

Green Nanostructured Corrosion Inhibitors for Steel in Saline and Acidic Media: Mechanisms and Effects of Concentration and Temperature: A Review

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Abstract

The increasing demand for sustainable corrosion protection has driven significant research interest toward green and nano-enabled corrosion inhibitors. This review critically examines recent advances in plant-based and bio-assisted nano-inhibitors, with particular emphasis on the influence of inhibitor concentration and temperature on corrosion inhibition performance. A comprehensive analysis of reported studies reveals that increasing nano-inhibitor concentration generally enhances inhibition efficiency due to improved surface coverage and adsorption stability, reaching optimal performance at specific concentration ranges.

Temperature plays a dual role in corrosion inhibition behavior, while elevated temperatures often accelerate corrosion processes, effective nano-inhibitors maintain high inhibition efficiency through strong chemisorption or mixed adsorption mechanisms. Thermodynamic and kinetic parameters, including activation energy and Gibbs free energy, are systematically reviewed to elucidate adsorption behavior and temperature sensitivity. Comparative evaluation using gravimetric, electrochemical impedance spectroscopy (EIS), and potentiodynamic polarization (PDP) techniques demonstrates that several green-synthesized nanoparticles achieve inhibition efficiencies exceeding 90% in aggressive acidic and environments such as HCl and NaCl media.

This review provides a unified and comparative perspective on the combined effects of inhibitor concentration and temperature on the performance of green-synthesized nano-corrosion inhibitor, an aspect that has not been systematically addressed in previous review. Unlike earlier studies that primarily focus on inhibitor efficiency under fixed experimental conditions, this work correlates concentration-dependent inhibition behavior with thermal stability and adsorption mechanisms across different acidic and saline media. By integrating electrochemical, gravimetric, and thermodynamic analyses from recent literature, this review identifies critical concentration thresholds and temperature regimes governing nano-inhibitor effectiveness, thereby offering new insights for rational design and optimization of eco-friendly nano-inhibitors for practical corrosion control applications.

Keywords :- *Green corrosion inhibitors; Nanostructured; Mild steel; Carbon steel; Acidic media; Saline environments; Inhibition Efficiency; Inhibitor concentration; Temperature effect; Eco-friendly materials.*

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Introduction

An unavoidable natural process, corrosion presents serious problems for infrastructures, businesses, and environmental settings[1]. Globally, the ongoing deterioration of metallic structures—particularly mild steel—due to corrosion causes significant financial losses as well as negative environmental effects[2]. In addition to endangering the materials' structural integrity, this degradation has a detrimental effect on ecosystems and public safety. Corrosion's effects on the environment are a complex issue. Water quality, agricultural production, and biodiversity are all negatively impacted when metal ions and rust byproducts are released into soil and water systems[3].

In response to environmental interactions, metals naturally experience corrosion, an electrochemical process that erodes the metal's surface[4]. The two main elements that lead to corrosion are moisture and oxygen since they trigger the formation of corrosion cells. Corrosion may take several forms, such as tarnish on copper and brass and rust on iron and steel. Corrosion is a major problem in many industries because it compromises the integrity of infrastructure and operational efficiency[5]. Over \$2.5 trillion is spent annually on corrosion globally[6]. The corrosion of pipelines in the oil and gas sector raises the risk of spills and environmental damage. According to NACE study, the annual cost of corrosion to the oil and gas industry \$1.372 billion is the producing industry[7]. This sum may be split into three categories: \$589 million for surface pipeline and facility costs, \$463 million for annual downhole tube expenses, and an extra \$320 million for capital expenditures due to corrosion[8]. In these conditions, corrosion may be roughly classified as either sweet or sour, with the former mostly taking place in settings with high partial pressures of CO₂ and H₂S (P_{CO2} and P_{H2S}) [9]. Sweet and sour corrosion is the most prevalent kind and the main cause of corrosion-related problems in the oil and gas sector. The maritime industry combats corrosion in ships and offshore constructions because they are subjected to corrosive saltwater conditions. Corrosion expenses in the maritime sector range from \$50 to \$80 billion annually, excluding indirect costs[10].

Numerous chemical and inorganic inhibitors are created and employed to address this problem[11]. Organic and inorganic chemical inhibitors, which work by adhering to metal surfaces and creating protective layers, are a major component of conventional corrosion prevention techniques. Although many of these inhibitors are linked to toxicity, they can successfully lower corrosion rates, environmental tenacity and legal limitations. Therefore, the hunt for greener options that strike a balance between efficiency and ecological responsibility has been fueled by growing awareness of environmental sustainability [12].

Review Methodology

This review was conducted based on a literature search performed using Scopus and Google Scholar, covering studies published between 2014-2026. The search employed combination of the following keywords: “green corrosion inhibitor”, “green synthesized nanoparticles”, “carbon steel”, “mild steel”, “inhibition efficiency”.

Studies were included if they met the following criteria : (i) the corrosion inhibitor was synthesized via green/biological route (plant extract, biopolymer, or other biogenic reducing/stabilizing agent), (ii) the inhibitor was evaluated specifically on mild steel or carbon steel substrates, (iii) the corrosive medium was an acidic solution (HCl or H₂SO₄) or a saline (NaCl) solution, and (iv) the study reported quantitative inhibition efficiency (%IE) as a function of inhibitor concentration and temperature, using at least one standard evaluation technique weight loss (WL), potentiodynamic polarization (PDP), or electrochemical impedance spectroscopy (EIS).

Studies were excluded if: (i) the inhibitor was evaluated on substrates other than mild steel or carbon steel (e.g., copper, aluminum, zinc, or stainless steel), or (ii) the corrosion inhibitor was based on plant extracts prepared in their conventional (non-nanostructured) form, without nanoparticles synthesis. A total of 36 studies meeting these criteria were compiled and are summarized in table 1.

Corrosion Inhibition using Nanomaterials

Considering their distinct physicochemical characteristics, high surface-area-to-volume ratio, and adjustable surface chemistry, green-synthesised nanoparticles have drawn interest as novel corrosion inhibitors. Usually, microbes, plant extracts, or other biological agents that serve as stabilizing and reducing agents, doing away with the necessity for dangerous chemicals. These synthesis methods add bio-organic molecules that improve adsorption onto metal surfaces while also lessening their influence on the environment. [13].

nanoparticles having a mean diameter between 1 and 100 nanometers, and they have distinctive qualities that set them apart from their bulk counterparts[14]. These traits quantum effects and their larger surface area are responsible for their properties. To create nanoparticles with precise size, shape, and composition, several techniques are used, including chemical, physical, and biological ones[15].

According to recent research, metal nanoparticles with significant corrosion prevention efficiency in acidic environments include silver, zinc oxide, copper oxide, and iron nanoparticles.

Additionally, metal sulfide nanoparticles-especially silver sulfide-show better performance. Because of their combined ionic-covalent bonding, they have more stability and surface contacts. Despite these developments, there is still little knowledge on metal versus metal sulfide nanoparticles, particularly those made using environmentally friendly methods[16].

In medicine, nanoparticles are used to accurately and minimally deliver drugs with adverse effects[17]. Nanoparticles enhance component performance in electronics performance and the effectiveness of the gadget[18]. They are employed in environmental research to filter water and eliminate contaminants[19]. Furthermore, since they make it easier to create new materials with improved conductivity, strength, and other desired properties, nanoparticles are essential to the study of material science[20]. Other uses for nanoparticles include energy storage, catalysis, imaging, and sensors, which show how versatile they are in solving different issues and advancing several industries[21]. Recently, green nanoparticles—which originate from sustainable sources—have drawn a lot of interest as efficient corrosion-prevention agents[22].

