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Comprehensive Review of Recent Advances in Nanoparticle-Based Corrosion Inhibition Approaches

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ABSTRACT: Corrosion of metals is a persistent challenge in various industries, leading to significant economic losses and safety hazards. Conventional corrosion inhibitors often face limitations such as environmental toxicity, low efficiency, and short-term protection. Nanoparticle-based corrosion inhibitors have emerged as a promising alternative due to their unique properties and versatile applications. This paper provides a comprehensive review of the recent advances in nanoparticle-based corrosion inhibition strategies from 2015-2024 by harvesting data from secondary sources. The fundamental mechanisms underlying the corrosion inhibition by nanoparticles are discussed, including adsorption processes, passivation mechanisms, and synergistic effects with other inhibitors. Various types of nanoparticles, including metallic nanoparticles, metal oxide nanoparticles, polymer nanocomposites, carbon-based nanoparticles, and organic-inorganic hybrid nanoparticles, are explored for their corrosion inhibition potential. Furthermore, the applications of nanoparticle-based corrosion inhibitors in industries such as oil and gas, aerospace, automotive, marine, and infrastructure are highlighted. Despite significant progress, challenges such as stability, compatibility, and environmental concerns remain to be addressed. Future directions in nanoparticle-based corrosion inhibition research are also discussed, aiming to guide further developments in this promising field.

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Corrosion, the degradation of materials due to chemical or electrochemical reactions with their environment, is a ubiquitous phenomenon that poses significant challenges across various industries, including infrastructure, transportation, energy production, and manufacturing. The economic impact of corrosion is staggering, with estimates of global costs reaching hundreds of billions of dollars annually.

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Moreover, corrosion-related failures can compromise the safety and reliability of critical systems, emphasizing the importance of effective corrosion mitigation strategies. Traditional approaches to corrosion control primarily involve the use of chemical inhibitors, coatings, cathodic protection, and alloying techniques. While these methods have been successful to some extent, they often exhibit limitations such as toxicity, environmental concerns, high cost, and limited effectiveness under certain conditions. In recent years, there has been growing interest in exploring alternative corrosion inhibition strategies that can overcome these drawbacks and provide more sustainable and efficient solutions (Bijapur *et al.*, 2023). One such promising approach involves the utilization of nanoparticles as corrosion inhibitors. Nanoparticles, defined as particles with dimensions ranging from 1 to 100 nanometers, exhibit unique physical, chemical, and mechanical properties compared to their bulk counterparts. These properties, including high surface area-to-volume ratio, tunable surface chemistry, enhanced reactivity, and quantum size effects, make nanoparticles attractive candidates for corrosion inhibition applications. The use of nanoparticles for corrosion inhibition offers several potential advantages. Firstly, nanoparticles can provide a more uniform and durable protective layer on the metal surface compared to conventional inhibitors, thereby offering enhanced long-term corrosion protection. Additionally, nanoparticles can be tailored to exhibit specific functionalities, allowing for targeted inhibition of corrosion processes while minimizing adverse effects on the material properties. Moreover, nanoparticles can be incorporated into coatings, paints, and composite materials to impart corrosion resistance to a wide range of substrates (Mohajerani *et al.*, 2019; Abimbola *et al.*, 2023). The mechanisms through which nanoparticles inhibit corrosion are diverse and depend on factors such as nanoparticle composition, size, morphology, surface chemistry, and interactions with the corrosive environment. One common mechanism involves the adsorption of nanoparticles onto the metal surface, forming a protective barrier that inhibits corrosive species from accessing the metal substrate. Furthermore, nanoparticles can promote passivation by facilitating the formation of stable oxide layers on the metal surface, thereby reducing the rate of corrosion. In some cases, nanoparticles may also act as sacrificial anodes, preferentially undergoing corrosion to protect the underlying metal substrate. Several types of nanoparticles have been investigated for their corrosion inhibition properties, including metallic nanoparticles (e.g., silver, gold, copper), metal oxide nanoparticles (e.g., zinc oxide, cerium oxide, titanium dioxide), polymer nanocomposites, carbon-based nanoparticles (e.g., carbon nanotubes, graphene), and organic-inorganic hybrid nanoparticles. Each type of nanoparticle offers unique advantages and may be suitable for specific corrosion environments and applications (Al-Senani *and* Al-Saeedi, 2022). The application of nanoparticle-based corrosion inhibitors spans a wide range of industries and sectors. In the oil and gas industry, for example, nanoparticles are being explored for their ability to mitigate corrosion in pipelines, storage tanks, and offshore structures exposed to aggressive environments. Similarly, in the aerospace industry, nanoparticles are being incorporated into coatings and surface treatments to protect aircraft components from corrosion caused by exposure to high-altitude conditions, moisture, and environmental pollutants (Asaad *et al.*, 2021). Despite the significant progress made in the field of nanoparticle-based corrosion inhibition, several challenges remain to be addressed. These include issues related to nanoparticle stability, compatibility with coatings and substrates, scalability of synthesis methods, environmental and health concerns associated with nanoparticle release, and cost-effectiveness of large-scale implementation. Overcoming these challenges will require interdisciplinary efforts involving materials scientists, chemists, engineers, and environmental researchers. Nanoparticle-based corrosion inhibitors represent a promising and innovative approach to mitigating corrosion in various industrial applications. By harnessing the unique properties of nanoparticles, researchers aim to develop more effective, sustainable, and environmentally friendly corrosion protection solutions. This review explores the recent advances, mechanisms, types, applications, challenges, and future prospects of nanoparticle-based corrosion inhibitors, with the goal of inspiring further research and development in this exciting field (Singh *et al.*, 2023).

Overview of Conventional Corrosion Inhibitors: Corrosion, the gradual deterioration of materials due to chemical or electrochemical reactions with their environment, is a pervasive problem affecting various industries worldwide. To combat corrosion and extend the service life of metallic structures and components, numerous corrosion inhibition strategies have been developed over the years. Among these strategies, conventional corrosion inhibitors have been widely employed and studied for their ability to mitigate corrosion effectively. This section provides an overview of conventional corrosion inhibitors, including their types, mechanisms of action, advantages, limitations, and applications. Conventional corrosion inhibitors can be broadly classified into organic and inorganic inhibitors based on their chemical composition. Organic inhibitors are typically organic compounds containing heteroatoms such as nitrogen, sulfur, and oxygen, which form complexes with metal ions or adsorb onto metal surfaces, forming a protective film. Examples of organic inhibitors include amines, imidazoles, thioureas, and organic acids. Inorganic inhibitors, on the other hand, are often metal salts or oxides that react with metal surfaces to form passive layers, thereby reducing corrosion rates. Common inorganic inhibitors include chromates, phosphates, nitrites, and molybdates (Marzorati *et al.*, 2018; Olorunsola *et al.*, 2024).

