



Recent Advances in Nanoparticle-Based Corrosion Inhibition of Metals: A Review

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Abstract

Increasing concerns over the environmental impacts of conventional corrosion inhibitors have driven research toward more sustainable solutions. Nanotechnology has emerged as a promising eco-friendly alternative, with nanoparticles offering superior corrosion inhibition due to their high surface-area-to-volume ratio and tunable surface functionalities. This review evaluates the performance of nanoparticles synthesised through various methods, particularly green synthesis, in mitigating metal corrosion across industrial applications. Studies have reported inhibition efficiencies ranging from 55% to as high as 98.5% in aggressive media such as 1 M HCl and 3.5% NaCl, depending on nanoparticle type, size, and functionalisation. Nanoparticles such as ZnO, TiO₂, AgNPs, and hybrid composites have demonstrated strong protective capabilities by forming adherent passive films that block corrosion pathways. The review discusses synthesis strategies, adsorption mechanisms, and environmental implications while identifying key parameters influencing performance. It also highlights ongoing challenges in reproducibility, scalability, and standardisation and proposes future directions for improving nanoparticle-based corrosion protection, especially under aggressive environmental conditions.

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1. 0. Introduction

Metals break down due to chemical reactions with their environment through processes of corrosion, which create major difficulties across industries such as oil and gas, construction, marine infrastructure, and transportation. This degradation not only threatens structural integrity but also results in substantial economic losses. According to a NACE International study, the global annual cost of corrosion is estimated to exceed US\$2.5 trillion, equivalent to approximately 3.4% of the global GDP [1-5]. Corrosion is fundamentally a spontaneous thermodynamic process, often accelerated by aggressive ions such as chlorides, sulphates, and carbonates that promote metal dissolution in harsh environments. Traditional corrosion control strategies have shown efficacy but are increasingly scrutinised for their environmental impact, cost, and limitations under extreme operating conditions [6–10]. Consequently, recent research efforts have prioritised the development of sustainable, high-performance alternatives. Among these, nanoparticle-

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based corrosion inhibitors have emerged as a promising solution due to their unique physicochemical properties including high surface-area-to-volume ratios and tunable surface functionalities [11]. Several studies have demonstrated that nanoparticles can significantly enhance corrosion resistance by forming uniform, adherent passive films that hinder electrochemical reactions at metal interfaces [12-15]. Particularly, nanoparticles synthesised from renewable or biological sources align with green chemistry principles, as they avoid toxic reagents and promote environmental sustainability. These green-synthesised nanoparticles have shown effective inhibition performance even in aggressive media, though their efficiency is highly dependent on factors such as particle size, morphology, and surface chemistry [16-19]. While physical and chemical synthesis methods offer precision in nanoparticle fabrication, they often involve hazardous reagents and energy-intensive procedures that limit large-scale application [20]. In contrast, biosynthetic approaches using plant extracts, fungi, or microbial agents have gained attention due to their low cost, biocompatibility, scalability, and eco-friendliness [21–26]. Despite their advantages, variability in biological precursors and limited control over particle characteristics remain ongoing challenges [27]. This review evaluates the recent trends that use nanoparticles for corrosion inhibition. The research also investigates different natural-based sources along with green synthesis methods by analysing their benefits and their limitations. The review examines the inhibitive mechanisms of these nanoparticles through research-based experimental findings and recent studies. The review examines the progress of natural-derived nanoparticles towards their development as sustainable corrosion inhibitors for metals in aggressive corrosive conditions [28].

2.0. Concept of metallic corrosion process

Metallic corrosion occurs when metals degrade through environmental reactions [29-33]. Relevant transformations apply to metal changes where it becomes more chemically stable through processes that result in oxides, hydroxides, or sulphides [34, 35]. All metal structures and components are bound to deteriorate through corrosion because it is a fundamental natural process that generates severe damage leading to financial loss and security threats. The natural environment makes most metallic building materials prone to corrosion degradation. Oxygen, along with water in the environment, triggers metal oxidation during corrosion processes while metal atoms display remarkable mechanical properties coupled with cost-effectiveness. Various conditions, including reactivity levels, solution pH value, temperature variations, impurities in materials and industrial operations like acidising, pickling and de-scaling, accelerate corrosion [36]. The acceleration of corrosion occurs faster in more reactive metals because they easily discard electrons to form compounds with environmental elements [37]. The solution pH plays a role in determining corrosion rate by affecting the dissolution of the metal. Higher environmental temperatures tend to accelerate chemical reactions, while impurities create localised corrosion cells, and industrial processes remove protective coatings which expose the metal to corrosion [38]. Among various types of metallic corrosion, the most acknowledged form is uniform corrosion. This electrochemical process uniformly damages all parts of exposed metal surfaces [39]. Galvanic corrosion involves different metal types which interact in corrosive environment, yet localised corrosion occurs in covered metal surface regions. Pitting corrosion results in microscopic pit formation which appears as holes on metal surfaces according to [40, 41]. The boundaries between crystallites undergo preferential corrosion in intergranular corrosion, thus making them more susceptible to damage when compared to interior material regions [42-43]. Corrosive loss of individual elements from solid alloys represents different behaviour than selective leaching because it does not affect elemental composition [44]. Erosion-corrosion describes the increased rate of metal dissolution due to the combined effect of mechanical wear and corrosion in a corrosive system [45, 46]. Uniform or general corrosion leads to the majority of metal surface damage among all corrosion types [4, 47, 48].

2.1 Mechanism of Metallic corrosion

Corrosion of metallic materials in industrial environments is primarily driven by electrochemical reactions, where anodic metal dissolution and cathodic reduction occur simultaneously, often exacerbated by aggressive ions such as chlorides and sulphates [49, 50]. Oxidation occurs at the anode (anodic reaction) and reduction at the cathode (cathodic reaction). The reduction reaction uses electrons from oxidation to transform hydrogen ions into hydrogen gas or to reduce oxygen molecules. The anodic reaction causes metal atoms to release electrons, resulting in their transformation into metal ions, which subsequently dissolve into the corrosive medium [51]. Eq. 1 depicts the anodic reaction process.



Where, M is the metal, M^{n+} is the metal ion, n is the number of electrons lost. In this chemical reaction oxygen remains absent which leads to the oxidized atom acquiring a positive charge. This process is consequently termed oxidation. The anodic reaction during iron corrosion follows the equations presented in research [52-54].



Iron atoms at the anodic sites shed electrons during oxidation to form ferrous ions (Fe^{2+}) that then enter the corrosive environment [55]. The electrons produced through this oxidation process move toward cathodic sites where they participate in reduction reactions. The general cathodic reactions were expressed in Eq. 2-5.