Green Synthesis of Nanocorrosion Inhibitors from Plant Extracts

The use of nanotechnology in corrosion mitigation increases the longevity and general performance of materials and contributes to the development of sustainable and eco-friendly solutions in a variety of industries[23]. Green nanocorrosion inhibitors are showing promise as economical and environmentally friendly corrosion prevention techniques in a variety of industries[24]. Because they are derived sustainably from plant extracts or biopolymers, these inhibitors have a number of benefits over traditional chemical inhibitors. Greater adhesion to metal surfaces and improved surface coverage are made possible by their nanoscale size, which create a stronger protective barrier against corrosive substances[25]. Their eco-friendliness ensures that their use, manufacture, and disposal have minimal negative effects on the environment[26]. Since green nanocorrosion inhibitors solve industry-specific corrosion challenges and are in line with the growing worldwide emphasis on green and sustainable technology[27-30]. Numerous research examining the ability of green nanoparticles to resist corrosion over an extended period of time have shown encouraging results. Time. For example, research has shown that green nanoparticles comprised of biopolymers or natural extracts can provide long-lasting corrosion protection for a variety of metals, including copper, aluminum, and steel, in hostile environments like those found in industrial or maritime settings. For example, Fetouh et al. discovered that the corrosion inhibition effect of silver nanoparticles, based on silver nanoparticles-chitosan (CT) nanocomposite (NC), for mild steel in chilled water circuits remained effective and showed comparable inhibition efficiency even after a year of aging. Two-hour freshly produced samples had an IE of 97.6%, whereas one-year-old samples had an IE of 95.5%. [31].

Table 1 : Green Nanoinhibitors for Steel Corrosion Conditions and Efficiency

SN	Plant Name	Plant part	Nano particle	Med.	Alloy used	Conc. rang	Temp. rang (K)	Max %IE and Tech.	Ref
1	<i>Pomegranate peel</i>	Fruit	Fe ₃ O ₄ -NPs	1M HCl	Carbon Steel	(3-11)×10 ⁻⁶ M	298-318	75.2 at WL	32
2	<i>Cassia fistula</i>	leaves	WO ₃ -NPs	1M HCl	Mild-steel	(50-500) ppm	----	85	33
3	<i>Tobacco</i>	leaves	AgNPs	1N HCl	Carbon Steel	(50-200) ppm	303-333	97.9 at WL 95.3 at PDP 93.2 at EIS	34
4	<i>Brassaiopsis hainla</i>	leaves	AgNPs	1M HCl	Carbon Steel	(200-1000) ppm	----	69.5	35
5	Egg white	----	CoO/Co ₃ O ₄ NPs	1M HCl	Low-carbon steel	(10-80) ppm	298-333	93% at EIS 94% at PDP	36
6	<i>Senna occidentalis</i>	Root	AgNPs	0.5M H ₂ SO ₄	Mild-steel	(1, 2, 3, 4, 5) gdm ⁻³	298-308	65.59	37
7	<i>Jatropha curcas</i>	leaves	AgNPs	Sea water	Carbon Steel	(7.5-10) ml	298	87.1 PDP at	38
8	<i>Cashew Anacardium occidentale</i>	leaves	AgNPs	3.5% NaCl	Mild steel	(0.1-0.3) g/L	313-353	96.2 at PDP 94.3 at EIS 94.3 at WL	39
9	<i>Arum Italicum</i>	Root	AgNPs	1M HCl	Carbon Steel	(100-800) ppm	298	97.8 at PDP 97.2 at EIS	40
10	<i>Artemisia annua</i> <i>Sida acuta</i>	leaves	AgNPs	0.5M HCl	Mild steel	(2-6)ml/l	289	87.8 at PDP 78.3 at PDP	41
11	<i>Allium cepa</i>	Peels	AgNPs	1M HCl	Carbon Steel	(100-500) mg/L	303-333	93.6 at WL	42

12	<i>Citrus aurantium</i>	Leaves	AgNPs	0.5M H ₂ SO ₄	Low-carbon steel	(2-10)ml/l	303-333	91.3 at WL	43
13	<i>Zygophyllum album</i>	Leaves Flower Grains	AgNPs	1M HCl	Carbon-steel	(0.920)g/l	Room temperature	88.34 at WL	44
14	<i>Syzygium Cumini</i>	Leaves	ZrO-NPs	0.5M H ₂ SO ₄	Carbon-steel	(100-500) ppm	----	95.5 at PDP 85 at EIS 92 at WL	45
15	<i>Lonchocarpus laxiflorus</i> Stem Bark	Stem	AgNPs	1M HCl	Mild-steel	(100-500) ppm	303-333	96.44 at PDP 80.90 at WL	46
16	Starch	----	AgNPs	0.5M HCl	Mild steel	(1-500) mg/l	303-343	63.1 at WL	47
	Honey + Starch							67.6 at WL	
17	<i>Opuntia fragilis</i>	Leaves	ZnO-NPs	0.5-2.5 M HCl	Mild-steel	(100-500) mg/l	299-333	78.3 at PDP 79.1 at EIS 77.3 at WL	48
18	<i>kolanut nitida</i>	pod	AgNPs	1M HCl	Mild-Steel	(5-20) µg/ml	298	99.59 at PDP 52 at WL	49
19	<i>Cannabis sativa</i>	Leaves	Cr ₂ O ₃ -NPs	0.5M HCl HNO ₃ NH ₃	Mild-Steel	(250-1000) ppm	303-323	81.5 at WL	50
								78.9 at WL	
								88.8 at WL	
20	<i>Musa sapientum</i>	peels	Fe-NPs	1M HCl	Mild- steel	(1-10)ml	303-333	96.2 at PDP 92.3 at EIS 96.2 at WL	51
21	<i>Cordia dichotoma</i>	Leaves	AgNPs	1M HCl	Mild-steel	(100-400) ppm	298-308	94.9 at PDP 87.3 at EIS	52
22	<i>Eastern Nigerian propolis</i>	----	AgNPs	1M HCl	Carbon-steel	(200-1000) ppm	303-343	91.3 at EIS 98.2 at WL	53

23	<i>Natural Myrrh</i>	resin	ZnO-NPs	1M HCl	Steel	(0.0025-0.02) g/l	303	89.8 at PDP 92.2 at EIS	54
24	<i>Convolvulus arvensis</i>	Leaves	ZnO-NPs	1M HCl	Carbon Steel	(0.006-0.12) mg/ml	298-333	91.2 at PDP 90.4 at EIS 91.8 at WL	55
25	<i>Syzygium cumini</i>	Leaves	CdO-NPs	0.5M H ₂ SO ₄	mild steel	(100-500) ppm	----	91 at PDP 90 at EIS	56
26	<i>Cinnamomum verum</i>	Bark	AgNPs	1M HCl	Carbon steel	(100-500) ppm	298-308	94 at PDP 85 at EIS	57
27	<i>Elaeis guineensis</i>	Leaves	AgNPs	1M HCl	Mild-Steel	(2.5-15) %v/v	----	94.1 at PDP 94.1 at EIS 93.1 at WL	58
28	<i>Sida acuta</i>	Leaves and Stem	AgNPs	0.1M H ₂ SO ₄	Mild-Steel	(2-6)%	303	88 at PDP	59
29	Gum Arabic	Solid glue	AgNPs	15% HCl	Steel	(50-1000) ppm	298-333	92.9 at PDP 88.6 at EFM 92.6 at TP	60
				15% H ₂ SO ₄				90.9 at EIS 84.5 at EFM 90.9 at TP	
30	<i>Clusia pulchella bush</i>	Leaves	ZnO-NPs	0.5 HCl	Mild-Steel	(10-40) mg	289	85 at PDP 85.4 at EIS 89.4 at WL	61
31	Onion mesocarp	Fruit	Ni-EtNPs	1M HCl	Carbon Steel	(100-1000) ppm	323-343	91.6	62

32	<i>Acacia nilotica</i>	Bark	ZrO ₂ -NPs	1M H ₂ SO ₄	Carbon Steel	(40-200) ppm	298	88.7 at PDP 88.2 at EIS 95.2 at WL	63
33	<i>Eucalyptus globulus</i>	Bark	ZrO ₂ -Gly-NPs	1M HCl	Mild-steel	(50-500) ppm	313-343	93.7% PDP 82.6 at EIS 82.1 at WL	64
34	Olive	Leave	Ti-NPs	1M HCl	Mild-steel	(0.01-0.1) g/L	303-333	96.5 at PDP 96.3 at EIS 94.3 at WL	65
35	Red onion	Peel	AqAg-NPs	1M HCl	Carbon Steel	(15-25) w/w%	303-333	90.6 at PDP 91.3 at EIS 95.1 at WL	66
36	<i>Sargassum muticum</i>	Brown algae	ZnO/CuO-NPs	1M HCl	Carbon Steel	(25-150) ppm	298	92.3 at PDP 93.9 at EIS	67

Experimental Condition used in Nanocorrosion studies

Corrosive Media

When assessing the effectiveness of corrosion inhibitors based on nanoparticles, the choice of the corrosive medium is crucial. The majority of research on green-synthesized nanoinhibitors has been carried out in acidic environments, especially hydrochloric acid (HCl) and sulfuric acid (H₂SO₄), because of their strong corrosive properties and industrial significance, as Table 1. summarizes. Acidic solutions, like 1.0M HCl, are frequently used to mimic harsh conditions found in industrial processes like oil well acidizing, acid picking, and descaling. Under extreme corrosion conditions, the predominance of acidic media allows for a trustworthy evaluation of thermodynamic parameters, adsorption behavior, and inhibition efficiency[68-69].