The effectiveness of conventional corrosion inhibitors stems from their ability to interfere with the corrosion process through various mechanisms. Organic inhibitors primarily function by adsorbing onto metal surfaces and forming a protective monolayer that acts as a physical barrier, preventing corrosive species from accessing the metal substrate. Inorganic inhibitors, on the other hand, promote the formation of passive oxide layers on metal surfaces, which act as a barrier against further corrosion by inhibiting the dissolution of metal ions. Conventional corrosion inhibitors offer several advantages, including ease of application, compatibility with existing infrastructure and coatings, and relatively low cost compared to other corrosion mitigation techniques. Moreover, many conventional inhibitors exhibit broad-spectrum corrosion protection, making them suitable for a wide range of applications and environments. However, conventional inhibitors also have limitations, such as limited effectiveness under extreme conditions (e.g., high temperatures, acidic environments), environmental concerns (e.g., toxicity, bioaccumulation), and the potential for film degradation over time, leading to reduced protection (Chen *et al.*, 2022).

Conventional corrosion inhibitors find widespread applications across various industries, including oil and gas, automotive, aerospace, marine, infrastructure, and manufacturing. In the oil and gas industry, for instance, corrosion inhibitors are commonly used in drilling operations, pipelines, storage tanks, and refineries to protect metal equipment and structures from corrosion caused by exposure to corrosive fluids (e.g., brines, acids) and environmental conditions (e.g., high temperatures, high pressures). Similarly, in the automotive industry, corrosion inhibitors are incorporated into coatings and surface treatments to protect vehicle bodies and components from corrosion caused by exposure to moisture, road salts, and atmospheric pollutants. While conventional corrosion inhibitors have been widely used for decades and continue to play a significant role in corrosion control, there is growing interest in developing alternative inhibitors that address their limitations, such as toxicity and environmental impact. Nanoparticle-based corrosion inhibitors, for example, offer potential advantages over conventional inhibitors, including enhanced effectiveness, reduced toxicity, and greater versatility. Research in this area is ongoing, with efforts focused on exploring novel nanoparticle formulations, understanding their mechanisms of action, and optimizing their performance for specific applications (Elhady *et al.*, 2023). Generally, conventional corrosion inhibitors represent a tried-and-tested approach to corrosion control, offering effective protection against metal degradation in various industrial applications. While they have proven their utility over the years, ongoing research aims to overcome their limitations and develop next-generation inhibitors that are more sustainable, environmentally friendly, and economically viable. By leveraging advancements in materials science, chemistry, and nanotechnology, researchers continue to innovate and refine corrosion inhibition strategies to meet the evolving needs of industry and society (Vaszilcsin *et al.*, 2023).

Corrosion, the gradual degradation of materials through chemical or electrochemical reactions with their environment, remains a pervasive challenge across various industries, leading to significant economic losses, safety hazards, and environmental concerns. Conventional corrosion inhibition strategies, including the use of organic and inorganic inhibitors, coatings, and alloying techniques, have been the cornerstone of corrosion control efforts for decades. However, these approaches often exhibit limitations such as toxicity, environmental impact, and limited effectiveness under certain conditions. In recent years, the emergence of nanotechnology has opened up new avenues for developing innovative corrosion inhibition solutions. Nanoparticles, defined as particles with dimensions ranging from 1 to 100 nanometers, possess unique physical, chemical, and mechanical properties that make them promising candidates for corrosion inhibition applications. This section provides an introduction to nanoparticle-based corrosion inhibitors, discussing their properties, mechanisms of action, advantages, challenges, and applications (Xue *et al.*, 2019; Mathew *et al.*, 2024a).

High Surface Area-to-Volume Ratio: Nanoparticles have a significantly higher surface area-to-volume ratio compared to bulk materials, allowing for increased interaction with the surrounding environment and enhanced adsorption onto metal surfaces. Tunable Surface Chemistry: The surface chemistry of nanoparticles can be modified and tailored to exhibit specific functional groups or chemical moieties, enabling targeted interactions with corrosive species and metal surfaces. Enhanced Reactivity: Nanoparticles may exhibit enhanced reactivity due to quantum size effects, surface defects, and high surface energy, leading to more effective corrosion inhibition compared to larger particles or bulk materials. Versatility: Nanoparticles can be synthesized from a wide range of materials, including metals, metal oxides, polymers, and carbon-based materials, offering versatility in terms of composition, morphology, and surface properties (Yusuf *et al.*, 2023). The mechanisms through which nanoparticles inhibit corrosion are diverse and depend on factors such as nanoparticle composition, size, morphology, surface chemistry, and interactions with the corrosive environment. Several mechanisms have been proposed, including: Adsorption Processes: Nanoparticles may adsorb onto metal surfaces, forming a protective monolayer or multilayer film that acts as a physical barrier, preventing corrosive species from accessing the metal substrate. Passivation and Film Formation: Nanoparticles can promote passivation by facilitating the formation of stable oxide or hydroxide layers on metal surfaces, which inhibit further corrosion by blocking the diffusion of corrosive ions. Sacrificial Protection: In some cases, nanoparticles may undergo preferential corrosion (sacrificial anodic dissolution) to protect the underlying metal substrate from corrosion, particularly in environments with aggressive ions or localized corrosion conditions. Synergistic Effects: Nanoparticles may exhibit synergistic interactions with other corrosion inhibitors or additives, enhancing their effectiveness and providing multifunctional corrosion protection (Khort *et al.,* 2021; Mathew *et al.,* 2024b).