Reduction of hydrogen ions:



Reduction of oxygen in acidic medium:



Reduction of oxygen in neutral or alkaline medium,



Metal ion reduction or deposition are infrequent reactions that use up electrons during the corrosion process. Both anodic and cathodic processes depend on each other, so slowing down either process can delay overall corrosion [56-58]. As a result, when a metal surface is covered with protective film or coatings, the rates of both anodic and cathodic processes are significantly lowered, ultimately leading to a decrease in the corrosion rate [59, 60]. The tendency for metals to corrode and the effectiveness of corrosion inhibition processes mainly rely on the composition of anions in the corrosion-inhibitive fluid. Recently, there has been a rise in research on hydrogen-induced corrosion in oil and gas pipelines, introducing new corrosion mechanisms that impact these systems. This has led to an increased scientific interest in this field [61]. Recent studies have demonstrated that nanoparticles, especially those synthesised through green methods, can significantly mitigate these reactions by adsorbing onto metal surfaces and forming compact, protective films that inhibit both anodic and cathodic processes. In industrial settings such as pipelines, marine vessels, and chemical reactors, localised corrosion forms like pitting, crevice, and galvanic corrosion are predominant due to fluctuating pH, temperature, and the presence of biofilms or stray currents. Nanoparticles offer site-specific inhibition by targeting active corrosion sites and altering the local electrochemical environment, according to recent studies by Basik et al. [62] and Al-Senami [63], where ZnO nanoparticles achieved over 90% inhibition efficiency in acidic and saline conditions. The mechanism of inhibition typically involves strong chemisorption through functional groups like $-OH$, $-COOH$, and $-NH_2$, which bind with metal atoms and form a stable passive layer. Smart nanoparticles, such as polymer-functionalised or responsive nanomaterials, can self-adjust under corrosive stimuli, releasing inhibitors or restructuring films in real-time, a trend highlighted in emerging research [64-74]. Studies utilising electrochemical impedance spectroscopy (EIS), in situ atomic force microscopy (AFM), and density functional theory (DFT) modelling have further confirmed the capacity of nanoparticles to modulate charge transfer and reduce corrosion current density at metal-electrolyte interfaces. For instance, Cys/Ag-Au nanocomposites and ZrO_2 -based systems have shown efficient blockage of diffusion pathways and suppression of localised attack through monolayer adsorption mechanisms [62, 75]. In oil and gas and marine applications, nanoparticle-based inhibitors have outperformed conventional inhibitors by offering longer durability, multifunctionality, and adaptability to complex environments [71]. This evolving understanding underscores that nanoparticles not only serve as physical barriers but also actively participate in electrochemical regulation, making them ideal for next-generation industrial corrosion control.

2.2 Nano particles Fabrication Techniques

Nanotechnology involves the synthesis of nanoparticles to create materials with excellent properties and characteristics for different applications [76]. There are several approaches towards the creation of the nanoparticles, and each method has a specific advantage or characteristic.

2.2.1 Top-Down Approach

The top-down approach involves the fabrication of nanostructures by breaking down bulk materials into nanoscale components. This method enables precise control over the size and morphology of the resulting nanoparticles by sequentially reducing larger fragments. Two widely used techniques under this approach are thermal decomposition and laser ablation. Thermal decomposition is a chemically driven process in which a precursor compound decomposes upon heating beyond its decomposition temperature, leading to the formation of nanoparticles. This method typically produces uniformly sized particles in the range of 10–30 nm, depending on the precursor and reaction conditions [76-78]. The size uniformity arises from the controlled thermal energy input, which enables consistent breakdown of chemical bonds and nucleation of nanocrystals [79]. Laser ablation, on the other hand, is a physical technique where a high-energy laser pulse is directed at a solid metal target immersed in a solvent (commonly water or organic media), leading to vaporisation and subsequent condensation of a plasma plume into nanoparticles. This method can produce nanoparticles with diameters typically ranging from 10 to 50 nm and has the advantage of avoiding chemical contaminants due to its solvent-based, surfactant-free nature [80-95]. Moreover, laser ablation allows for high-purity nanoparticle synthesis with good scalability, although it is often more energy-intensive and costlier than bottom-up methods like sol-gel or biosynthesis, especially for large-scale production. Nonetheless, the top-down approach remains valuable for applications requiring precise dimensional control and material purity [96].

2.2.2 Bottom-Up Approach

Bottom-up fabrication methods construct nanostructures from atomic or molecular precursors, in contrast to top-down methods, which reduce bulk materials to the nanoscale [97]. These approaches offer enhanced control over composition, morphology, and crystallinity at the atomic level, making them ideal for producing uniform, highly functional nanoparticles [98-100]. Common bottom-up synthesis techniques include sol-gel processing, chemical vapour deposition (CVD), and biological synthesis, each offering distinct benefits depending on the intended application [101]. Among these, sol-gel processing is widely favoured due to its operational simplicity, low-temperature requirements, and the ability to finely tune nanoparticle characteristics. It involves the transformation of chemical precursors into a colloidal sol, followed by hydrolysis, condensation, and subsequent drying or calcination, which leads to the formation of a solid nanoparticulate network [101-102]. Chemical Vapour Deposition (CVD) is another prominent bottom-up approach wherein volatile precursors are introduced into a reaction chamber and deposited as thin films on substrates through vapour-phase chemical reactions [103, 104]. In plasma-enhanced CVD (PECVD), plasma is employed to lower the activation energy of the process, allowing for deposition at lower temperatures critical for fabricating heat-sensitive nanomaterials. CVD is extensively used for producing carbon nanotubes, semiconductor nanoparticles, and metal oxides and is valued for its ability to produce nanoparticles with high purity, uniform size distribution, and precise compositional control. It is also highly scalable for large-area deposition, making it suitable for industrial applications in electronics, catalysis, and corrosion-resistant coatings [105-110]. Despite the advantages of bottom-up methods in producing well-defined nanostructures, each technique carries trade-offs in terms of cost, scalability, and material compatibility. To clarify these differences, a comparative summary between bottom-up and top-down approaches is presented in Table 1.

Table 1. Comparison of Bottom-Up vs Top-Down Nanoparticle Synthesis Techniques

Feature	Bottom-Up Approach	Top-Down Approach
Starting Material	Atoms or molecules	Bulk material
Control over Size & Morphology	Excellent; atomic-scale precision	Moderate; often requires post-processing
Typical Particle Size	1–100 nm (tunable and uniform)	10–50 nm (varies depending on method)

Common Methods	Sol-gel, CVD, PECVD, biosynthesis	Laser ablation, mechanical milling, thermal decomposition
Purity of Product	High (especially in CVD)	May contain surface defects or contamination
Scalability	Moderate to high (CVD is industrially scalable)	Generally high (especially for laser-based ablation)
Cost	Medium to high (CVD/PECVD more expensive)	Often lower initial cost, but energy-intensive
Material Waste	Minimal	Potentially high
Environmental Impact	Favorable (especially for green biosynthesis)	Less favorable (some methods involve toxic solvents or high energy)
Applications	Electronics, sensors, biomedical, corrosion protection	Catalysts, coatings, structural materials