Sodium chloride (NaCl) solutions are frequently used as neutral or mildly aggressive corrosive environments in nanocorrosion inhibition studies, in addition to acidic media. Saline solutions, which usually contain 3.5 weight percent NaCl, are thought to be representative of coastal and marine environments where corrosion caused by chloride is predominant. Pitting and crevice corrosion are examples of localized corrosion phenomena that are known to be accelerated by chloride ions, especially on steel surfaces. Therefore, studying nanoparticle-based inhibitors in NaCl

media improves the practical relevance of laboratory results to real-world service environments and offers insightful information about their protective behavior under chloride-rich conditions[70].

Green nanoparticles in sustainable corrosion protection for steel alloys

Although it can be alloyed with other elements like nickel, cobalt, chromium, and manganese, steel is primarily an alloy made of iron and carbon. These alloying components enhance particular characteristics of steel, including wear resistance, corrosion resistance, strength, toughness, and resistance to high temperatures [71]. Steel corrosion in acidic aqueous solutions is a major problem in many industries where acids are used extensively for processes like pickling, cleaning, descaling, and acidizing oil wells. Because of the general aggression of the acidic solution[72], building components corrode easily. Corrosion must be successfully prevented in order to preserve the integrity of steel alloys, both financially and ecologically[73,]. Chemical coatings and inhibitors are commonly used in traditional corrosion mitigation techniques, which may cause environmental problems. Because of this, scientists are now more interested in developing economical, effective inhibitors that have little to no negative effects on the environment. Easy biodegradability, environmental friendliness, carbon-based composition, and low cost are characteristics of green corrosion inhibitors. Components derived from plants are widely used in the creation of corrosion inhibitors that are safe for the environment[74] Numerous plant extracts, such as leaves, roots, stems, bark, pulp, and fruits, have been effectively used as long-term corrosion inhibitors for a variety of metals and alloys, according to a review of the literature.

Distinction Between Carbon Steel and Mild Steel in Corrosion Inhibition Studies

Carbon steel and mild steel are frequently investigated in corrosion inhibition studies. however, their metallurgical compositions and corrosion behaviors exhibit notable differences that directly influence inhibitor performance[75]. Carbon steel typically contains a higher carbon content, which enhances its mechanical strength and hardness but also increases its susceptibility to localized corrosion due to microstructural heterogeneity. In contrast, mild steel possesses a lower carbon content and a more uniform ferritic microstructure, resulting in comparatively higher ductility and more homogeneous electrochemical behavior in corrosion environments. These compositional and structural differences affect surface reactivity, passive film stability, and adsorption characteristics of corrosion inhibitors[76]. Consequently, green nano-inhibitors may exhibit varying inhibition efficiencies, adsorption mechanisms, and thermal stability when applied to carbon steel versus mild steel, particularly under acidic and chloride-rich conditions[77]. Therefore, distinguishing between these two-steel type is essential for accurately interpreting inhibition performance and ensuring reliable comparison of experimental result across different studies[78]. This distinction is particularly relevant in the present review, as both carbon steel and mild steel are extensively examined under varying concentration and temperature conditions.

Mechanism of steel corrosion

Anodic areas of the surface, where ferrous ions enter the solution, are where corrosion begins. Electrons are liberated from the anodic surface and pass through the metallic structure to adjacent cathodic sites, where they combine with water and oxygen to create hydroxyl ions. At the anodic site, these hydroxyl ions react with ferrous ions to form ferrous hydroxide, which is then further oxidized in air to create hydrated ferric oxide (rust). Over time, rust may build up on the surface and obstruct the corrosion process. On the other hand, corrosion may continue if new anodic sites form in nearby regions. General or uniform corrosion is the term used to describe the relatively uniform loss of metal over the surface caused by this protracted process. The electrical circuit that drives the corrosion process is based on the discharge of electrons at anodic sites and their receipt at cathodic sites[79]. Displays the graphic illustration of the mechanism behind steel rusting. Al-Mhyawi et al. studied the corrosion inhibition of carbon steel using silver nanoparticles made from tobacco leaf, and they found that the inhibition efficacy may reach 97.9% at 200 ppm in 1.0 N hydrochloric acid[80].

Mechanism of Green Corrosion Inhibitors

Green corrosion inhibitors, particularly those derived from plant extracts and bio-based compounds, function primarily through adsorption phenomena on the metal surface, thereby blocking active corrosion sites and forming a protective barrier that mitigates metal dissolution and anodic/cathodic reaction[81]. The adsorption of inhibitor molecules or nanostructures involves the interaction of heteroatoms involves the interaction of heteroatoms such as oxygen, nitrogen, and sulfur, as well as π -electrons from aromatic ring, with the vacant d-orbitals of the metal surface, facilitating electron donation and back-donation processes[82,83].

Depending on nature of the inhibitor and the environmental condition, adsorption can occur via physical adsorption (physisorption), chemical adsorption (chemisorption), or a combination of both[84]. Physisorption is generally characterized by weaker electrostatic forces and is favored at lower temperature, while chemisorption involves the formation of stronger coordinate bonds between the inhibitor and metal surface. In many green inhibitor systems, a mixed adsorption mechanism is observed, which enhances the stability and resilience of the protective layer[85].

Once adsorbed, the inhibitor molecules impede the diffusion of aggressive species such as chloride ions (Cl^-) and hydrogen ions (H^+) toward the metal interface, thus retarding both anodic metal dissolution and cathodic reduction reaction. The formation of a compact adsorbed film also increases the charge transfer resistance (R_{ct}) and reduces double layer capacitance (C_{dl}), as evidenced in electrochemical impedance spectroscopy (EIS) measurements. Consequently, the comprehensive inhibition effect is achieved through surface coverage, blockage of active sites, and modification of the electrochemical pathways responsible for corrosion[86-88].

Green Nanomaterial-Based Corrosion Inhibitors and Their Inhibition Mechanism

Green nanomaterial-based corrosion inhibitors have emerged as sustainable and highly efficient alternative to conventional corrosion inhibitors due to their enhanced surface activity, environmental compatibility, and superior inhibition performance. These inhibitors are typically synthesized using plant extracts, biopolymer, or naturally derived compounds, which act as both reducing and stabilizing agent during nanoparticle formation[89]. The nanoscale dimensions significantly increase the surface area to volume ratio, enabling stronger interaction with metallic substrates and improved adsorption behavior[90].

The corrosion inhibition mechanism of green nanoinhibitors is primarily governed by adsorption processes, where nano-sized particles and their functionalized organic molecules adhere to the steel surface through physical adsorption (electrostatic interactions) and chemical adsorption (coordination bonding)[91,92]. Functional groups such as hydroxyl ($-\text{OH}$), amine ($-\text{NH}_2$), carbonyl ($-\text{C}=\text{O}$), and aromatic π -electrons facilitate electron donation to vacant d-orbitals of iron atoms, forming a compact protective film[93].

In chloride-containing media, such as NaCl solutions, green nanoinhibitors play a crucial role in suppressing localized corrosion by blocking active anodic sites and preventing chloride ion penetration into surface defects[94]. The formation of a dense and adherent nanostructured reduces both anodic metal dissolution and cathodic oxygen reduction reaction[95]. Moreover, the synergistic effect between the organic green molecules and inorganic nanoparticles enhances film stability under varying temperatures and inhibitor concentrations leading to improved inhibition efficiency[96].

In acidic media, green nanoinhibitors adsorb onto the steel surface forming a protective layer that suppresses anodic iron dissolution and cathodic hydrogen evolution enhancing inhibition efficiency even under highly aggressive conditions[97].