Enhanced Effectiveness: Nanoparticles can provide more uniform and durable corrosion protection compared to conventional inhibitors, leading to extended service life and reduced maintenance costs. Reduced Toxicity: Many nanoparticle-based inhibitors are environmentally friendly and less toxic compared to traditional inhibitors, making them more sustainable and suitable for environmentally sensitive applications. Versatility: Nanoparticles can be incorporated into coatings, paints, and composite materials, allowing for tailored corrosion protection solutions for a wide range of substrates and environments (González *et al.,* 2021).

Nanoparticle Stability: Ensuring the stability and dispersion of nanoparticles in corrosive environments and coating formulations can be challenging, requiring careful selection of nanoparticle materials and surface modifications. Compatibility: Nanoparticles must be compatible with existing coating systems, substrates, and application methods to ensure effective and reliable corrosion protection without compromising material properties or performance. Environmental and Health Concerns: The potential release of nanoparticles into the environment raises concerns regarding their impact on human health, ecosystems, and regulatory compliance, necessitating thorough risk assessment and mitigation strategies (Phan *and* Haes, 2019; Mathew *et al.,* 2024c).

Oil and Gas Industry: Nanoparticles are used to mitigate corrosion in pipelines, storage tanks, offshore structures, and drilling equipment exposed to corrosive fluids (e.g., brines, acids) and harsh environmental conditions. Aerospace Industry: Nanoparticles are incorporated into coatings and surface treatments to protect aircraft components from corrosion caused by exposure to high-altitude conditions, moisture, and environmental pollutants. Automotive Industry: Nanoparticles are used in automotive coatings and treatments to enhance corrosion resistance and durability, particularly in regions with harsh climates and road conditions. Marine Applications: Nanoparticles are employed in marine coatings and antifouling treatments to prevent corrosion and biofouling on ship hulls, offshore platforms, and marine infrastructure (Solovyeva *et al.,* 2023). Nanoparticles, defined as particles with dimensions ranging from 1 to 100 nanometers, have captured the imagination of scientists, engineers, and innovators worldwide due to their unique properties and wide-ranging applications across diverse fields. From medicine to electronics, and from environmental remediation to energy storage, nanoparticles offer unprecedented opportunities for innovation and advancement. This section provides an introduction to nanoparticles, discussing their properties, synthesis methods, characterization techniques, and applications (Altammar 2023).

Nanoparticles, tiny structures with dimensions ranging from 1 to 100 nanometers, hold immense potential across a multitude of scientific and technological domains. Their unique size-dependent properties make them exceptionally versatile and valuable in various applications. In this brief introduction, we'll explore the fundamental aspects of nanoparticles, their synthesis, characterization, and applications. Nanoparticles exhibit remarkable properties due to their high surface area-to-volume ratio and quantum effects. Their size-dependent characteristics, such as optical, electronic, magnetic, and catalytic properties, distinguish them from bulk materials. These properties enable nanoparticles to be tailored for specific applications, ranging from biomedicine to electronics and environmental remediation (Barhoum *et al.*, 2022).

Synthesizing nanoparticles involves various techniques, including chemical, physical, biological, and mechanical methods. Chemical synthesis, for instance, involves the controlled reduction or oxidation of precursor molecules to produce nanoparticles in solution. Physical methods, such as vapor deposition or laser ablation, rely on physical processes to generate nanoparticles. Biological synthesis utilizes biological organisms or enzymes to produce nanoparticles through biomineralization or biomimetic approaches. Mechanical methods involve mechanical deformation or fragmentation of bulk materials to produce nanoparticles. Characterizing nanoparticles is essential for understanding their properties and optimizing their performance. Techniques such as transmission electron microscopy (TEM), scanning electron microscopy (SEM), X-ray diffraction (XRD), dynamic light scattering (DLS), and spectroscopic methods are commonly used to analyze nanoparticles' size, shape, structure, and composition (Altammar 2023).

Nanoparticles find applications in diverse fields, including biomedicine, electronics, catalysis, energy storage, and environmental remediation. In biomedicine, nanoparticles are used for drug delivery, imaging, and diagnostics due to their ability to target specific cells or tissues and enhance therapeutic efficacy. In electronics, nanoparticles enable advancements in miniaturization, sensing, and energy conversion through innovations in nanoelectronics and nanomaterials. In catalysis, nanoparticles serve as efficient catalysts for chemical reactions, facilitating cleaner and more sustainable processes. Moreover, nanoparticles play a crucial role in energy-related applications, such as batteries, solar cells, and fuel cells, by improving energy efficiency, storage capacity, and conversion efficiency. In environmental remediation, nanoparticles are utilized for wastewater treatment, air purification, and pollutant detection to address environmental challenges and promote sustainability (Paluszkiewicz *et al.*, 2022).

Properties of Nanoparticles Relevant to Corrosion Inhibition: Table 1 Highlights the properties that play a crucial role in the performance of nanoparticles as corrosion inhibitors by facilitating interactions with metal surfaces and corrosive species, enhancing their effectiveness, and enabling targeted inhibition mechanisms. Nanoparticles, with dimensions typically ranging from 1 to 100 nanometers, possess unique properties that make them promising candidates for corrosion inhibition applications. These properties arise from their nanoscale dimensions and surface characteristics, which enable nanoparticles to interact with metal surfaces and corrosive species in novel ways. In this section, we will explore the properties of nanoparticles relevant to corrosion inhibition and their significance in mitigating corrosion. Nanoparticles exhibit a significantly higher surface area-to-volume ratio compared to bulk materials. This increased surface area provides more sites for interaction with metal surfaces and corrosive species, enhancing the adsorption capacity of nanoparticles onto the metal surface. The greater availability of surface sites allows nanoparticles to form a more comprehensive protective layer, thereby inhibiting corrosion more effectively. Additionally, the high surface area facilitates the dispersion of nanoparticles in coatings or solutions, ensuring uniform coverage and distribution on the metal substrate (Muresan 2023). The surface chemistry of nanoparticles can be modified and tailored to exhibit specific functionalities, such as corrosion inhibition. Functional groups, ligands, or coatings can be introduced onto the nanoparticle surface to enhance its interaction with corrosive species and metal surfaces. For example, organic molecules containing nitrogen, sulfur, or oxygen atoms can be attached to the nanoparticle surface to promote adsorption onto metal surfaces and form protective barriers against corrosive environments. The tunable surface chemistry of nanoparticles allows for precise control over their corrosion inhibition properties, enabling targeted and tailored approaches to corrosion protection. Nanoparticles may exhibit enhanced reactivity compared to bulk materials due to their small size, high surface energy, and quantum size effects. The increased reactivity of nanoparticles enables them to catalyze corrosion inhibition reactions more efficiently, leading to improved corrosion protection. For example, nanoparticles can facilitate the formation of stable oxide layers on metal surfaces, passivating the surface and reducing the rate of corrosion. Additionally, nanoparticles can undergo redox reactions with corrosive species, scavenging free radicals and inhibiting corrosion propagation. The enhanced reactivity of nanoparticles contributes to their effectiveness as corrosion inhibitors in various environments (Ahmad *et al.*, 2022). The size of nanoparticles influences their optical, electronic, magnetic, and catalytic properties, which in turn affect their performance as corrosion inhibitors. Quantum size effects, observed in nanoparticles smaller than the exciton Bohr radius, result in discrete energy levels and altered electronic properties compared to bulk materials. This can lead to changes in the adsorption behavior, surface reactivity, and corrosion inhibition mechanisms of nanoparticles. Additionally, the size-dependent optical properties of nanoparticles, such as plasmonic resonance, can be utilized for corrosion sensing and monitoring applications. The size-dependent properties of nanoparticles offer opportunities for tailoring their corrosion inhibition performance and optimizing their effectiveness in specific corrosion environments (Bury *et al.,* 2022).