2.2.3. Biosynthesis Approach

The biological synthesis of nanoparticles employs microorganisms, plant extracts, and various biological molecules to produce nanoscale materials in an environmentally friendly and sustainable manner [111–115]. This green chemistry method utilises biological agents such as fungi, yeast, bacteria, and plant phytochemicals as natural reducing and stabilising agents for nanoparticle synthesis [116]. These organisms and biomolecules mediate the reduction of metal ions through proteins, enzymes, and metabolites, facilitating controlled nucleation and growth of nanoparticles [117, 118]. Green synthesis offers several advantages over traditional chemical routes, including lower toxicity, reduced energy input, and scalability for industrial applications. It also allows for the production of nanoparticles under ambient conditions, often in aqueous media, contributing to lower environmental impact [119–125]. Recent studies have shown that biogenic nanoparticles can achieve particle sizes in the range of 10–40 nm, with good uniformity and stability. For example, CuO nanoparticles synthesised using *Moringa oleifera* leaf extract were reported to have average diameters of 20–35 nm, exhibiting excellent inhibition efficiency in acidic media [107]. Similarly, silver nanoparticles synthesised from *Aloe vera* extract demonstrated a size distribution of 15–25 nm, with a reported yield of over 85% metal conversion within 24 hours under ambient conditions [126]. These values are comparable to or even better than many conventional methods, especially considering the absence of hazardous chemicals and lower energy input. The increasing efficiency and reproducibility of biological synthesis techniques have positioned them as a leading innovation in nanotechnology. As sustainable practices are prioritised in research and industrial processes, the development of inorganic, organic, and hybrid nanoparticles using biosynthetic routes is becoming a central focus [127–139]. Plant extracts, fungal biomass, bacterial suspensions, and algal filtrates have been widely explored as biotemplates due to their accessibility, reactivity, and functional versatility. These green-produced nanoparticles are now being actively integrated into corrosion inhibitor formulations, where their surface-active biomolecules enhance metal binding and film formation. In corrosion-related applications, biogenic nanoparticles such as Ti-CO, ZnO, and AgNPs have shown inhibition efficiencies exceeding 90% in hydrochloric acid environments, validating their performance as viable substitutes for chemically synthesised alternatives [112–114]. Overall, the use of biosynthesised nanoparticles is not only aligned with green chemistry goals but also technically viable, with demonstrable particle size control, high yields, and strong corrosion inhibition performance. Optimising these biosynthetic pathways further offers great promise for producing next-generation, eco-friendly corrosion inhibitors [113].

2.3 Adsorption mechanism of nanomaterials on metal surface

The interactions between nanoparticles and metals include both physisorption and chemisorption processes that are dictated by particle properties, metal surface characteristics, and environmental factors [128]. While physisorption occurs through weak van der Waals forces and is readily reversible, chemisorption involves the formation of strong covalent or ionic bonds and is generally irreversible. Recent characterisation methods like X-ray Photoelectron

Spectroscopy (XPS), Atomic Force Microscopy (AFM), and Density Functional Theory (DFT) modelling have aided elucidating adsorption mechanisms at the molecular and atomic scales. XPS studies have shown the formation of strong metal oxygen and metal nitrogen bonds at metal surface nanoparticle interfaces, confirming the prevalence of chemisorption in some systems [129-132]. AFM analysis of adsorption on metal surfaces reveals morphological changes and surface roughness improvements due to the presence of biofunctionalised inhibitors [133]. DFT modelling provides insights into how specific functional groups bind with metal atoms. For instance, DFT-based simulations of plant-derived polyphenol-functionalised ZnO nanoparticles indicate that hydroxyl and carboxyl groups preferentially bind with Fe(110) surface atoms through strong coordination interactions, which helps block corrosion pathways [129].

Adsorption capability is strongly influenced by nanoparticle characteristics such as composition, shape, size, and surface energy. Uniform coatings on metal surfaces can be achieved using spherical and rod-like nanoparticles. Additionally, smaller particle sizes lead to stronger adsorption due to increased surface area. Surface functional groups such as $-OH$, $-COOH$, $-NH_2$, and $-SH$ are critical to adsorption strength because they promote electrostatic interactions, hydrogen bonding, and covalent bonding with the metal surface [124-138]. In acidic environments, the positively charged metal surfaces can attract negatively charged species or protonated nanoparticles. Aslam et al. [71] demonstrated that ZrO_2 nanoparticles functionalised with amino acids have a strong tendency to adsorb onto mild steel. Using DFT and XPS, they found that the oxygen atoms in the carboxyl groups adsorbed onto the Zr_{6f} site, forming stable complexes (as shown in Figure 1). Mild steel tends to attract chloride ions in acidic media, leading to localised corrosion. The application of ZrO_2 -Gly nanocomposites introduced both electrostatic and chemical adsorption mechanisms, resulting in the formation of a dense, coherent protective layer on the steel surface. This observation, supported by experimental XPS binding energy shifts and reduced surface roughness measured via AFM, suggests a synergistic inhibition effect that significantly reduces corrosion rates. Environmental conditions such as pH, temperature, and ionic strength also influence nanoparticle adhesion. Higher temperatures can enhance diffusion and adsorption rates but may also cause desorption of loosely bound particles. Under highly acidic or saline conditions, high adsorption strength and stability are required to ensure long-term nanoparticle attachment.

The adsorption behaviour of nanoparticles is often described using adsorption isotherm models. The Langmuir isotherm, typically associated with chemisorption, assumes monolayer adsorption onto a surface with a finite number of identical sites and no interaction between adsorbed species [131]. In contrast, the Freundlich isotherm is an empirical model better suited to describe physisorption, where adsorption occurs on heterogeneous surfaces and may involve multilayer adsorption [132]. Including these models helps to provide a more complete theoretical framework for interpreting adsorption phenomena in corrosion protection systems. A detailed understanding of these mechanisms, supported by surface characterisation techniques and theoretical modelling, not only clarifies the inhibition effects of nanomaterials but also facilitates the rational design of more efficient and environmentally friendly corrosion-resistant coatings.