Effect of Inhibitor concentration on corrosion inhibition performance

The concentration of corrosion inhibitors plays a critical role in determining their inhibition efficiency particularly in nanomaterial-based corrosion protection systems[98]. As evidenced by the compiled data in table 1, a clear dependence of inhibition efficiency (%IE) on inhibitor concentration is observed across different steel substrates and corrosive environments. In most studies, increasing the inhibitor concentration led to marked enhancement in %IE until an optimum concentration is reached, beyond which marginal or negligible improvements are reported[99].

This behavior is primarily attributed to the progressive adsorption of inhibitor molecules or nanoparticles onto the metal surface, resulting in the formation of compact and protective adsorbed layer[100]. At low concentrations, surface coverage such as chloride or hydrogen ions to penetrate the metal-solution interface. However higher concentration promotes increased surface coverage, improved film continuity, and enhanced barrier properties against charge and mass transfer processes[101].

The reviewed studies demonstrate that effective inhibition can be achieved over a wide concentration range, spanning from micromolar levels (10^{-6}M) to higher dosages expressed in ppm, g/L or mL/L, depending on the inhibitor type and formulation Table 1. Notably, nanostructured inhibitors often exhibit superior performance at relatively lower concentrations compared to conventional inhibitors, owing to their high surface area, enhanced adsorption affinity, and synergistic interactions with the metal surface[102].

Nevertheless, excessive inhibitor concentrations may lead to aggregation phenomena, saturation of adsorption sites, or destabilization of the protective layer, resulting in reduced inhibition efficiency. Therefore, optimizing inhibitor concentration is essential for achieving maximum economic and environmental sustainability[103].

Effect of Temperature on the Inhibition Performance of Nanomaterial-Based Corrosion Inhibitors

Temperature is a crucial parameter influencing both the corrosion rate of metallic substrates and inhibition performance of corrosion inhibitors particularly those on nanomaterials. As summarized in Table 1, the inhibition efficiency (%IE) generally decreases with increasing temperature for most inhibitor systems, indicating a temperature-dependent adsorption process[104,105].

However, several studies have reported sustained or only slightly reduced inhibition efficiencies at higher temperature, suggesting the involvement of chemical adsorption mechanisms[106]. In such cases, strong coordinate bonds form between heteroatoms or functional groups present in the inhibitor and the metal surface, resulting in enhanced thermal stability of the protective film[107]. Nanomaterial-based inhibitors, in particular, have demonstrated improved resistance to temperature-induced degradation owing to their high surface area, strong adsorption affinity, and synergistic interactions between organic moieties and metallic or metal oxide nanoparticles[108].

Thermodynamic parameters such as activation energy (E_a), enthalpy (ΔH_{ads}°), and free energy of adsorption (ΔG_{ads}°) are frequently employed to elucidate the effect of temperature on inhibition behavior[109,110]. An increase in activation energy in the presence of inhibitors typically confirms their effectiveness by increasing the energy barrier for corrosion reaction. Therefore, understanding the temperature dependence of inhibition efficiency is essential for assessing the practical applicability of corrosion inhibitors under industrial operating conditions[111].

Statistical Analysis of Reported Inhibition Efficiencies and Thermodynamic Parameters

To complement the qualitative discussion above, the reported maximum inhibition efficiencies (%IE) from the 36 studies summarized in Table 1, ($n = 38$ data points, accounting for studies reporting multiple media or formulations) were statistically analyzed. Across the dataset, %IE values ranged from 65.59% to 99.59%, with a mean of $89.85 \pm 8.55\%$ and a median of 92.55%, confirming that the majority of green nano-inhibitors achieve efficiencies above 85% regardless of the specific plant source or nanoparticle type. When grouped by nanoparticle category,

zirconium-oxide-based systems (ZrO₂-Gly-NPs, n = 3) exhibited the highest average efficiency (94.8%), followed by silver nanoparticles (AgNPs, n = 22, mean = 89.33%), which remain the most extensively studied system, and zinc-oxide nanoparticles (ZnO-NPs, n = 4, mean = 88.12%). Iron-oxide-based inhibitors showed comparatively lower and more variable performance (mean = 85.7%, n = 2). These comparative results are illustrated in Figure 1. With respect to the corrosive medium, inhibitors evaluated in HCl solutions (n = 28) achieved a marginally higher average efficiency (90.17%) than those tested in H₂SO₄ (n = 7, mean = 88.21%), consistent with the more extensive optimization reported for HCl systems in the literature.

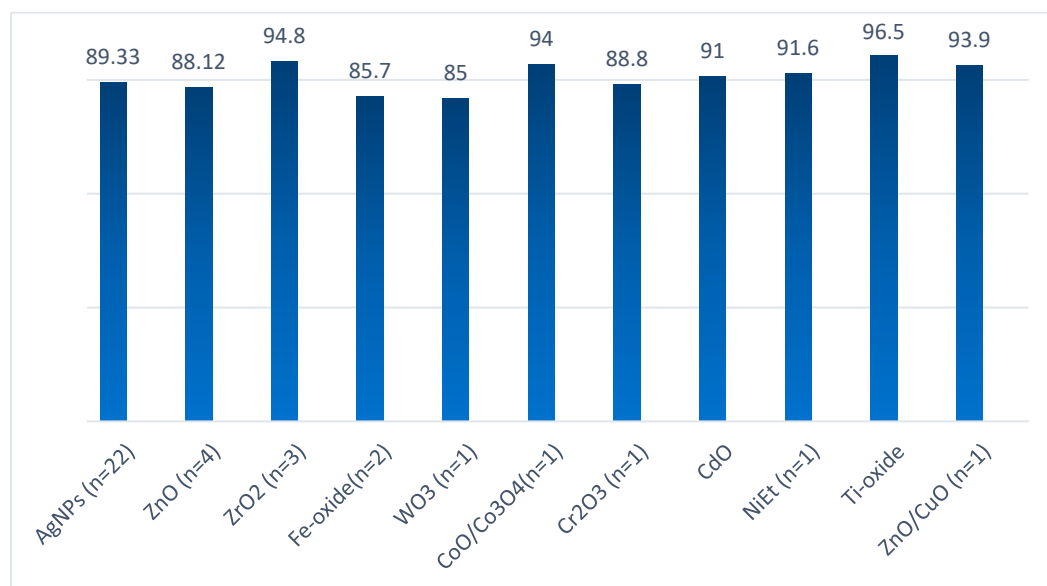


Figure 1 : Average maximum inhibition efficiency %IE by nanoparticle type across the reviewed studies (n = 38 data points from 36 studies)

Analysis of the thermodynamic dataset in Table 2 further supports the mechanistic interpretation discussed above. Among the systems reporting activation energy (E_a) both in the absence and presence of inhibitor (n = 10), the addition of green nano-inhibitors increased E_a by an average of 22.5 kJ/mol (excluding one anomalous system that showed a decrease), consistent with a physisorption-dominated or mixed adsorption mechanism in which the inhibitor raises the energy barrier for the corrosion reaction. Moreover, systems classified as exhibiting mixed (physisorption + chemisorption) adsorption displayed a more negative average Gibbs free energy of adsorption ($\Delta G_{ads}^\circ = -26.76$ kJ/mol, n = 9) compared with systems classified as purely physisorption-dominated ($\Delta G_{ads}^\circ = -16.46$ kJ/mol n = 5). This quantitative trend reinforces the qualitative observation that mixed-mechanism systems form a more thermodynamically stable and strongly bound protective film, which likely underlies their improved retention of inhibition efficiency at elevated temperatures.

Discussion of Thermodynamic Parameters

As summarized in Table 2, the Langmuir adsorption isotherm was the dominant model reported across nearly all reviewed studies, indicating monolayer coverage with negligible lateral interaction between adsorbed inhibitor species on the steel surface. The calculated ΔG_{ads}° values ranged from approximately -4.3 to -37.54 kJ/mol across most systems, consistent with a physisorption-dominated or mixed physisorption/chemisorption mechanism, in agreement with the general trend of decreasing inhibition efficiency at elevated temperatures discussed earlier.