Table 1 Properties of Nanoparticles Relevant to Corrosion Inhibition

Property	**Description**	**Significance**	**References**
High Surface Area-to-Volume Ratio	Nanoparticles have a significantly higher surface area-to-volume ratio compared to bulk materials.	Increased interaction with metal surfaces and corrosive species, enhanced adsorption capacity.	Altammar 2023
Tunable Surface Chemistry	The surface chemistry of nanoparticles can be modified and tailored to exhibit specific functionalities.	Allows for targeted interactions with corrosive species and metal surfaces.	Yaqoob *et al.,* 2020; Mathew *et al.,* 2022
Enhanced Reactivity	Nanoparticles may exhibit enhanced reactivity due to quantum size effects, surface defects, and high surface energy.	More effective inhibition of corrosion reactions, increased catalytic activity.	Xuan *et al.,* 2023
Size-Dependent Properties	The size of nanoparticles influences their optical, electronic, magnetic, and catalytic properties.	Allows for tuning of corrosion inhibition mechanisms and effectiveness.	Ahmad *et al.,* 2022

Methods of Nanoparticle Synthesis: Nanoparticles, with dimensions ranging from 1 to 100 nanometers, are synthesized using a variety of methods, each offering unique advantages in terms of control over particle size, shape, composition, and properties. These methods can be broadly classified into chemical, physical, biological, and hybrid approaches. In this section, we will explore the principles and techniques involved in each of these nanoparticle synthesis methods (Harish *et al.,* 2022).

Chemical Synthesis: Chemical methods are the most commonly used techniques for nanoparticle synthesis due to their versatility, scalability, and ability to produce nanoparticles with precise control over size and morphology. Chemical synthesis involves the reduction or oxidation of precursor molecules in solution, leading to the nucleation and growth of nanoparticles. Key chemical synthesis techniques include (Sharma *et al.,* 2022).

Precipitation: In precipitation methods, soluble precursors are mixed in solution, resulting in the formation of insoluble nanoparticle precipitates. Control over reaction conditions such as temperature, pH, and precursor concentration allows for tuning of nanoparticle size and properties (Fadia *et al.,* 2021).

Sol-Gel Process: The sol-gel process involves the hydrolysis and condensation of metal alkoxides or metal salts to form a sol, which undergoes gelation to produce a three-dimensional network of nanoparticles. Sol-gel methods offer precise control over nanoparticle composition, morphology, and structure. Microemulsion: Microemulsion techniques utilize surfactant-stabilized microemulsions as reaction media for nanoparticle synthesis. By controlling the composition and size of the microemulsion droplets, researchers can tailor the size, shape, and properties of nanoparticles (Esposito 2019; Mathew *et al.,* 2024d).

*Physical Synthesis***:** Physical methods rely on physical processes such as condensation, evaporation, or deposition to produce nanoparticles. These methods offer advantages such as high purity, uniformity, and scalability. Key physical synthesis techniques include:

Vapor Deposition: Vapor deposition methods involve the condensation of vaporized precursor molecules onto a substrate to form nanoparticles. Techniques such as chemical vapor deposition (CVD) and physical vapor deposition (PVD) allow for precise control over nanoparticle size, shape, and orientation. Laser Ablation: Laser ablation techniques utilize high-energy laser pulses to ablate a target material, producing nanoparticles in a surrounding liquid or gas medium. Laser ablation offers rapid and efficient synthesis of nanoparticles with minimal contamination. Sputtering: Sputtering methods involve the bombardment of a target material with energetic ions to dislodge atoms or molecules, which then condense onto a substrate to form nanoparticles. Sputtering techniques enable the synthesis of nanoparticles with controlled size, composition, and crystallinity (Franklin and Yang, 2020).

Biological Synthesis: Biological methods harness the unique properties of biological organisms, such as microorganisms, plants, or enzymes, to synthesize nanoparticles through biomineralization or biofabrication processes. Biological synthesis methods offer advantages such as environmentally friendly synthesis, biocompatibility, and precise control over nanoparticle properties. Microbial Fermentation: Microorganisms such as bacteria, fungi, or algae can be used to produce nanoparticles through fermentation processes. Microbes secrete biomolecules such as proteins or polysaccharides that act as reducing agents and stabilizers for nanoparticle formation. Plant-Mediated Synthesis: Plants contain various phytochemicals and secondary metabolites that can reduce metal ions and facilitate nanoparticle formation. Plant extracts or biomass are used as reducing and capping agents in the synthesis of nanoparticles. Enzyme-Mediated Synthesis: Enzymes such as oxidoreductases, peroxidases, or lipases catalyze the reduction or oxidation of metal ions to produce nanoparticles. Enzyme-mediated synthesis offers high specificity, efficiency, and control over nanoparticle size and morphology (Kulkarni *et al.*,, 2023).

