hydrochloric acid environment: Experimental, and surface investigation, *Mater. Today: Proc.*, 2021, **44**, 2337–2341. doi: 10.1016/j.matpr.2020.12.431

158. L.M. Shaker, A. Alamiery, W.N.R.W. Isahak and W.K. Al-Azzawi, Corrosion in solar cells: challenges and solutions for enhanced performance and durability. *J Opt*., 2023. doi: 10.1007/s12596-023-01277-9
159. A. Alamiery, Short report of mild steel corrosion in 0.5 M H_2SO_4 by 4-ethyl-1-(4-oxo-4-phenylbutanoyl)thiosemicarbazide, *J. Tribol*., 2021, **30**, 90–99. doi:
160. A.A. Alamiery, W.N.R.W. Isahak and M.S. Takriff, Inhibition of mild steel corrosion by 4-benzyl-1-(4-oxo-4-phenylbutanoyl)thiosemicarbazide: Gravimetrical, adsorption and theoretical studies, *Lubricants*, 2021, **9**, no. 9, 93. doi: 10.3390/lubricants9090093
161. A.A. Alamiery, Anticorrosion effect of thiosemicarbazide derivative on mild steel in 1 M hydrochloric acid and 0.5 M sulfuric Acid: Gravimetrical and theoretical studies, *Mater. Sci. Energy Technol*., 2021, **4**, 263–273. doi: 10.1016/j.mset.2021.07.004
162. S.B. Al-Baghdadi, A.A. Al-Amiery, T.S. Gaaz and A.A.H. Kadhum, Terephthalohydrazide and isophthalo-hydrazide as new corrosion inhibitors for mild steel in hydrochloric acid: Experimental and theoretical approaches, *Koroze Ochr. Mater*., 2021, **65**, no. 1, 12–22. doi: 10.2478/kom-2021-0002
163. M.M. Hanoon, A.M. Resen, L.M. Shaker, A.A.H. Kadhum and A.A. Al-Amiery, Corrosion investigation of mild steel in aqueous hydrochloric acid environment using N-(naphthalen-1yl)-1-(4-pyridinyl)methanimine complemented with antibacterial studies, *Biointerface Res. Appl. Chem*., 2021, **11**, no. 2, 9735–9743. doi: 10.33263/BRIAC112.97359743
164. S. Al-Baghdadi, T.S. Gaaz, A. Al-Adili, A.A. Al-Amiery and M.S. Takriff, Experimental studies on corrosion inhibition performance of acetylthiophene thiosemicarbazone for mild steel in HCl complemented with DFT investigation, *Int. J. Low-Carbon Technol*., 2021, **16**, no. 1, 181–188. doi: 10.1093/ijlct/ctaa050
165. A.A. Al-Amiery, Anti-corrosion performance of 2-isonicotinoyl-N-phenylhydrazinecarbothioamide for mild steel hydrochloric acid solution: Insights from experimental measurements and quantum chemical calculations, *Surf. Rev. Lett*., 2021, **28**, no. 3, 2050058. doi: 10.1142/S0218625X20500584
166. A.A. Alamiery, Investigations on corrosion inhibitory effect of newly quinoline derivative on mild steel in HCl solution complemented with antibacterial studies, *Biointerface Res. Appl. Chem*., 2022, **12**, no. 2, 1561–1568. doi: 10.33263/BRIAC122.15611568
167. M.A. Dawood, Z.M.K. Alasady, M.S. Abdulazeez, D.S. Ahmed, G.M. Sulaiman, A.A.H. Kadhum, L.M. Shaker and A.A. Alamiery, The corrosion inhibition effect of a pyridine derivative for low carbon steel in 1 M HCl medium: Complemented with antibacterial studies, *Int. J. Corros. Scale Inhib*., 2021, **10**, no. 4, 1766–1782. doi: 10.17675/2305-6894-2021-10-4-25
168. A.A. Alamiery, W.N.R.W. Isahak, H.S.S. Aljibori, H.A. Al-Asadi and A.A.H. Kadhum, Effect of the structure, immersion time and temperature on the corrosion inhibition of 4-pyrrol-1-yl-N-(2,5-dimethyl-pyrrol-1-yl)benzoylamine in 1.0 M HCl solution, *Int. J. Corros. Scale Inhib*., 2021, **10**, no. 2, 700–713. doi: 10.17675/2305-6894-2021-10-2-14