Several nano inhibitor systems (e.g., Anacardium/AgNPs, Allium cepa/Et-AgNPs, Eucalyptus globulus/ZrO₂-Gly-NPs) exhibited a notable increase in activation energy (Ea) upon inhibitor addition, rising from blank values of 14.7-39.6 kJ/mol to inhibited values of 30.0-68.99 kJ/mol. This increase in the energy barrier for the corrosion reaction supports a physisorption-controlled mechanism, wherein the inhibitor's protective effect diminishes at higher temperature as previously adsorbed species undergo desorption. Conversely, system classified as "physicochemical" (mixed) adsorption, such as CoO/Co₃O₄NPs and ZrO₂-Gly-NPs, displayed relatively small shifts in ΔG_{ads}° across the studied temperature range, suggesting a more thermally stable protective layer attributable to partial chemisorptive bonding.

Table 2 : Thermodynamic and Kinetic Parameters of Green Nano-Inhibitors for Steel Corrosion

SN	Plant	Ea (kJ/mol) Blank	Ea (kJ/mol) Inhibited	ΔG_{ads}° (kJ/mol)	ΔH_{ads}° (kJ/mol)	Adsorption Isotherm	Adsorption Mechanism	Ref.
1	Tobacco/AgNPs	NR	NR	-37.54	NR	Langmuir	Physisorption	34
2	Egg white/ CoO/Co ₃ O ₄ NPs	NR	NR	-32.9 -33.1	-31.2	Langmuir	Mixed (Physisorption + Chemisorption)	36
3	Cashew - Anacardium occidentale/AgNPs	18.45	34.12	-18.42 -22.15	+14.28	Langmuir	Mixed (Physisorption + Chemisorption)	39
4	Arum Italicum/AgNPs	NR	NR	-9.9024	NR	Langmuir	Physisorption	40
5	Allium cepa/Et-AgNPs	39.64	63.47 at 500 mg/L	-21.52 -34.28	-47.92	Langmuir	Mixed (Physisorption + Chemisorption)	42
6	Citrus aurantium/AgNPs	21.15	53.21 at 10 ml/L	-17.11	-41.133	Langmuir	Mixed (Physisorption + Chemisorption)	43
7	Lonchocarpus laxiflorus/AgNPs	22.017	30.004 at 500 ppm	-4.308 -0.583	+8.881	Langmuir	Physical adsorption/ (mixed-type, associative)	46
8	Cordia dichotoma/AgNPs	NR	NR	-24.98 -25.17	NR	Langmuir	Mixed (Physisorption + Chemisorption)	52
9	Propolis/AgNPs	14.68	41.71 at 1000 ppm	-6.95 -3.91	-38.76	Langmuir	Physisorption	53
10	Natural Myrrh	NR	NR	-33.18	NR	Langmuir	Physical/Mixed	54
11	Convolvulus arvensis/ZnO-NPs	NR	NR	-23.08 -25.47	-2.66	Langmuir	Mixed (Physisorption + Chemisorption)	55
12	Cinnamomum verum/AgNPs	25.2	49.7	-29.68 -30.69	NR	Langmuir	Mixed (Physisorption + Chemisorption)	57

13	Onion mesocarp/ EtNPs	29.30	48.06 at 1000 ppm	NR	-33.74	Spontaneously physically adsorbed	Physisorption + mixed type	62
14	Eucalyptus globulus/ ZrO ₂ -Gly-NPs	80.12	66.70 at 500 ppm	-24.51 -35.21	+52.64	Langmuir	Mixed (Physisorption + Chemisorption)	64
15	Olive/Ti-NPs	42.57	68.99 at 10×10 ⁻²	-17.75 -19.18	-1.89	Langmuir	Physisorption	65
16	Red onion/AgNPs	39.64	66.26 at 30% v/v	NR	-37.15 -63.39	----	Physisorption	66
17	Sargassum muticum/ ZnO/CuO-NPs	NR	NR	-10.95	NR	Langmuir	Physisorption	67

This trend is illustrated in Figure 2, which compares the average Gibbs free energy of adsorption for system classified as purely physisorption-dominated versus those exhibiting a mixed adsorption mechanism.

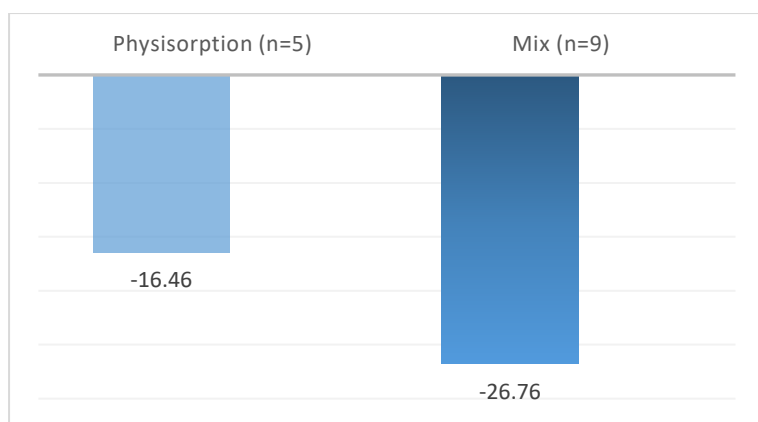


Figure 2 : Average Gibbs Free energy of adsorption (ΔG_{ads}°) for green nano-inhibitor system classified as physisorption versus mixed (physisorption + chemisorption) mechanisms

The activation energy values before (blank) and after inhibitor addition for the ten systems reporting both parameters are presented in Figure 3, illustrating the general increase in E_a upon inhibitor adsorption with the exception of the Eucalyptus globulus/ZrO₂-gly-NPs system discussed below.

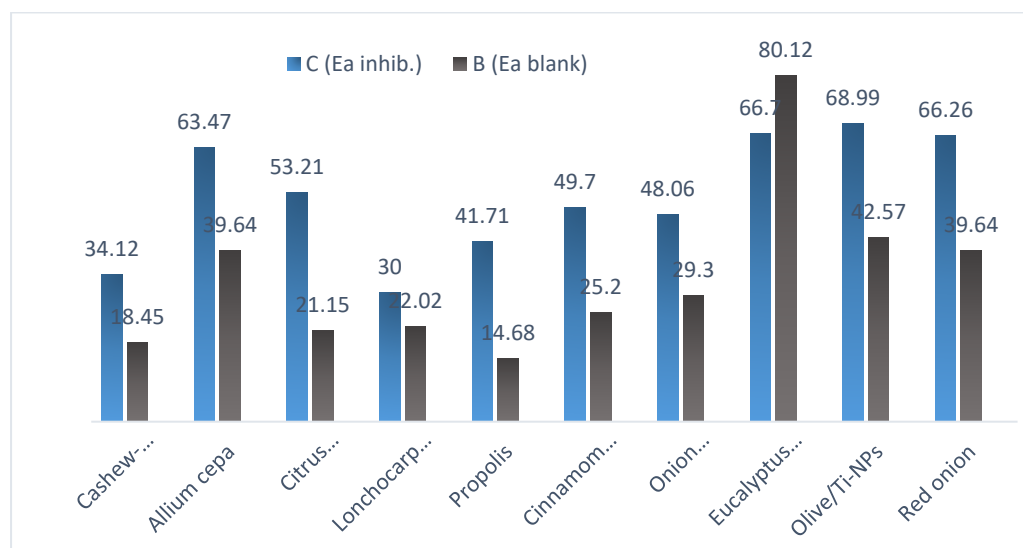


Figure 3 : Activation energy (Ea) of the corrosion reaction in the absence (blank) and presence (inhibited) of green nano-inhibitors for ten reviewed system

It is worth nothing the ten-system reporting both blank and inhibited activation energies, nine exhibited the expected increase in Ea upon inhibitor, consistent with a physisorption-dominated mechanism. However, the Eucalyptus globulus/ZrO₂-Gly-NPs system reported a decrease in Ea (from 80.12 to 66.70 kJ/mol) deviating from this general trend. This behavior may reflect a genuine mechanistic distinction-for instance, a shift toward a more chemisorption-dominated pathway that alters the reaction route rather than merely blocking active sites-or may result from a transcription or calculation discrepancy in the original source. Given that this system was independently classified under a mixed adsorption mechanism, the anomaly warrants verification against the primary reference before being generalized, and is highlighted here for transparency rather than excluded from the dataset.