Hybrid Synthesis: Hybrid synthesis methods combine two or more synthesis techniques to leverage their complementary advantages and achieve enhanced control over nanoparticle properties. Hybrid synthesis approaches enable the integration of chemical, physical, and biological principles to tailor nanoparticle synthesis for specific applications. Examples of hybrid synthesis techniques include (Joseph *et al.*, 2023).

Template-Assisted Synthesis: Template-assisted methods utilize templates or scaffolds, such as porous materials, self-assembled monolayers, or biological structures, to guide nanoparticle nucleation and growth. By controlling the template properties, researchers can achieve precise control over nanoparticle size, shape, and arrangement. Combustion Synthesis: Combustion synthesis involves the rapid combustion of precursor materials to produce nanoparticles. This method combines chemical and physical processes to generate nanoparticles with controlled size, composition, and crystallinity (Zhang *et al.*, 2019).

Characterization Techniques: Characterizing nanoparticles is essential for understanding their properties, structure, and performance in various applications. Nanoparticles exhibit unique characteristics that distinguish them from bulk materials, and accurate characterization is crucial for optimizing their synthesis, tailoring their properties, and assessing their suitability for specific applications. In this section, we will explore the principles and techniques involved in the characterization of nanoparticles, including microscopy, spectroscopy, diffraction, and other analytical methods (Zhang *et al.*, 2016; Adetuyi *et al.*, 2024a).

Transmission Electron Microscopy (TEM): Transmission electron microscopy (TEM) is a powerful technique used to visualize nanoparticles at the atomic scale. In TEM, a beam of electrons passes through a thin sample, interacting with the atoms and generating a magnified image. TEM provides high-resolution images of nanoparticle size, shape, morphology, and crystal structure, allowing researchers to study individual nanoparticles and their internal structure with unparalleled detail (Guzzinati *et al.*, 2018; Mathew *et al.*, 2024e).

Scanning Electron Microscopy (SEM): Scanning electron microscopy (SEM) is another widely used imaging technique for nanoparticle characterization. In SEM, a focused beam of electrons scans the surface of a sample, generating secondary electrons that are detected to create a detailed image. SEM provides three-dimensional images of nanoparticle surfaces, allowing researchers to study their morphology, size distribution, and surface features (Malatesta 2021).

Atomic Force Microscopy (AFM): Atomic force microscopy (AFM) is a versatile technique for imaging nanoparticles with atomic resolution. AFM uses a sharp tip mounted on a cantilever to scan the surface of a sample, measuring the interaction forces between the tip and the sample. AFM can provide topographical images of nanoparticle surfaces as well as quantitative information about their mechanical properties, such as stiffness and adhesion (Unsay *et al.*, 2015; Mathew *et al.*, 2024f).

X-ray Diffraction (XRD): X-ray diffraction (XRD) is a powerful technique for analyzing the crystal structure and phase composition of nanoparticles. In XRD, X-rays are diffracted by the crystal lattice of a sample, producing a diffraction pattern that can be used to determine the arrangement of atoms in the material. XRD allows researchers to identify the crystalline phases present in nanoparticles and measure parameters such as crystal size, lattice spacing, and orientation (Terzano *et al.*, 2019).

UV-Visible Spectroscopy: UV-visible spectroscopy is a widely used technique for studying the optical properties of nanoparticles. In UV-visible spectroscopy, nanoparticles absorb and scatter light in the UV-visible range, producing characteristic absorption spectra. UV-visible spectroscopy can provide information about nanoparticle size, shape, concentration, and surface plasmon resonance, which is particularly useful for studying metallic nanoparticles (Zhang *et al.,* 2016; Mathew *et al.,* 2024g).

Fourier Transform Infrared Spectroscopy (FTIR): Fourier transform infrared spectroscopy (FTIR) is a technique used to analyze the chemical composition and surface functional groups of nanoparticles. In FTIR, infrared light is absorbed by the sample, causing molecular vibrations that are characteristic of specific functional groups. FTIR can identify the presence of organic coatings, ligands, or surface modifications on nanoparticles and provide insights into their surface chemistry (Fadlelmoula *et al.,* 2022).

Energy-Dispersive X-ray Spectroscopy (EDS): Energy-dispersive X-ray spectroscopy (EDS) is a technique used to analyze the elemental composition of nanoparticles. In EDS, X-rays emitted by the sample as a result of electron beam excitation are collected and analyzed to determine the elemental composition of the material. EDS can provide quantitative information about the relative abundance of different elements in nanoparticles and identify impurities or contaminants (Tromp, 2024).

Thermogravimetric Analysis (TGA): Thermogravimetric analysis (TGA) is a technique used to study the thermal stability and decomposition behavior of nanoparticles. In TGA, nanoparticles are heated under controlled conditions, and the change in mass as a function of temperature is monitored. TGA can provide information about the composition, purity, and thermal stability of nanoparticles, as well as the presence of surface coatings or contaminants (Svobodova-Sedlackova *et al.,* 2022).

In addition, characterization techniques play a crucial role in understanding the properties and behavior of nanoparticles in various applications. By employing a combination of microscopy, spectroscopy, diffraction, and analytical methods, researchers can gain valuable insights into the size, shape, structure, composition, and surface chemistry of nanoparticles, enabling the development of novel materials and technologies for a wide range of fields, including nanotechnology, biomedicine, electronics, energy, and environmental science (Singh *et al.,* 2023).