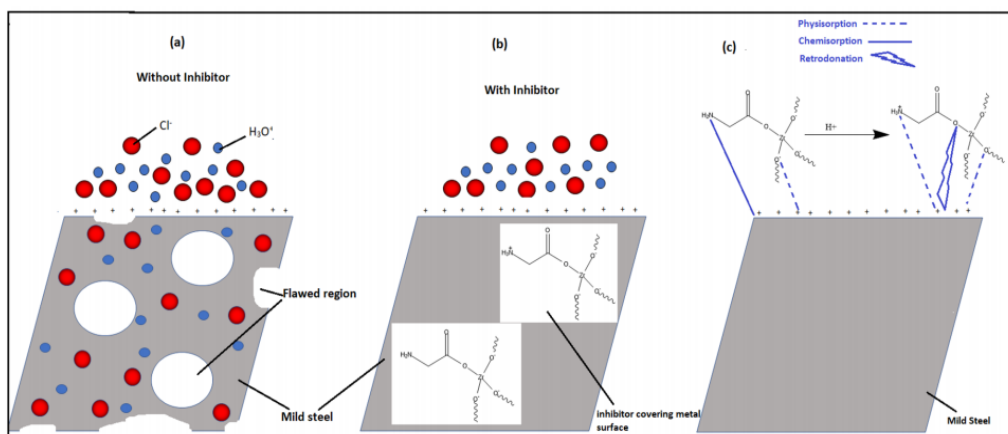


Fig. 1. Adsorption mechanism of ZrO_2 -Gly NC on the metal surface [75]

2.4 Nanoparticles for Corrosion Protection of Metals

Metallic alloys such as carbon steel, stainless steels, mild steel and aluminium are prone to oxidation in a corrosive environment [138]. Several research studies have reported sufficient protection against corrosion by the formulation of some nanomaterials [139]. These have been shown to have multi-adsorption sites on the metal surface to provide inhibition [140, 141]. Nanomaterials ZrO_2 , Ag, TiO_2 , Cr_2O_3 , ZnO, CoO/Co_3O_4 and biomass-derived substances to protect metals have been investigated [141, 142]. Olasehinde et al. [112] use *Chromolaena odorata* leaf extract to bio-synthesized titanium-based nanocomposite (Ti-Co) to mitigate mild steel corrosion in an acidic environment. According to this study, the conversion of the extract into a nanocomposite improved the inhibition potency and enhanced surface protection as assessed by the surface characterisation using scanning electron microscopy and high-resolution transmission electron microscopy and also the gravimetric technique and electrochemical measurements. At 298K to 328K temperatures, 1g/L titanium-based nanocomposites (Ti-Co) were reported to inhibit acidic corrosion rates with 91.36% and 83.87% efficiencies in respect to temperature (Fig.2). The inhibition efficiency that was achieved was said to rise for concentrations of nanomaterials. Indicating an enhanced anticorrosion exhibited by the addition of the nanocomposite (Ti-Co) inhibitor to reduce active corrosion, the adsorption of nanomaterial on the steel surface inhibited the surface from further corrosion.

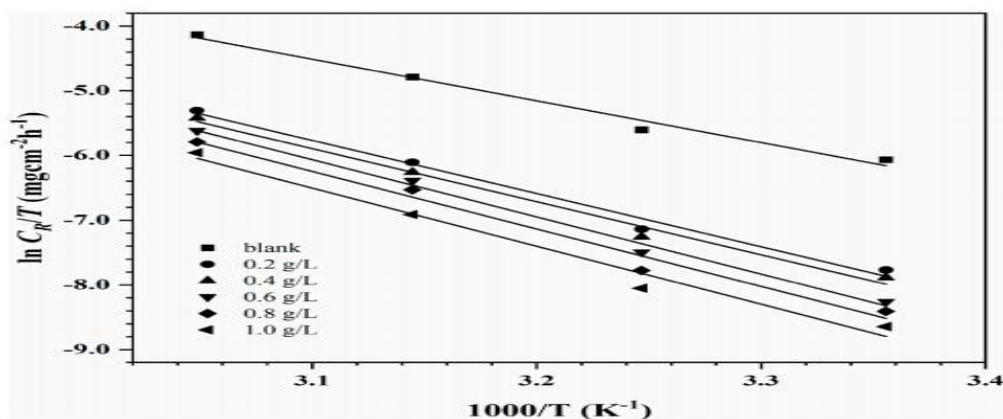


Fig. 2 Plots of Titanium Nanocomposite (Ti-Co) excellently inhibit acidic corrosion at 298 K and 328K temperatures [112].

The research by Basheer et al. [143] focused on corrosion problems in surface facilities within the oil industry by exploring how nanocomposite inhibitors have become prevalent for solving this issue. The research examined how to prepare and evaluate the corrosion-inhibiting properties of the novel nanocomplex $TiO_2 \cdot B_2O_3$ -[TBID] intended for carbon steel (CS.45). The alloy and environmental conditions duplicate the conditions present in the southern Iraqi Halfaya oilfield. The analytical tools X-ray diffraction, energy dispersive X-ray, atomic force microscopy, field emission scanning electron microscopy, transmission electron microscopy, FT-IR spectra and nuclear magnetic resonance spectroscopy (¹H-NMR) were employed to characterise the prepared nanocomposite. Researchers used an electrochemical corrosion test cell (Tafel plots) to examine the performance of the $TiO_2 \cdot B_2O_3$ -[TBID] inhibitor. Researchers evaluated carbon steel test samples throughout multiple inhibitor concentration levels (100, 200, 300, 400, and 500 ppm) within a 1 M HCl solution at 35°C. The point of maximum inhibition efficiency reached 99.91% when using a 100 ppm concentration of $TiO_2 \cdot B_2O_3$ -[TBID] inhibitor within the acidic solution.

Basik et al. [62] conducted research on Cys/Ag-Au NCz synthesis by applying FTIR, XRD, UV-Vis, SEM, EDAX, TGA, and TEM analytical methods to characterize the cysteine-based silver-gold nanocomposite. The combination of gravimetric analysis with PDP and EIS alongside SEM and EDAX confirmed the inhibitor achieves an inhibition efficiency of 96% at 303 K and 300 ppm concentration in 1M HCl solution. The nanocomposite substance acted as a mixed-type inhibitor that influenced anodic and cathodic processes while forming a protective surface film on steel through adsorption that followed Langmuir isotherm conditions according to EIS and SEM results. Aslam et al. [75] synthesised ZrO_2 -Glycine nanocomposites (ZrO_2 -Gly NC) by environmentally friendly synthetic methods. The authors evaluated how well their nanocomposite inhibitor protected mild steel from corrosion in 1M HCl solutions.

The highest inhibition efficiency of 81.01% was reached by the solution containing 500 ppm and operating at 70°C, yet the inhibition decreased slightly at 80°C. The nanocomposite acted as a mixed-type inhibitor which followed the Langmuir isotherm during adsorption. Surface testing showed that the steel surface developed a surface film that acted as a protective layer.

The evaluation of CdO nanoparticles (CdO-NPs) as carbon steel corrosion inhibitors in 0.5 M H₂SO₄ used potentiodynamic polarisation (PDP), electrochemical impedance spectroscopy (EIS) and weight loss measurements in the study by Sivalingam et al. [144]. A higher concentration of CdO-NPs blocked all active corroding sites while simultaneously decreasing the cathodic currents. The aggressive environment mass loss of mild steel decreased while inhibition efficiency improved when CdO-NP concentration increased during the study. The FT-IR, XRD and SEM-EDX spectroscopy examined newly prepared CdO-NPs. A similar investigation was conducted by Al-Senami [63] who studied ZnO nanoparticles obtained from *Convolvulus arvensis* leaf extract and expired ZnCl₂ for carbon steel corrosion suppression in 1 M HCl. Analysis through SEM showed that the ZnO nanoparticle solution existed within the range of 0.006 - 0.12 mg/mL (Fig. 3). The tests for corrosion inhibition assessment, including potentiodynamic polarisation, EIS and weight loss, showed improved protective efficiency with elevated nanoparticle ZnO concentrations. The inhibitory mechanism fit into a mixed-type category with an efficiency rate surpassing 89%, while the Langmuir mechanism proved the adsorption pattern. The thermodynamic data showed an exothermic adsorption process which took place spontaneously while acting as a mixed mechanism. The surface of carbon steel showed a protective film according to SEM images. The inhibition efficiency of nanoparticles used for corrosion protection is presented in Table 2.