Conclusion :-

This review demonstrates that green nanoinhibitors, particularly those derived from plant extracts, offer a highly efficient and environmentally sustainable approach to steel corrosion protection, with several system achieving inhibition efficiencies exceeding 90-98% in HCl, H₂SO₄, and NaCl media (Table 1). Their inhibition mechanisms proceed through physisorption, chemisorption, or mixed adsorption onto the metal surface, forming a compact protective layer that suppresses both anodic and cathodic reaction, and mitigates chloride-induced pitting crevice corrosion.

The reviewed literature confirms two consistent trends: (i) inhibition efficiency generally increases with inhibitor concentration up to an optimum threshold, beyond which marginal or negative effects (e.g., aggregation, desorption) may occur, and (ii) temperature effects are inhibitor-specific while most systems show decreasing %IE with rising temperature (consistent with physisorption-dominated behavior), several nanostructured inhibitor retain high efficiency at elevated temperature due to chemisorption and strong coordinate bonding, as reflected in activation energy and Gibbs free energy values.

Despite these promising results, important gaps remain. First, most studies rely on short-term laboratory testing (hours to days), long-term field or industrial-scale performance data remain scarce. Second, the potential toxicity and environmental fate of certain metal/metal-oxide nanoparticles (e.g., silver-based systems) upon disposal

have not been systematically addressed, which is a notable inconsistency given the “eco-friendly” framing of this research area. Third, direct comparative studies under standardized conditions (same steel type, same medium, same technique) across different green nano-inhibitors are lacking, limiting the ability to draw definitive structure-performance conclusions. Fourth scale-up and cost-effectiveness of green nanoparticle synthesis for industrial application remain largely unexplored.

Future research should prioritize: (1) standardized, multi-technique validation protocols to enable cross-study comparability, (2) long-term and field-representative corrosion testing, (3) systematic eco-toxicological assessment of green nano-inhibitors, and (4) techno-economic evaluation to support industrial translation. Addressing these gaps will be essential for advancing green nanostructured inhibitor from laboratory-scale promise to practical sustainable corrosion control solutions.

References :-

- 1) De la Fuente D, Díaz I, Simancas J, Chico B, Morcillo M. Long-term atmospheric corrosion of mild steel. *Corrosion Science*. 2011 Feb 1;53(2):604-17. 2.
- 2) Kahyarian A, Achour M, Nesic S. CO₂ corrosion of mild steel. *Trends in Oil and Gas Corrosion Research and Technologies*. 2017 Jan 1:149-90.
- 3) Sanghamitra Sarmah, Gitalee Sharma. Green Corrosion Inhibitors for Mild Steel: A Comprehensive Review. *Current Trends Pharm Res*, 2023;10 (2): 36-44.
- 4) F.-M. Li, L. Huang, S. Zaman, W. Guo, H. Liu, X. Guo, B.Y. Xia, Corrosion chemistry of electrocatalysts, *Adv. Mater.* 34 (2022) 2200840.
- 5) R. Bender, D. Feron, D. Mills, S. Ritter, R. Bäßler, D. Bettge, I. De Graeve, A. Dugstad, S. Grassini, T. Hack, M. Halama, E.-H. Han, T. Harder, G. Hinds, J. Kittel, R. Krieg, C. Leygraf, L. Martinelli, A. Mol, D. Neff, J.-O. Nilsson, I. Odneval, S. Paterson, S. Paul, T. Prošek, M. Raupach, R.I. Revilla, F. Ropital, H. Schweigart, E. Szala, H. Terry, J. Tidblad, S. Virtanen, P. Volovitch, D. Watkinson, M. Wilms, G. Winning, M. Zheludkevich, Corrosion challenges towards a sustainable society, *Mater. Corros.* 73 (2022) 1730–1751.
- 6) A. El-Sherik, *Trends in Oil and Gas Corrosion Research and technologies: Production and Transmission*, Woodhead Publishing, 2017.
- 7) A.R. Prasad, A. Kunyankandy, A. Joseph, Corrosion inhibition in oil and gas industry, corrosion inhibitors in the oil and gas industry 2020, pp. 135–150.
- 8) V. Burt, S. Lampman, B.R. Sanders, Corrosion in the petrochemical industry. ASM International Materials Park, 2015.
- 9) I.B. Obot, A.A. Sorour, C. Verma, T.A. Al-Khalidi, A.S. Rushaid, Key parameters affecting sweet and sour corrosion: impact on corrosion risk assessment and inhibition, *Eng. Fail Anal.* 145 (2023) 107008.
- 10) Sandeep Yadav, Anirudh P.S. Raman, Madhur B. Singh, Iona Massey, Prashant Singh, Chandrabhan Verma, Akram AlFantazi, Green nanoparticles for advanced corrosion protection: Current perspectives and future prospects, *Applied Surface Science Advances* 21 (2024) 100605.
- 11) Brycki BE, Kowalczyk IH, Szulc A, Kaczerewska O, Pakiet M. Organic corrosion inhibitors. Corrosion inhibitors, principles and recent applications. 2018 Apr 4;3:33.
- 12) Awodele, T. and Olaseinde, D., 2023. Effects Of Zinc Oxide Nanoparticles on Corrosion Behaviour of Api 5L Steel in Acidic, Alkaline and Chloride Environment.
- 13) Alsaiani, N.S., Alzahrani, F.M., Amari, A., Osman, H., Harharah, H.N., Elboughdiri, N. and Tahoona, M.A., 2023. Plant and microbial approaches as green methods for the synthesis of nanomaterials: synthesis, applications, and future perspectives. *Molecules*, 28(1), p.463.
- 14) Nuha. M. Obaida, Noor H. Faisal, Nuha W. Ali, Ruqaia G. Ibrahim, Ayat N. Hassan, Ayat J. Kadhum, Ali A.A. Al-Shawi, Mohammed E. Mohammed, Mohnad Abdalla. Synthesis, characterization, and biological activity of silver

- nanofibers essential oils of prunus dulcis. Egyptian Pharmaceutical Journal· January 2025. DOI: 10.21608/epj.2025.402838. <https://www.researchgate.net/publication/387945052>.
- 15) Noor H. Faisal, Nuha A. M. Obaid, Nuha W. Ali, Ali A. A. Al-Shawi, Ruaa G. Ibrahim¹, Ayat N. Hassan, Ayat J. Kadhum, Osama A. Mohsein, Iman N Luaibi. Green Synthesis of Silver Nanoparticles Using the Seeds of *Lupinus luteus*: Characterization and Assessment the Antibacterial and Anticancer Activities. Silver Nanoparticles of *Lupinus luteus*. DOI:10.31557/APJCP.2025.26.9.3405.
 - 16) Adejo, S.O., Egbeneje, V.O., Gbertyo, J.A., Okhale, S.E., Ogbogo, I.O. and Enyi, S.O., Green Synthesis of Silver Sulfide Nanoparticles from *Musa paradisiaca* Extract for Corrosion Inhibition of Mild Steel in 0.5 M Sulphuric Acid.
 - 17) V. Chandrakala, V. Aruna, G. Angajala, Review on metal nanoparticles as nanocarriers: current challenges and perspectives in drug delivery systems, Emergent. Mater. 5 (2022) 1593–1615.
 - 18) H. Zhu, W. Luo, P.N. Ciesielski, Z. Fang, J. Zhu, G. Henriksson, M.E. Himmel, L. Hu, Wood-derived materials for green electronics, biological devices, and energy applications, Chem. Rev. 116 (2016) 9305–9374.
 - 19) M. Nasrollahzadeh, M. Sajjadi, S. Irvani, R.S. Varma, Green-synthesized nano catalysts and nanomaterials for water treatment: current challenges and future perspectives, J. Hazard. Mater. 401 (2021) 123401.
 - 20) L.M. Gilbertson, J.B. Zimmerman, D.L. Plata, J.E. Hutchison, P.T. Anastas, Designing nanomaterials to maximize performance and minimize undesirable implications guided by the Principles of Green Chemistry, Chem. Soc. Rev. 44 (2015) 5758–5777.
 - 21) I. Chakrabarty, K.R. Hakeem, Green nanomaterials in energy conversion and storage applications, CRC Press 2024.
 - 22) G. Szekely, A.G. Livingston, Sustainable nanoscale engineering: from materials design to chemical processing, Elsevier 2019.
 - 23) H. Aljibori, A. Alamiery, A. Kadhum, Advances in corrosion protection coatings: a comprehensive review, Int. J. Corros. Scale Inhib. 12 (2023) 1476–1520.
 - 24) M. Thakur, A. Sharma, M. Chandel, D. Pathania, Modern applications and current status of green nanotechnology in environmental industry, Green functionalized nanomaterials for environmental applications, Elsevier (2022) 259–281.
 - 25) C. Verma, M. Quraishi, Nanotechnology in the service of corrosion science: considering graphene and derivatives as examples, Corrosion Engineering, Sci. Technol. 57 (2022) 1–18.
 - 26) M. Madani, S. Hosny, D.M. Alshangiti, N. Nady, S.A. Alkhursani, H. Alkhaldi, S. A. Al-Gahtany, M.M. Ghobashy, G.A. Gaber, Green synthesis of nanoparticles for varied applications: green renewable resources and energy-efficient synthetic routes, Nanotechnol. Rev. 11 (2022) 731–759.
 - 27) C.M. Hussain, C. Verma, B. El Ibrahim, J.V. Nardeli, L. Guo, Sheetal, B.C., S. Thakur, B. Pani, A.K. Singh, Sustainable Corrosion Inhibitors I: fundamentals, methodologies, and Industrial Applications, ACS Publications 2021.
 - 28) S.H. Alrefaee, K.Y. Rhee, C. Verma, M. Quraishi, E.E. Ebenso, Challenges and advantages of using plant extract as inhibitors in modern corrosion inhibition systems: recent advancements, J. Mol. Liq. 321 (2021) 114666.
 - 29) C.M. Hussain, C. Verma, M. Quraishi, D.S. Chauhan, L.B. Furtado, R. Nascimento, U. Eduok, S. Kaya, S. Erkan, S. Sims,ek, Sustainable Corrosion Inhibitors II: synthesis, design, and Practical Applications, ACS Publications 2021.
 - 30) C. Verma, Handbook of science & engineering of green corrosion inhibitors: modern theory. Fundamentals & Practical Applications, Elsevier, 2021.
 - 31) H. Fetouh, A. Hefnawy, A. Attia, E. Ali, Facile and low-cost green synthesis of eco-friendly chitosan-silver nanocomposite as novel and promising corrosion inhibitor for mild steel in chilled water circuits, J. Mol. Liq. 319 (2020) 114355.