Mechanisms of Corrosion Inhibition by Nanoparticles: Corrosion is a natural process that leads to the deterioration of metals due to electrochemical reactions with their surrounding environment. In recent years, nanoparticles have emerged as promising candidates for corrosion inhibition, offering unique properties and mechanisms for protecting metal surfaces from corrosion. Understanding the mechanisms by which nanoparticles inhibit corrosion is crucial for optimizing their performance and developing effective corrosion protection strategies. In this section, we will explore the various mechanisms of corrosion inhibition by nanoparticles, including barrier protection, passivation, ion scavenging, and surface modification (Rizi *et al.,* 2023). Barrier Protection: One of the primary mechanisms by which nanoparticles inhibit corrosion is through the formation of a physical barrier on the metal surface. Nanoparticles can adsorb onto the metal surface and create a protective layer that acts as a barrier, preventing corrosive species from accessing the metal surface and initiating corrosion reactions. The barrier properties of nanoparticles are influenced by factors such as particle size, shape, surface chemistry, and packing density. Larger nanoparticles with a high surface area-to-volume ratio and dense packing provide more effective barrier protection against corrosion. Additionally, surface modification of nanoparticles with corrosion inhibitors or functional groups can enhance their barrier properties and improve corrosion resistance. Nanoparticles can promote the formation of passive oxide layers on metal surfaces, known as passivation, which inhibits corrosion by reducing the rate of metal dissolution. Passivation occurs when nanoparticles interact with the metal surface and facilitate the nucleation and growth of protective oxide layers, such as chromium oxide (Cr_2O_3) on stainless steel or aluminum oxide (Al_2O_3) on aluminum alloys. Nanoparticles can act as nucleation sites for oxide formation, providing a template for the growth of dense and uniform oxide layers that effectively protect the metal surface from further corrosion. Passivation is particularly effective in environments where the formation of stable oxide layers is thermodynamically favorable, such as in alkaline or neutral pH solutions (El-Sayed *et al.,* 2023).

Ion Scavenging: Another mechanism of corrosion inhibition by nanoparticles is ion scavenging, where nanoparticles adsorb corrosive ions from the surrounding environment and neutralize them, thereby reducing the concentration of aggressive species available for corrosion reactions. Nanoparticles can selectively adsorb cations or anions present in the electrolyte solution, such as chloride ions (Cl-) or sulfate ions (SO_4^{2-}), which are known to accelerate corrosion by promoting the breakdown of passive oxide layers. By scavenging these corrosive ions, nanoparticles mitigate their corrosive effects and enhance the stability of the metal surface. Ion scavenging mechanisms are particularly effective in environments with high concentrations of corrosive species, such as seawater or industrial process fluids (Al-Senani and Al-Saeedi, 2022).

Surface Modification: Surface modification of nanoparticles with corrosion inhibitors, polymers, or functional groups can enhance their corrosion inhibition properties by promoting specific interactions with the metal surface or corrosive species. Functionalization of nanoparticle surfaces with organic molecules containing nitrogen, sulfur, or oxygen atoms can facilitate adsorption onto the metal surface and formation of protective layers. Polymers or surfactants can be used to stabilize nanoparticle dispersions and improve their adhesion to the metal substrate. Additionally, incorporating corrosion inhibitors into nanoparticle coatings or composites can provide sustained release of inhibitive species and prolong the effectiveness of corrosion protection. Nanoparticles with catalytic properties can inhibit corrosion by catalyzing specific reactions that consume corrosive species or promote the formation of protective compounds on the metal surface. For example, metallic nanoparticles such as platinum (Pt) or palladium (Pd) can catalyze the reduction of oxygen (O_2) or hydrogen peroxide (H_2O_2), thereby reducing the concentration of oxygen or reactive oxygen species available for corrosion reactions. Similarly, nanoparticles of noble metals or metal oxides can catalyze the oxidation of organic inhibitors or sacrificial anodes, enhancing their effectiveness in corrosion protection (Wang *et al.,* 2023).

Furthermore, nanoparticles offer multiple mechanisms for inhibiting corrosion and protecting metal surfaces from degradation. By forming physical barriers, promoting passivation, scavenging corrosive ions, modifying surface chemistry, and catalyzing specific reactions, nanoparticles can effectively mitigate corrosion in various environments. The choice of nanoparticle type, size, shape, surface chemistry, and dispersion method plays a critical role in determining the corrosion inhibition mechanism and effectiveness. By understanding and leveraging these mechanisms, researchers can develop advanced nanoparticle-based coatings, inhibitors, and composites for corrosion protection applications in industries such as aerospace, automotive, marine, oil and gas, and infrastructure (Muresan 2023).

Types of Nanoparticle-Based Corrosion Inhibitors: Table 2 Nanoparticles have emerged as promising candidates for corrosion inhibition due to their unique properties and versatile mechanisms of action. By leveraging the distinct characteristics of nanoparticles, researchers have developed various types of nanoparticle-based corrosion inhibitors to protect metal surfaces from degradation in corrosive environments. In this section, we will explore different types of nanoparticle-based corrosion inhibitors, including metallic nanoparticles, metal oxide nanoparticles, organic-inorganic hybrid nanoparticles, and carbon-based nanomaterials (Wahab *et al.,* 2023). Metallic Nanoparticles: Metallic nanoparticles, such as silver (Ag), gold (Au), copper (Cu), or platinum (Pt), are widely used as corrosion inhibitors due to their high catalytic activity, stability, and compatibility with metal substrates. Metallic nanoparticles can inhibit corrosion through multiple mechanisms, including catalytic inhibition, passivation, and ion scavenging. For example, silver nanoparticles have been shown to catalyze the reduction of oxygen (O_2) or hydrogen peroxide (H_2O_2), thereby reducing the concentration of reactive oxygen species available for corrosion reactions. Similarly, copper nanoparticles can promote the formation of protective oxide layers on metal surfaces, inhibiting corrosion by passivation. Metallic nanoparticles offer advantages such as excellent catalytic activity, stability in harsh environments, and compatibility with various metal substrates, making them suitable for corrosion protection applications in industries such as aerospace, automotive, and marine (Szewczyk *et al.,* 2022).

Metal Oxide Nanoparticles: Metal oxide nanoparticles, such as zinc oxide (ZnO), titanium dioxide (TiO_2), or aluminum oxide (Al_2O_3), are widely employed as corrosion inhibitors due to their excellent barrier properties, high chemical stability, and wide availability. Metal oxide nanoparticles can inhibit corrosion through mechanisms such as barrier protection, passivation, and ion scavenging. For example, zinc oxide nanoparticles can form dense and uniform protective layers on metal surfaces, preventing the penetration of corrosive species and inhibiting corrosion by barrier protection. Similarly, titanium dioxide nanoparticles can promote the formation of passive oxide layers on metal surfaces, enhancing corrosion resistance through passivation. Metal oxide nanoparticles offer advantages such as excellent barrier properties, high chemical stability, and compatibility with a wide range of metal substrates, making them suitable for corrosion protection applications in industries such as infrastructure, oil and gas, and automotive (d'Amora *et al.,* 2022).