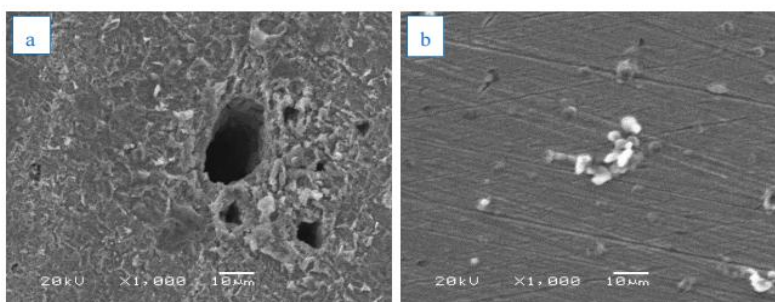


Fig. 3. SEM images of carbon steel immersed in (a) 1 M HCl and (b,) also in the presence of 0.06 mg/ml of ZnO-Nanomaterial for 3 h at 298 K [63].

Table 2. Nanoparticles Inhibition Efficiency Summary

S/N	Nano particles Types	Metallic substrate	Media	Inhibition Efficiency (%)	Ref.
1	Ti-CO	Mild steel	1M HCl	91.36%	[112]
2	NiNPs	X80 Steel	1M HCl	91.90%	[145]
3	AgNPs	X80 Steel	Injection well and flow station water	76.20%	[146]]
4	AgNPs	Mild steel	1M HCl	70.50%	[147]
6	CuONPs	mild steel	3.5%NaCl	56%	[148]
7	NiNPs	X80 steel	1M HCl	94.40%	[149]
10	<i>Fe NP</i>	mild steel	1M HCl	92%	[150]
11	ZnO-NPs	Low carbon steel	1M HCl	92.00%	[113]
12	LPM NPs	mild steel	1M HCl	72.63%	[144]
15	(CoO/Co ₃ O ₄ NPs	Mild steel	1M HCl	93%	[142]

18	CuO NPs	Mild steel	1M HCl	95.06%	[126]
19	CuoNPs	Ti-6Al-4V alloy	Dental solution	58%	[152]
20	CdO-NPs	Mild steel	0.5M H ₂ SO ₄	89.09%	[144]
21	Zno NPs	X65 Steel	1M HCl	91%	[63]
23	Cys/Ag-Au Nps	Mild steel	1M HCl	96%	[62]
24	ZrO ₂ -Gly	Mild steel	1M HCl	73.50%	[75]
25	CuO	X60 steel	5% HCl	90.35%	[153]
26	AgNPs	Mild steel	1M HCl	96.40%	[154]
27	TiNPs	Mild steel	1M HCl	84.27%	[155]
28	AuNPs	Aluminum, mild steel and Stainless steel	1M HCl	88%, 98% and 96% respectively	[156]
30	AgNPs	Mild steel	0.5M HCl	70%	[157]
31	AgNPs	Mild steel	Recirculating Cooling Water System	59%	[158]
32	AgNPs	Mild steel	Simulated seawater	90%	[114]
33	Y ₂ O ₃ NPs	Cabon steel	CaCl ₂ solution	78.74%	[159]
34	ZnONPs	Mild steel	1M HCl	77.31%	[160]
35	ZnONPs	Mild steel	1M HCl	98.50%	[161]
36	ZnONPs	Carbon steel	1M HCl	78.50%	[162]
37	AgNPs	Steel	1M HCl	86.69%	[163]
38	CeCO ₂	Mild steel	0.1M HCl	89.4	[116]
39	CuO	Copper	3.5%NaCl	86.7	[22]

2.5 Critical Assessment of Nanoparticle-Based Corrosion Inhibitors

The comprehensive evaluation of nanoparticles for corrosion inhibition requires not only efficiency reporting but also an analysis of performance disparities among different nanoparticles, alongside considerations of synthesis trade-offs and reproducibility issues across studies. The superior performance of certain nanoparticles, such as ZnO and Ag-based composites, is primarily attributed to their high surface-area-to-volume ratio, chemical inertness, and strong adsorption capabilities, which enable the formation of stable and protective surface films [75, 130]. These nanoparticles typically possess functional groups such as hydroxyl, amine, and carboxyl groups that enhance adhesion to metal surfaces and contribute to the development of dense, adherent layers that inhibit both anodic and cathodic reactions. Furthermore, their morphological features, such as spherical or rod-like shapes, promote effective surface coverage and improved inhibition efficiency, especially under aggressive environmental conditions. Multiple studies have confirmed that the physicochemical characteristics of nanoparticles critically influence their corrosion resistance properties [68, 164]. However, despite their potential, nanoparticles produced through different synthesis methods face specific challenges. Green synthesis methods using plant extracts, fungi, or microbial agents are gaining attention due to their eco-friendliness, low cost, and scalability. Yet, they often suffer from broader particle size distributions, non-uniform morphologies, lower crystallinity, and a higher tendency for particle aggregation. These factors can reduce the consistency and effectiveness of corrosion inhibition [165-172]. In contrast, methods like sol-gel synthesis, chemical vapour deposition, and laser ablation yield nanoparticles with more uniform sizes, controlled shapes, and high purity, resulting in superior performance. However, these approaches are often associated with high production costs, poor scalability, low reproducibility in large-scale batches, and environmental concerns due to the use of toxic solvents and high energy input. This highlights a critical trade-off: while green-synthesised nanoparticles are generally more sustainable and economically viable for large-scale deployment, their corrosion-inhibiting performance often requires further optimisation [173]. Specifically, controlled synthesis protocols are needed to improve particle uniformity, morphology, and long-term stability. Additionally, although biosynthesis is promoted as an eco-friendly approach, it is important to note that some processes may still involve the use of toxic solvents or chemical agents during post-synthesis purification and treatment steps. These factors must be carefully considered when evaluating the overall environmental and performance profiles of biosynthesised nanomaterials for corrosion protection. This highlights a critical trade-off: while green-synthesised nanoparticles are more sustainable and economically viable for large-scale deployment, their corrosion-inhibiting performance [174-177].

Another issue with respect to reproducibility in nanoparticle corrosion inhibition with green synthesis is the variation in green precursors. There is no standardisation for plant species, harvesting time, location, and extraction procedure, leading to variations in the physical and chemical properties of synthesised nanoparticles that are relevant for inhibition performance. Further variations in experimental setup, substrate, media, and characterisation methods contribute to poor reproducibility across studies and laboratories. Absence of common guidelines for synthesis and testing leads to inconsistent and inapplicable benchmarks for comparison and hence a low chance of industrial implementation. It is proposed that one must address these challenges in terms of understanding the factors affecting the performance, balancing synthesis trade-offs, and improving reproducibility in order to pave the way for using green-synthesised nanoparticles as effective corrosion inhibitors [178].