169. A. Alamiery, E. Mahmoudi and T. Allami, Corrosion inhibition of low-carbon steel in hydrochloric acid environment using a Schiff base derived from pyrrole: gravimetric and computational studies, *Int. J. Corros. Scale Inhib.*, 2021, **10**, no. 2, 749–765. doi: 10.17675/2305-6894-2021-10-2-17
170. A.J.M. Eltmimi, A. Alamiery, A.J. Allami, R.M. Yusop, A.H. Kadhum and T. Allami, Inhibitive effects of a novel efficient Schiff base on mild steel in hydrochloric acid environment, *Int. J. Corros. Scale Inhib.*, 2021, **10**, no. 2, 634–648. doi: 10.17675/2305-6894-2021-10-2-10
171. I.A.A. Aziz, I.A. Annon, M.H. Abdulkareem, M.M. Hanoon, M.H. Alkaabi, L.M. Shaker, A.A. Alamiery, W.N.R.W. Isahak and M.S. Takriff, Insights into corrosion inhibition behavior of a 5-mercapto-1,2,4-triazole derivative for mild steel in hydrochloric acid solution: Experimental and DFT studies, *Lubricants*, 2021, **9**, no. 2, 122. doi: 10.3390/lubricants9120122
172. A. Alamiery, Corrosion inhibition effect of 2-N-phenylamino-5-(3-phenyl-3-oxo-1-propyl)-1,3,4-oxadiazole on mild steel in 1 M hydrochloric acid medium: Insight from gravimetric and DFT investigations, *Mater. Sci. Energy Technol.*, 2021, **4**, 398–406. doi: 10.1016/j.mset.2021.09.002
173. M.S. Abdulazeez, Z.S. Abdullahe, M.A. Dawood, Z.K. Handel, R.I. Mahmood, S. Osamah, A.H. Kadhum, L.M. Shaker and A.A. Al-Amiery, Corrosion inhibition of low carbon steel in HCl medium using a thiadiazole derivative: weight loss, DFT studies and antibacterial studies, *Int. J. Corros. Scale Inhib.*, 2021, **10**, no. 4, 1812–1828. doi: 10.17675/2305-6894-2021-10-4-27
174. D.M. Jamil, A.K. Al-Okbi, M.M. Hanon, K.S. Rida, A.F. Alkaim, A.A. Al-Amiery, A. Kadhim and A.A.H. Kadhum, Carbethoxythiazole corrosion inhibitor: as an experimentally model and DFT theory, *J. Eng. Appl. Sci.*, 2018, **13**, no. 11, 3952–3959. doi: 10.36478/jeasci.2018.3952.3959
175. A.Z. Salman, Q.A. Jawad, K.S. Ridah, L.M. Shaker and A.A. Al-Amiery, Selected bis-thiadiazole: Synthesis and corrosion inhibition studies on mild steel in HCl Environment, *Surf. Rev. Lett.*, 2020, **27**, no. 12, 2050014. doi: 10.1142/S0218625X20500146
176. A.S. Fouda, A.-S. Ahmed and E. El-Katori, Thiazole derivatives as corrosion inhibitors for C-steel in sulphuric acid solution, *Eur. J. Chem.*, 2010, **1**, no. 4, 312–318. doi: 10.5155/eurjchem.1.4.312-318.105
177. S.B. Al-Bghdadi, M.M. Hanoon, J.F. Odah, L.M. Shaker and A.A. Al-Amiery, Benzylidene as efficient corrosion inhibition of mild steel in acidic solution, *Proceedings*, 2019, **41**, no. 1, 27. doi: 10.3390/ecsoc-23-06472
178. B.S. Mahdi, H.S.S. Aljibori, M.K. Abbass, W.K. Al-Azzawi, A.H. Kadhum, M.M. Hanoon, W.N.R.W. Isahak, A.A. Al-Amiery and H.Sh. Majdi, Gravimetric analysis and quantum chemical assessment of 4-aminoantipyrine derivatives as corrosion inhibitors, *Int. J. Corros. Scale Inhib.*, 2022, **11**, no. 3, 1191–1213. doi: 10.17675/2305-6894-2022-11-3-17