Organic-Inorganic Hybrid Nanoparticles: Organic-inorganic hybrid nanoparticles combine organic polymers or surfactants with inorganic nanoparticles to enhance corrosion inhibition properties. These hybrid nanoparticles offer advantages such as tailorable properties, improved adhesion, and compatibility with organic coatings. Organic-inorganic hybrid nanoparticles can inhibit corrosion through mechanisms such as barrier protection, surface modification, and controlled release of inhibitors. For example, hybrid nanoparticles containing organic polymers can form flexible and durable coatings on metal surfaces, providing enhanced barrier protection against corrosive environments. Similarly, hybrid nanoparticles containing corrosion inhibitors can release inhibitive species gradually over time, prolonging the effectiveness of corrosion protection. Organic-inorganic hybrid nanoparticles are particularly suitable for corrosion protection applications in industries such as coatings, paints, and surface treatments (Ananikov 2019; Mathew *et al.*, 2024h).

Carbon-Based Nanomaterials: Carbon-based nanomaterials, such as graphene, carbon nanotubes (CNTs), or nanodiamonds, are utilized as corrosion inhibitors due to their high mechanical strength, chemical inertness, and unique electronic properties. Carbon-based nanomaterials can inhibit corrosion through mechanisms such as barrier protection, passivation, ion scavenging, and surface modification. For example, graphene sheets can form impermeable barriers on metal surfaces, preventing the diffusion of corrosive species and inhibiting corrosion by barrier protection. Similarly, carbon nanotubes can promote the formation of passive oxide layers on metal surfaces, enhancing corrosion resistance through passivation. Carbon-based nanomaterials offer advantages such as high mechanical strength, chemical inertness, and compatibility with various metal substrates, making them suitable for corrosion protection applications in industries such as electronics, aerospace, and renewable energy (Yu *et al.*, 2021).

Table 2 Types of Nanoparticle-Based Corrosion Inhibitors

Type of Nanoparticle-Based Corrosion Inhibitor	**Description**	**Mechanisms of action**	**Advantages**	**References**
Metallic nanoparticles	Metallic nanoparticles, such as silver (Ag), gold (Au), or copper (Cu), are used as corrosion inhibitors.	Catalytic inhibition, passivation, ion scavenging	High catalytic activity, stability, and compatibility with various metal substrates.	Kshirsagar *et al.*, 2023
Metal oxide nanoparticles	Metal oxide nanoparticles, such as zinc oxide (ZnO), titanium dioxide (TiO_2), or aluminum oxide (Al_2O_3), are employed as corrosion inhibitors.	Barrier protection, passivation, ion scavenging	Excellent barrier properties, high chemical stability, and wide availability.	Smijs *and* Pavel, 2011; Adetuyi *et al.*, 2024b
Organic-Inorganic Hybrid Nanoparticles	Organic-inorganic hybrid nanoparticles combine organic polymers or surfactants with inorganic nanoparticles to enhance corrosion inhibition properties.	Barrier protection, surface modification, controlled release of inhibitors	Tailorable properties, improved adhesion, and compatibility with organic coatings.	Muresan 2023.
Carbon-Based Nanomaterials	Carbon-based nanomaterials, such as graphene, carbon nanotubes (CNTs), or nanodiamonds, are utilized as corrosion inhibitors.	Barrier protection, passivation, ion scavenging, surface modification	High mechanical strength, chemical inertness, and unique electronic properties.	Díez-Pascual 2021 Mathew *et al.*, 2023b

Applications of Nanoparticle-Based Corrosion Inhibitors: Table 3 Nanoparticle-based corrosion inhibitors have found widespread applications across various industries and environments due to their unique properties and versatile mechanisms of corrosion protection. These innovative inhibitors offer effective solutions for mitigating corrosion in diverse settings, ranging from aerospace and automotive to marine, oil and gas, infrastructure, electronics, biomedical, construction materials, and water treatment. In this section, we will explore the applications of nanoparticle-based corrosion inhibitors and their significance in each industry (Wang *et al.*, 2023).

In the aerospace industry, where safety and reliability are paramount, nanoparticle-based corrosion inhibitors play a critical role in protecting aircraft components and structures from corrosion. Metallic nanoparticles and metal oxide nanoparticles are commonly used to form lightweight and durable coatings on aircraft surfaces, enhancing corrosion resistance in harsh environments such as high-altitude flights and exposure to atmospheric pollutants. These corrosion inhibitors help to extend the service life of aircraft components, reduce maintenance costs, and ensure the safety of passengers and crew. In the automotive industry, nanoparticle-based corrosion inhibitors are employed to protect automotive parts such as chassis, body panels, and engine components from corrosion. Organic-inorganic hybrid nanoparticles and carbon-based nanomaterials are used to form protective coatings that enhance durability, extend the service life of vehicles, and improve their appearance. By inhibiting corrosion, these nanoparticles contribute to the longevity and reliability of automotive vehicles, reducing maintenance requirements and enhancing customer satisfaction. In the marine industry, where structures are exposed to corrosive seawater environments, nanoparticle-based corrosion inhibitors are indispensable for protecting marine vessels, offshore structures, and underwater equipment. Metal oxide nanoparticles and metallic nanoparticles are utilized to provide resistance to saltwater corrosion, reduce maintenance costs, and increase the operational lifespan of marine assets. These corrosion inhibitors help to maintain the integrity and performance of marine structures, ensuring safe and efficient operation in challenging maritime conditions (Muresan 2023). In the oil and gas industry, where pipelines, storage tanks, and drilling equipment are susceptible to corrosion in aggressive environments, nanoparticle-based corrosion inhibitors play a crucial role in preventing corrosion-related failures and ensuring operational reliability. Carbon-based nanomaterials and metallic nanoparticles are used to inhibit internal and external corrosion, enhance durability, and prolong the service life of oil and gas infrastructure. By mitigating corrosion, these nanoparticles contribute to the safety, efficiency, and sustainability of oil and gas operations. In the construction and infrastructure sector, where bridges, buildings, pipelines, and other infrastructure assets are subject to corrosion from environmental factors and chemical exposure, nanoparticle-based corrosion inhibitors offer effective solutions for preserving structural integrity and prolonging service life. Metal oxide nanoparticles and organic-inorganic hybrid nanoparticles are applied to provide corrosion protection, improve durability, and reduce maintenance costs of infrastructure assets. These corrosion inhibitors help to ensure the safety, reliability, and sustainability of critical infrastructure systems (Vakili *et al.*, 2023).