2.6 Critical Parameters Affecting Nanoparticle-Based Corrosion Inhibition: Standardization, Surface Chemistry, Morphology, and Environmental Performance

Despite significant progress in the development of nanosized corrosion inhibitors, especially those from green synthesis, several critical issues are yet to be addressed. They include the absence of unified test protocols, lack of clear understanding of the role of surface functionalisation, the contribution of morphological variations, and the diversity in assessment in different media. These issues need to be addressed in order to enhance the reproducibility, comparability and industrial implementation of the nanoparticle inhibitors.

2.6.1 Standardized Testing Protocols and Reproducibility

The key challenge of inconsistency in the experimental setup is that the majority of the reports used variable durations of the test time, concentrations of the electrolyte, methods of the sample surface preparation, and temperatures, which could result in inconclusive data and a lower reproducibility rate among different laboratories. This difference leads to difficulties in comparing results from different research laboratories, which use the same experimental methodology and method of evaluation (PDP, EIS, weight-loss measurement) [60]. There are ASTM G1, G31, and ISO 16773 international standards that regulate the corrosion evaluation process, but several studies do not report whether or not the research process adhered to them, which makes it challenging to reproduce and translate them to an industrial scale [76]. The immersion time varies from 1 h to several days, and the electrolyte solution could have different pH, which has a significant impact on the corrosion rate. Another issue is the reporting of the concentration of the inhibitors, the roughness of the test coupon, and the statistical interpretation of the electrochemical data. Baig et al. [60] noted that this inconsistency makes it impossible to conduct a meaningful meta-analysis and set a performance threshold. The researchers proposed the use of a standardised test methodology where researchers should not only report the efficiency of the inhibitor but also report the standard deviation, surface characterisation, and mechanistic information of the test conditions [30,130]. If this standardisation cannot be reached, the promising green synthesised nanoparticles might not perform as well as expected in the field environment because the test condition is not controlled.

2.6.2. Surface Functionalization and Chemical Interaction

Surface functionalisation has a significant effect on adsorption efficiency and corrosion inhibition of nanoparticles. The presence of functional groups such as $-\text{COOH}$, $-\text{OH}$, $-\text{NH}_2$, and $-\text{SH}$ provides multiple bonding options, including electrostatic adsorption, hydrogen bonding, and chemical bonding with metal surfaces. Nanoparticles decorated with plant-derived phytochemicals, biopolymers, or amino acids exhibit strong adherence and stability on metal substrates, producing thicker and more effective inhibition films. For example, ZrO_2 nanoparticles functionalised with glycine displayed better film formation and corrosion inhibition of mild steel by electrostatic and chemical adsorption [68]. Moreover, Vera et al. [174] found that ZnO nanoparticles prepared using plant extract rich in polyphenols exhibited higher inhibition efficiency due to better surface interaction.

2.6.3 Influence of Nanoparticle Size, Shape, and Morphology

Particle size, shape, and surface area play a critical role in determining the efficiency of nanoparticle-based corrosion inhibitors. As particle size decreases, the surface-area-to-volume ratio increases, enhancing the likelihood of contact between the nanoparticles and the metal surface. This promotes the formation of dense, coherent, and adherent protective films that effectively block the ingress of corrosive agents. Nanoparticles with regular shapes, such as nanospheres and nanorods, ensure more uniform distribution across the metal surface, reducing uncoated or poorly

covered regions that could serve as initiation points for localised corrosion. Conversely, irregularly shaped nanoparticles often lead to patchy coverage, reducing the overall protective efficiency. For example, Thakur et al. [175] reported that ZnO nanospheres with an average diameter of ~25 nm provided significantly better corrosion resistance compared to irregularly shaped aggregates averaging 80–120 nm, due to improved surface coverage and film integrity. Similarly, Ituen et al. [147] demonstrated that shape-controlled silver nanoparticles (AgNPs), predominantly spherical with diameters around 15–20 nm, yielded more compact and uniform protective layers on mild steel surfaces, resulting in lower corrosion current densities compared to non-uniform counterparts. Beyond initial performance, these morphological characteristics also influence the long-term stability of the protective films under real-world field conditions. Spherical and uniformly shaped nanoparticles tend to maintain structural coherence and adhesion over time, even under thermal cycling, mechanical stress, and prolonged exposure to aggressive environments. In contrast, films formed by irregular particles are more susceptible to cracking, delamination, or dissolution, leading to compromised protection over extended durations. Therefore, further research is needed to improve shape and size control, particularly during green synthesis methods, to ensure consistent performance, durability, and reliability of nanoparticle-based corrosion inhibitors in various service conditions.

2.6.4 Environmental Variability in Inhibitor Performance

Nanoparticle performance is strongly influenced by the type of corrosive medium, acidic, saline, or alkaline, as each environment alters surface charge interactions and stability. In acidic media, the metal surface typically becomes positively charged, promoting the adsorption of negatively charged or polar nanoparticles. This enhanced adsorption facilitates the formation of dense protective films, and corrosion inhibition efficiencies exceeding 90% have been reported for ZnO, TiO₂, and Fe₃O₄ nanoparticles in acidic conditions [116, 176]. In saline environments, such as 3.5% NaCl solutions, corrosion is primarily driven by aggressive chloride ion activity, which leads to pitting and localised attack. Compared to acidic media, the formation of a long-lasting barrier layer is more challenging due to chloride ion penetration. However, composite or polymer-modified nanoparticles have shown improved performance under these conditions because of enhanced film-forming ability, chloride ion scavenging, and increased chemical stability. For example, Ti-Co composites have demonstrated the ability to form robust passive layers that effectively block Cl⁻ ion ingress [109]. In contrast, studies on corrosion inhibition in alkaline media are relatively limited, largely due to the additional challenges posed by high pH environments. Alkaline conditions can destabilise many nanoparticles, leading to aggregation, poor dispersion, or alteration of surface functional groups, all of which reduce their protective efficacy. For instance, unmodified metal oxide nanoparticles tend to agglomerate in high-pH solutions due to decreased electrostatic repulsion, forming non-uniform coatings with limited adhesion and coverage [178]. One study by Kumar et al. [177] noted that Fe₃O₄ nanoparticles required surface modification with silane coupling agents to maintain dispersion and effectiveness in alkaline solutions. Such modifications can enhance particle stability, improve binding to the metal surface, and ultimately increase corrosion resistance. Therefore, tailoring the surface chemistry of nanoparticles through functionalisation or composite formation is critical in each corrosive medium to ensure effective protection. In alkaline media particularly, strategies to mitigate aggregation and improve dispersion remain essential for optimising the long-term performance and service life of nanoparticle-based corrosion inhibitors [179, 180]. Table 3 presents a summarised nanoparticle type mechanism, substrate and performance across environments.