179. A.A. Alamiery, Study of corrosion behavior of N′-(2-(2-oxomethylpyrrol-1-yl)ethyl)piperidine for mild steel in the acid environment, *Biointerface Res. Appl. Chem*., 2022, **12**, no. 3, 3638–3646. doi: 10.33263/BRIAC123.36383646
180. A. Alamiery, A.B. Mohamad, A.A.H. Kadhum and M.S. Takriff, Comparative data on corrosion protection of mild steel in HCl using two new thiazoles, *Data Brief*, 2022, **40**, 107838. doi: 10.1016/j.dib.2022.107838
181. A.M. Mustafa, F.F. Sayyid, N. Betti, L.M. Shaker, M.M. Hanoon, A.A. Alamiery, A.A.H. Kadhum and M.S. Takriff, Inhibition of mild steel corrosion in hydrochloric acid environment by 1-amino-2-mercapto-5-(4-(pyrrol-1-yl)phenyl)-1,3,4-triazole, *S. Afr. J. Chem. Eng*., 2022, **39**, 42–51. doi: 10.1016/j.sajce.2021.11.009
182. W.K. Al-Azzawi, S.M. Salih, A.F. Hamood, R.K. Al-Azzawi, M.H. Kzar, H.N. Jawoosh, L.M. Shakier, A. Al-Amiery, A.A.H. Kadhum, W.N.R.W. Isahak and M.S. Takriff, Adsorption and theoretical investigations of a Schiff base for corrosion inhibition of mild steel in an acidic environment, *Int. J. Corros. Scale Inhib*., 2022, **11**, no. 3, 1063–1082. doi: 10.17675/2305-6894-2022-11-3-10
183. A.H.M.J. Al Obaidy, A. Kadhum, S.B. Al-Baghdadi, A.A.H. Al-Amiery, A.A.H. Kadhum, E. Yousif and A.B. Mohamad, Eco-friendly corrosion inhibitor: experimental studies on the corrosion inhibition performance of creatinine for mild steel in HCl complemented with quantum chemical calculations, *Int. J. Electrochem. Sci*., 2015, **10**, no. 1, 3961–3972. doi: 10.1016/S1452-3981(23)06594-X
184. A. Al-Amiery, L.M. Shaker, A.A.H. Kadhum and M.S. Takriff, Synthesis, characterization and gravimetric studies of novel triazole-based compound, *Int. J. Low-Carbon Technol*., 2020, **15**, no. 2, 164–170. doi: 10.1093/ijlct/ctz067
185. S. Junaedi, A.A.H. Kadhum, A.A. Al-Amiery, A.B. Mohamad and M.S. Takriff, Synthesis and characterization of novel corrosion inhibitor derived from oleic acid: 2-amino-5-oleyl-1,3,4-thiadiazol (AOT), *Int. J. Electrochem. Sci*., 2012, **7**, no. 4, 3543–3554. doi: 10.1016/S1452-3981(23)13976-9
186. I.A. Annon, A.S. Abbas, W.K. Al-Azzawi, M.M. Hanoon, A.A. Alamiery, W.N.R.W. Isahak and A.A.H. Kadhum, Corrosion inhibition of mild steel in hydrochloric acid environment using thiadiazole derivative: Weight loss, thermodynamics, adsorption and computational investigations, *S. Afr. J. Chem. Eng*., 2022, **41**, 244–252. doi: 10.1016/j.sajce.2022.06.011
187. H.S. Aljibori, A.H. Alwazir, S. Abdulhadi, W.K. Al-Azzawi, A.A.H. Kadhum, L.M. Shaker, A.A. Al-Amiery and H.Sh. Majdi, The use of a Schiff base derivative to inhibit mild steel corrosion in 1 M HCl solution: a comparison of practical and theoretical findings, *Int. J. Corros. Scale Inhib*., 2022, **11**, no. 4, 1435–1455. doi: 10.17675/2305-6894-2022-11-4-2
188. H.S. Aljibori, O.H. Abdulzahra, A.J. Al Adily, W.K. Al-Azzawi, A.A. Al-Amiery and A.A.H. Kadhum, Recent progresses in thiadiazole derivatives as corrosion inhibitors in hydrochloric acid solution, *Int. J. Corros. Scale Inhib*., 2023, **12**, no. 3, 842–866. doi: 10.17675/2305-6894-2023-12-3-3

189. S.B. Al-Baghdadi, F.G. Hashim, A.Q. Salam, T.K. Abed, T.S. Gaaz, A.A. Al-Amiery, A.A.H. Kadhum, K.S. Reda and W.K. Ahmed, Synthesis and corrosion inhibition application of NATN on mild steel surface in acidic media complemented with DFT studies, *Results Phys*., 2018, **8**, 1178–1184. doi: 10.1016/j.rinp.2018.02.007

♦ ♦ ♦