- 32) Dalal M. Ibrahim, Hanan F. Emrayed, Asma A. Youssef, Green and Chemical Synthesis of Magnetite Nanoparticles for Corrosion Inhibition Applications, IRAQI JOURNAL OF APPLIED PHYSICS Vol. 21, No. 1, January-March 2025, pp. 156-160.
- 33) Daniel Jildawa1, Iliya I. Nkafamiya, S.A. Osemeahon, J. M. Yelwa, Corrosion Inhibition of Mild Steel Using Green Synthesized Tungsten Oxide Nanoparticles in Acidic Media, International Journal of Scientific Research in Chemistry, Volume 10, Issue 2, March-April-2025.
- 34) Saedah R. Al-Mhyawi, Green synthesis of silver nanoparticles and their inhibitory efficacy on corrosion of carbon steel in hydrochloric acid solution, International Journal of Electrochemical Science, 18 (2023) 100210.
- 35) Sujan Budhathoki, Nabina Chaudhary, Biswash Guragain, Dipak Baral, Janak Adhikari, Narendra Kumar Chaudhary, Green synthesis of silver nanoparticles from *Brassaiopsis hainla* extract for the evaluation of antibacterial and anticorrosion properties, Heliyon 10 (2024) e35642.
- 36) Ghadah M. Al-Senani and Sameerah I. Al-Saeedi, The Use of Synthesized CoO/Co₃O₄ Nanoparticles as A Corrosion Inhibitor of Low-Carbon Steel in 1M HCl, Materials 2022, 15, 3129. <https://doi.org/10.3390/ma15093129>.
- 37) Victor O. Egbeneje, Samuel E. Okhale, Chinyere Imoisi, Isaac O. Ogbogol and Omolade Ojo, Evaluation of the Inhibitive Properties of Silver Nanoparticles in *Senna occidentalis* Root Extract as Corrosion Inhibitor of Mild Steel, Tanzania Journal of Science 49(3): 655-663, 2023.
- 38) Talabi Henry Kayode, Silver Nanoparticles' Biosynthesis and Characterization with the Extract of *Jatropha curcas* Leaf: Analysis of Corrosion Inhibition Activity, Makara Journal of Science: Vol. 26: Iss. 2, Article 8. DOI: 10.7454/mss.v26i2.1276, <https://scholarhub.ui.ac.id/science/vol26/iss2/8>.
- 39) Abdelrahman Osama Ezzat, Victor Sunday Aigbodion, bcd Hamad A. Al-Lohedanaand Chinemerem Jerry Ozoudee, Unveiling the corrosion inhibition efficacy and stability of silver nanoparticles synthesized using *Anacardium occidentale* leaf extract for mild steel in a simulated seawater solution, RSC Adv., 2024, 14, 18395.
- 40) Zouied D., Chettah W., Khelfaoui M.1, Bouzenad N., Abdennouri A., Dob K., Boulehsa A., Bouhali H., Karima Derdour K., Ammouchi N. and Zouaoui E., The use of *arum italicum* root extracts for protection against corrosion and green synthesis of silver nanoparticles: investigation of their photocatalytic and antimicrobial properties, Global NEST Journal, Vol 27, No 1, 06931, 2024.
- 41) A.S. Johnsona, I.B. Obota, U. S. Ukpanga, Green synthesis of silver nanoparticles using *Artemisia annua* and *Sida acuta* leaves extract and their antimicrobial, antioxidant and corrosion inhibition potentials, J. Mater. Environ. Sci. 5(3) (2014) 899-906.
- 42) Ekemini Ituen, Ambrish Singh, Lin Yuanhua, Onyewuchi Akaranta, Green synthesis and anticorrosion effect of *Allium cepa* peels extract-silver nanoparticles composite in simulated oilfield pickling solution, SN Applied Sciences (2021) 3:679, <https://doi.org/10.1007/s42452-021-04670-w>.
- 43) Ekemini Ituen, Ambrish Singh, Lin Yuanhua, Onyewuchi Akaranta, Green biosynthesis of silver nanoparticles from *Citrus aurantium* leaves plant as corrosion inhibitor for carbon steel in sulfuric acid, Next Nanotechnology 9 (2026) 100331.
- 44) Dellali Rachida, Djahnit Leilab, Benzahi Khedidjad, Hamdi Imanee and Benzahi Rabiaf, Green Synthesis of Silver Nanoparticles Using *Zygophyllum Album* L.f. from Ain Salah for Corrosion Inhibition and Phenol Red Dye Removal, *Phys. Chem. Res.*, Vol. 13, No. 3, 533-543, 2025.
- 45) Sivakumar Sivalingam, Megala Rajendran, Jayagopi Gayathri, S. Anu , Jyoti Kavirajwar, Mihi Ghosh, A novel green synthesis of ZrO nanoparticles as a corrosion inhibitor on ASTM-415 carbon steel in 0.5 M H₂SO₄, Results in Chemistry 12 (2024) 101877.
- 46) Godwin Abawulo Ijuo, Surma Nguamo, John Ogbaji Igoli, Ag-nanoparticles Mediated by *Lonchocarpus laxiflorus* Stem BarkExtract as Anticorrosion Additive for Mild Steel in 1.0 M HCl Solution, Progress in Chemical and Biochemical Research 2022, 5(2), 133-146.