Table. 3 Summary of Nanoparticles ,Mechanism and performance across various environments

S/N	Nanoparticles Type	Mechanism	Substrate	Performance across various Environments	Ref.
1	CuO Nps	Barrier layer formation, anodic inhibition	Copper	86.2% in 3.5% NaCl and 74.5% 2 mg/l NH ₃ respectively	[179]
2	AgNPs	Adsorption, protective film	Carbon steel	90.95 in 1M HCl Solution	[180]
3	PDANPs	Film formation, adsorption	Mild steel	86% in 1M HCl Solution	[139]
4	IONPs	Barrier and hydrophobic protection	Mild steel	80.88% in 0.5M HCl Solution	[140]

5	PANI/Ti ₂ NPs	Barrier and self-healing properties	Aluminum alloy(AI1050)	91.91% in 3.5% NaCl Solution	[141]
6	Mn ₂ O ₃ NPs	Passive film formation	Carbon steel	55.6% in 0.5M HCl Solution	[181]
7	SiO ₂ NPs	Barrier protection	Mild steel	45.5% in 1%HCl and 77.75% in 3.5% NaCl Solution respectively	[182]
8	CuO NPs	Adsorption inhibition	Mild steel	56% in 3.5% NaCl Solution	[148]
9	CdO NPs	Adsorption film	Mild steel	86% in 0.5M H ₂ SO ₄ Solution	[144]
10	Et-OME-NiNPs	Barrier and hydrogen evolution inhibition	Stainless steel	91.9% in 1M HCl Solution	[145]
11	AgNPs	Biocide and corrosion resistance	X80 Steel	93.9% in 1M HCl Solution	[146]
12	Chitosan–CuO	Barrier, enhanced by KI	X60 Steel	90.35 % in 5% HCl Solution	[153]
13	CoO/Co ₃ O ₄	Film formation	Mild steel	93% in 1M HCl Solution	[142]
14	AuNPs	Inhibition layer formation	Aluminum, mild steel and Stainless steel	88%, 98% and 96% respectively in 1M HCl Solution	[183]
15	Y ₂ O ₃ NPs	Film barrier	Carbon steel alloy	78.74% in CaCl ₂ solution	[159]
16	ZnONPs	Complex adsorption	Mild steel	98.5% in 1M HCl Solution	[161]
17	ZnONPs	Surface adsorption	Carbon steel	78.5% in 1M HCl Solution	[156]
18	CAPE-AgNPs	Adsorption film formation	Stainless steel	70% in 0.5M HCl Solution	[157]
19	ZnO	Barrier effect	Stainless steel	72% in 1M HCl Solution	[113]
20	Ti NPs	Adsorption film	Mild steel	84.27% in HCl Solution	[155]
21	AgNPs	Surface modification	Mild steel	86.69% in 1M HCl	[163]
22	AgNPs	Biofilm protection	Mild steel	59% in water system	[158]
23	AgNPs	Film formation	Mild steel	90% in Simulated seawater	[114]
24	CuONPs	Passive film resistance	Ti-6Al-4V alloy	58% in dental solution	[152]
25	SiO ₂ NPs	Hydrophobic coating	Aluminum	45% in 1% HCl and 77.5% in 3.5% NaCl Solution respectively	[182]
26	AgAuNPs	Film formation	Mild steel	96.1% in 1M HCl Solution	[183]
27	MnO NPs	Film barrier	Mild steel	92.5% in 1M HCl Solution	[184]
28	CoGO NPs	Protective barrier	Mild steel	51.46% in HCl Solution	[50]
29	WO ₃	Protective layer barrier	Steel alloy	79.66% in 3.5% NaCl Solution	[185]
30	Co ₃ ZnFe ₂ O ₃	Film formation	Carbon steel	74% in seawater	[186]

2.7 Research Trends in Nanoparticle-Based Corrosion Inhibition

Metal oxide nanoparticles such as ZnO and TiO₂ were explored in the early decade for their potential as a simple barrier to corrosion in mild steel. Progressively, more complex nanocomposites with multi-functional ingredients, such as conductive polymers, carbon-based nanomaterials, and green-synthesised nanoparticles, began to be explored [186]. The materials have been extended to bio-based, eco-friendly, and smart materials that can exhibit self-healing and responsive properties [157, 161]. The range of substrates has also expanded to include oilfield and marine alloys, in addition to the more commonly used mild steel. These developments illustrate the shift from laboratory-scale corrosion protection to the development of industrially applicable and sustainable formulations. Table 4 depicts research trends in nanoparticles as a corrosion prevention approach from 2011 to date.

Table 4. Research trends in nanoparticles as a corrosion prevention approach from 2011 to date.

S/N	Period	Research Focus	Nanoparticle Types	Target Metals	Key Developments	References
1	2011–2014	Early-stage applications, basic coating methods	TiO ₂ , ZnO, AgNPs, Fe ₃ O ₄	Mild steel, carbon steel	Barrier protection, passive film formation	[138]
2	2015–2017	Functional nanocomposites, green and conductive	CNTs, MnO ₂ , polypyrrole–TiO ₂ , ZnFe ₂ O ₄	Stainless steel, aluminum	Multifunctionality, pigment-based inhibition, electrochemical enhancements	[180]
3	2018–2020	Green synthesis, hybrid and plant-based systems	AgNPs, CuO, NiO, graphene oxide, Co ₃ O ₄	Carbon/mild steel, Cu	Use of biomass extracts, nano–bio hybrids, increased EIS usage	[179,181]
4	2021–2023	Smart, eco-efficient systems	ZnO–Tyrosine, Triumphetta nanocomposites, AuNPs	X80 steel, marine alloys	Biodegradable materials, self-healing/responsive coatings, modeling corrosion mechanisms	[75.112]
5	2024–Present	Industrial translation, multifunctional systems	CdO, Murraya–CuO, CoO/Co ₃ O ₄ , Onion–Ni NPs	Oilfield pipes, alloys	Large-scale synthesis, multifunctionality, targeted anticorrosion with biocidal and thermal resistance traits	144]