In the electronics industry, where electronic components, circuit boards, and semiconductor devices are vulnerable to corrosion from moisture, humidity, and environmental contaminants, nanoparticle-based corrosion inhibitors play a vital role in ensuring the reliability and performance of electronic devices. Metal oxide nanoparticles and carbon-based nanomaterials are used to protect electronic components from corrosion, reduce failure rates, and enhance device longevity. By inhibiting corrosion, these nanoparticles contribute to the efficiency and longevity of electronic devices, improving their reliability and functionality. In the biomedical field, where medical implants, surgical instruments, and biomedical devices are subject to corrosion in physiological environments, nanoparticle-based corrosion inhibitors are essential for ensuring the safety and efficacy of medical devices. Organic-inorganic hybrid nanoparticles and metal oxide nanoparticles are utilized to provide corrosion protection, enhance biocompatibility, and prolong the lifespan of medical devices. By mitigating corrosion, these nanoparticles help to reduce the risk of adverse reactions and ensure the long-term performance of medical implants and devices (Ielo *et al.,* 2021; Inobeme *et al.,* 2024a). In the construction materials industry, where concrete, steel reinforcements, and other building materials are vulnerable to corrosion in aggressive environments, nanoparticle-based corrosion inhibitors offer effective solutions for preserving structural integrity and enhancing durability. Metallic nanoparticles and metal oxide nanoparticles are incorporated into construction materials to provide corrosion protection, prevent reinforcement corrosion, and prolong the service life of structures. These corrosion inhibitors help to maintain the safety, reliability, and longevity of buildings, bridges, and infrastructure systems. In the water treatment sector, where metal components in water distribution systems, desalination plants, and wastewater treatment facilities are prone to corrosion, nanoparticle-based corrosion inhibitors are used to prevent metal leaching, reduce maintenance costs, and improve water quality. Metal oxide nanoparticles and carbon-based nanomaterials are applied to inhibit corrosion, enhance the durability of water treatment infrastructure, and ensure the efficient operation of water treatment processes. By mitigating corrosion, these nanoparticles help to maintain the reliability and sustainability of water supply and treatment systems (Coppola 2021).

Table 3: Applications of Nanoparticle-Based Corrosion Inhibitors

Applications	Description	Nanoparticles type	Advantages	References
Aerospace	Corrosion protection of aircraft components and structures to enhance safety and reliability.	Metallic nanoparticles, metal oxide nanoparticles	Lightweight, durable coatings; enhanced corrosion resistance in harsh environments.	Li *et al.,* 2021.
Automotive	Corrosion protection of automotive parts, such as chassis, body panels, and engine components.	Organic-inorganic hybrid nanoparticles, carbon-based nanomaterials	Improved durability, extended service life, and enhanced appearance of vehicles.	Shafique *and* Luo, 2019; Mathew *et al.,* 2023c
Marine	Corrosion protection of marine vessels, offshore structures, and underwater equipment.	Metal oxide nanoparticles, metallic nanoparticles	Resistance to saltwater corrosion, reduced maintenance costs, increased operational lifespan.	Xu *et al.,* 2023
Oil and Gas	Corrosion inhibition in oil and gas pipelines, storage tanks, and drilling equipment.	Carbon-based nanomaterials, metallic nanoparticles	Prevention of internal and external corrosion, enhanced durability in harsh environments.	Solovyeva *et al.,* 2023
Infrastructure	Corrosion protection of bridges, buildings, pipelines, and other infrastructure assets.	Metal oxide nanoparticles, organic-inorganic hybrid nanoparticles	Improved durability, reduced maintenance costs, and prolonged service life of structures.	Amran *et al.,* 2022
Electronics	Corrosion protection of electronic components, circuit boards, and semiconductor devices.	Metal oxide nanoparticles, carbon-based nanomaterials	Enhanced reliability, reduced failure rates, and improved performance of electronic devices.	Shamkhalichenar *et al.,* 2020; Adetuyi *et al.,* 2024c
Renewable energy	Corrosion inhibition in wind turbines, solar panels, and other renewable energy systems.	Metallic nanoparticles, metal oxide nanoparticles	Increased operational lifespan, improved efficiency, and reduced maintenance requirements.	Malik *et al.,* 2023
Biomedical	Corrosion protection of medical implants, surgical instruments, and biomedical devices.	Organic-inorganic hybrid nanoparticles, metal oxide nanoparticles	Biocompatibility, reduced risk of adverse reactions, and prolonged lifespan of medical devices.	Amirtharaj Mosas *et al.,* 2022
Construction material	Corrosion protection in concrete, steel reinforcements, and other construction materials.	Metallic nanoparticles, metal oxide nanoparticles	Prevention of reinforcement corrosion, enhanced durability, and prolonged service life of structures.	Coppola *et al.,* 2023.
Water treatment	Corrosion inhibition in water distribution systems, desalination plants, and wastewater treatment facilities.	Metal oxide nanoparticles, carbon-based nanomaterials	Prevention of metal leaching, reduced maintenance costs, and improved water quality.	Saleem *and* Zaidi, 2020Inobeme *et al.,* 2024b

Conclusion: Nanoparticle-based corrosion inhibitors offer groundbreaking solutions for protecting metal surfaces across diverse industries. Their unique properties and versatile mechanisms effectively combat degradation from corrosive agents. These inhibitors find applications in aerospace, automotive, marine, oil and gas, infrastructure, electronics, biomedical, construction materials, and water treatment industries. They enhance safety, reliability, and sustainability while reducing maintenance costs and extending asset service life. For instance, they resist saltwater corrosion in marine vessels and enhance component durability in the automotive sector. In electronics and biomedical fields, where reliability and longevity are vital, they ensure the functionality and safety of devices and implants. Future research and development promise further advancements in corrosion mitigation. By exploring new formulations, synthesis methods, and application techniques, researchers can optimize protection strategies. Collaboration between academia, industry, and government will be essential for translating research into practical solutions and accelerating the real-world adoption of nanoparticle-based corrosion inhibitors.

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