2.8 Future Constraints and Directions

The application of different nanoparticulate materials shows effective performance as metal corrosion inhibitors. The development of eco-friendly nanoparticles through green sources along with natural, sustainable materials remains an essential goal. The main bottleneck in green synthesis techniques stems from their non-uniform nature. Nanoparticle production based on environmental sources results in variations in particle size, shape, and surface attributes, all of which influence their corrosion inhibition performance [187]. These inconsistencies are driven by variability in raw material composition, environmental conditions, and the extraction or synthesis methods used. As a result, the reproducibility of scientific research using environmentally derived nanoparticles is often limited, hindering their broader industrial application [188]. Furthermore, natural raw materials used in green synthesis, such as plant extracts, are also vital resources in industries like food processing, pharmaceuticals, and cosmetics. Their limited availability due to cross-industry competition presents an additional constraint. Environmental nanoparticles also face challenges in maintaining structural and chemical stability under corrosive conditions. Biologically derived nanoparticles can degrade over time, especially when exposed to extremes of temperature, humidity, or pH. The

corrosion protection mechanism depends not only on the nanoparticles' ability to form strong bonds with metal surfaces but also on their long-term stability across diverse chemical environments. However, the understanding of these interfacial interactions remains limited, contributing to inconsistent performance across different metals and corrosive media [189]. Looking forward, waste-to-nanomaterial conversion offers promising potential for sustainable nanomaterial production. This refers to the process of transforming renewable waste resources into functional nanoparticles; for instance, rice husk can be converted into silica nanoparticles, which have shown promising anti-corrosive properties [190]. Similarly, coconut shells, fruit peels, and other agricultural residues can be processed to produce metal oxides or carbon-based nanomaterials. Additional research is needed to optimize this conversion process, improve nanoparticle stability, and enhance corrosion resistance. Importantly, integrating agricultural waste into nanoparticle synthesis supports environmental sustainability by reducing pollution and resource consumption [191, 192]. Moreover, nanoparticles synthesised from multiple biomass sources may lead to advanced hybrid systems with improved effectiveness and durability. Industrial waste streams and wastewater, rich in reusable materials like silica or metal ions, also represent untapped resources for nanomaterial production. Recent studies highlight the potential of carbon quantum dots (CQDs) as non-toxic, environmentally friendly corrosion inhibitors. For example, CQDs derived from sugarcane fruit and melon seed shell waste have demonstrated excellent corrosion protection for mild steel in acidic environments [193-197]. Their high surface area and abundance of reactive surface groups make CQDs ideal candidates for future corrosion protection technologies. Continued development of hybrid nanocomposites and improved green synthesis approaches will be essential for achieving high-performance, long-lasting protection in harsh corrosive conditions [198,199]. Figure 4 represents the future directions of nanoparticles for corrosion protection applications.

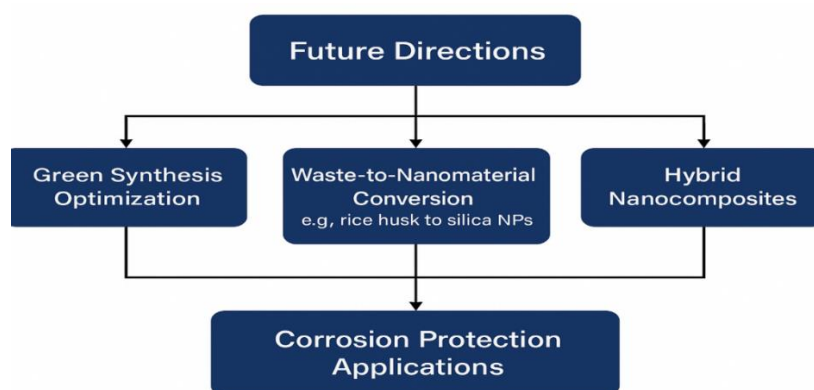


Fig.4. Flowchart showing future directions of nanomaterials for corrosion protection application

2.9 Environmental and Regulatory Considerations in the Use of Green-Synthesized Nanoparticles for Corrosion Protection

Although green synthesis of nanoparticles is often promoted as an environmentally friendly alternative to conventional chemical synthesis, it is crucial to consider the environmental hazards and regulatory challenges associated with the large-scale use of nanoparticles in corrosion inhibition applications. Even though green synthesis uses natural plant extracts, microorganisms, or biodegradable polymers in the synthesis, the final product, i.e., nanoparticles (especially those produced at the nanoscale), still pose ecological and toxicological hazards when released into the environment. Nanoparticles, irrespective of their origin, may have the potential to persist, bioaccumulate, and be toxic to aquatic organisms and soil microflora. For example, it has been demonstrated that even green-synthesised ZnO and Ag nanoparticles can affect cellular functions in algae and fish at low concentrations [116]. In addition, the stability and fates of nanoparticles in industrial media (e.g., cooling water, oil pipelines, ships) need a critical investigation. The leaching, agglomeration, or transformation of nanoparticles at different pH, temperature, or ionic strength can lead to secondary environmental impacts that are still not fully understood [60]. Although green synthesis reduces synthetic toxicity during production, it does not remove all of the risk caused by the nanoparticle itself. From the perspective of regulation, the governance of nanomaterials (including corrosion inhibitors) is not coordinated. Many countries have no framework for nanoparticle-based products, and the existing chemical safety laws (REACH in the EU, TSCA in the US) may not take into account the unique characteristics and behaviours of nanomaterials. In addition, there is no

unified protocol for ecotoxicological testing of green-synthesized nanoparticles, which makes it difficult to approve and commercialize them [60]. To address these issues, researchers and regulatory bodies need to develop comprehensive risk assessment frameworks, unified ecotoxicological testing protocols, and life cycle assessments for green nanomaterials. The use of biodegradable or self-degradable nanoparticles should be encouraged, as well as end-of-life impact assessments. Taking into account the impact on the environment from the beginning will ensure that the environmental benefits of green synthesis are not negated by potential environmental risks [200].

3.0. Conclusion

The present study examined recent advancements in green-synthesized nanoparticles as corrosion inhibitors, emphasizing natural and plant-based nanomaterials. These materials are increasingly favoured for their biodegradability, low toxicity, cost-effectiveness, and environmental compatibility. However, transitioning from laboratory success to industrial deployment requires a structured research framework. Standardized green synthesis methods, such as using well-characterized plant extracts, microbe-mediated routes, or enzyme-assisted techniques, are essential to control particle size, morphology, and surface chemistry, which directly influence inhibition performance. Beyond extensively studied nanoparticles like ZnO, TiO₂, and Fe₃O₄, underexplored candidates such as cerium oxide (CeO₂), graphene oxide-based hybrids, and biodegradable polymer-based nanoparticles (e.g., chitosan-coated NPs) merit investigation. These materials offer potential advantages in film formation and self-healing behaviour under corrosive conditions yet remain insufficiently characterized. A major knowledge gap persists in understanding the inhibition mechanisms at molecular and atomic scales. While adsorption and film formation are widely accepted, deeper mechanistic insights require advanced techniques such as in situ electrochemical AFM, XPS depth profiling, and DFT modelling to elucidate the role of surface functionalities under varied environmental conditions. For industrial application, critical challenges include batch-to-batch reproducibility, environmentally benign scale-up processes, regulatory compliance, long-term field testing, and comprehensive life-cycle assessments to evaluate durability, toxicity, and environmental fate. In summary, standardized synthesis protocols, mechanistic validation, and regulatory alignment remain critical for industrial transition of green-synthesized nanoparticles as next-generation corrosion inhibitors.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author's contribution

B. U. O conceptualize the research; S.O.O wrote the manuscript; B. U. O and S.O.O reviewed the manuscript.

4.0. References

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