- 47) Egbuniwe, A.F., Ekwumemgbor, P.A., Paul, E.D., SYNTHESIS OF STARCH SILVER NANOPARTICLES AND ITS SYNERGISM WITH HONEY FOR ENHANCED INHIBITION OF MILD STEEL CORROSION IN ACID MEDIUM, Nigerian Research Journal of Chemical Sciences, Vol. 5, 2018.
- 48) Abuchi Elebo, Uba Sani, Patricia A. Ekwumemgbo, Victor O. Ajibola, Green Synthesis and Zinc-Oxide Nanoparticles for Corrosion Inhibition and Modeling Corrosion Inhibition of Mild Steel in HCl Solutions, BIOSENSORS & NANO, Published online Mar 30, 2024.
- 49) TB Asafa1, JK Odusote, OS Ibrahim, A Lateef, MO Durowoju, MA Azeez, TA Yekeen, IC Oladipo, EA Adebayo, JA Badmus, YK Sanusi and O Adedokun, Inhibition efficiency of silver nanoparticles solution on corrosion of mild steel, stainless steel and aluminum in 1.0 M HCl medium, Nanotechnology Applications in Africa: Opportunities and Constraints, 805 (2020) 012018 IOP Publishing doi:10.1088/1757-899X/805/1/012018.
- 50) Uma Rani Sharma, Neeraj Sharma, Green Synthesis, Anti-cancer and Corrosion Inhibition Activity of Cr₂O₃ Nanoparticles, biointerface research, Volume 11, Issue 1, 2021, 8402 – 8412.
- 51) Ekemini Ituen, Victor Mkpenie, Ekere Ekemini, Adsorptive Fe-nanoparticles mediated by *Musa sapientum* peels extract as anticorrosion additive for aqueous oilfield descaling solution, Scientific African 3 (2019) e00075.
- 52) R.Q. Ibrahim, S.H. Ali, N.H. Faisal, S.Q. Ibrahim, A.A.A. Al-Shawi, A.N. Hassan, M.Y. Kadhum and A.S. AbdulNabi, Green synthesis of silver nanoparticles using *Cordia dichotoma* leaves and their application as a corrosion inhibitor of mild steel in 1.0 M HCl, *Int. J. Corros. Scale Inhib.*, 2026, **15**, no. 2, 253–271, doi: 10.17675/2305-6894-2026-15-2-15.
- 53) Godwin Abawulo Ijuo, Pius Oziri Ukoha, John Ogbaji Igoli, Utilization of Eastern Nigerian Propolis Extract for Synthesis of Corrosion Inhibitive Silver Nanoparticles on Carbon Steel in Acidic Medium, Letters in Applied Nano Bioscience, Volume 13, Issue 1, 2024, 21.
- 54) Reema H. Al-Dahiri1, Aisha M. Turkustani1,2, Mohamed Abdel Salam1, The Application of Zinc Oxide Nanoparticles as An Eco-Friendly Inhibitor for Steel in Acidic Solution, *Int. J. Electrochem. Sci.*, 15 (2020) 442 – 457.
- 55) Ghadah M. Al-Senani, Synthesis of ZnO-NPs Using a *Convolvulus arvensis* Leaf Extract and Proving Its Efficiency as an Inhibitor of Carbon Steel Corrosion, *Materials* 2020, 13, 890.
- 56) Sivakumar Sivalingam, Jyoti Kavirajwar, K. Seethalakshmi, Jayagopi Gayathri, and A. Ronibossa, Green synthesis of cadmium oxide nanoparticles (CdO-NPS) using *syzygium cumini*: exploring industrial applications of CdO NPs as a corrosion inhibitor of mild steel in the acidic environment, *RSC Adv.*, 2024, 14, 7932.
- 57) Ayat J. Kadhim, Ahmed S. Shanta Alsadkhan, Ghufra A. Mohammed, A M Jabbar, Ayat N. Hassan, Noor H. Faisal 4, Raneen S. Swadi 4, Zahraa M Khalid 1, Zahraa M Hammoud 1, Zaidon T. Al aqbi, Cinnamon (*Cinnamomum verum*) Mediated Silver Nanoparticles as Green Corrosion Inhibitors for C45 Steel in Hydrochloric Acid, *J Nanostruct* 16(4): 5027-5053, Autumn 2026, DOI: 10.22052/JNS.2026.04.046.
- 58) Mohammad Ali Asaad, Noor Nabilah Sarbini, Arizu Sulaiman, Mohammad Ismail, Ghasan Fahim Huseien, Zaiton Abdul Majid, Pandian Bothi Raja, Improved Corrosion Resistance of Mild Steel against Acid Activation: Impact of Novel *Elaeis guineensis* and Silver Nanoparticles, *Journal of Industrial and Engineering Chemistry*, Volume 63, 25 July 2018, Pages 139-148.
- 59) Muhammad Idrees, Saima Batool, Tanzila Kalsoom, Sadaf Raina, Hafiz Muhammad Adeel Sharif & Summera Yasmeen, Biosynthesis of silver nanoparticles using *Sida acuta* extract for anti-microbial actions and corrosion inhibition potential, *Environmental Technology* Volume 40, 2019.
- 60) Moses M. Solomona, Husnu Gerengia, Saviour A. Umoren, Nsikak B. Essienc, Uduak B. Essienc and Ertugrul Kaya, Gum Arabic-silver nanoparticles composite as a green anticorrosive formulation for steel corrosion in strong acid media, *Polymers* Volume, 1 February 2018, Pages 43-55.
- 61) Vikram Singh, Ruchi Bharti, Shivani Naik, Monika Verma, Renu Sharma, Sónia A. C. Carabineiro, Manas Sutradhar, Green synthesis of zinc oxide nanoparticles using *Clusia pulchella* (lightning bush) extract: characterization and corrosion inhibition performance, *Chemical Papers* (2026) 80:9335–9349, <https://doi.org/10.1007/s11696-026-04955-7>.

- 62) Ekemini Ituen, Ambrish Singh, Lin Yuanhua, Inhibitive effect of onion mesocarp extract-nickel nanoparticles composite on simultaneous hydrogen production and pipework corrosion in 1M HCl, international journal of hydrogen energy 45 (2020) 10814e 10825.
- 63) H. Mohamed Kasim Sheit, K. S. Mohan, N. Geetha, R. Lavanya, Karthik Kannan, S. Esakki Muthu, Manikandan Ayyar, Prabhu Paramasivam, Saravanan Rajendran, M. Santhamoorthy, S. Santhoshkumar & Ankush Mehta, Nanoengineered t-ZrO₂ coatings for superior corrosion resistance on steel surfaces, Scientific Reports (2026) 16:439.
- 64) Ruby Aslam, Mohammad Mobin, Mohd. Shoeb & Jeenat Aslam, Novel ZrO₂-glycine Nanocomposite as eco-friendly high temperature corrosion inhibitor for mild steel in hydrochloric acid solution, Scientific Reports (2022) 12:9274.
- 65) Edidiong A. Essien, Doga Kavaz, Ekemini B. Ituen & Saviour A. Umoren, Synthesis, characterization and anticorrosion property of olive leaves extract-titanium nanoparticles composite, Journal of Adhesion Science and Technology, 2018.
- 66) Ekemini Ituen, Ambrish Singh, Lin Yuanhua, Onyewuchi Akaranta, Biomass-mediated synthesis of silver nanoparticles composite and application as green corrosion inhibitor in oilfield acidic cleaning fluid, Cleaner Engineering and Technology 3 (2021) 100119.
- 67) Rawia F. Sadek, Hala A. Farrag, Shimaa M. Abdelsalam, ZMH Keiralla, Amany I. Raafat and Eman Araby, A Powerful Nanocomposite Polymer Prepared from Metal Oxide Nanoparticles Synthesized via Brown Algae as Anti-corrosion and Anti-biofilm, Frontiers in Materials, July 2019 Volume 6.
- 68) L. Guo, S. Zhu, S. Zhang, Q. He, W. Li, Theoretical studies of three triazole derivatives as corrosion inhibitors for mild steel in acidic medium, Corros. Sci. 87 (2014) 366–375.
- 69) I.B. Obot, S.A. Umoren, Z.M. Gasem, R. Suleiman, B. El Ali, J. Ind. Eng., Theoretical prediction and electrochemical evaluation of vinylimidazole and allylimidazole as corrosion inhibitors for mild steel in 1 M HCl, Chem. 21 (2015)1328–1339.
- 70) G. Gece, S. Bilgiç, Quantum chemical study of some cyclic nitrogen compounds as corrosion inhibitors of steel in NaCl media, Corros. Sci., 51 (2009) 1876–1878.
- 71) K. Satheesh Kumar and P. Kathireswari. Biological synthesis of silver nanoparticles (Ag-NPS) by Lawsonia inermis (Henna) plant aqueous extract and its antimicrobial activity against human pathogens. Int.J.Curr.Microbiol.App.Sci(2016)5(3):926-937.
- 72) Ambrish Singh, Eno E. Ebenso, and M. A. Quraishi. Corrosion Inhibition of Carbon Steel in HCl Solution by Some Plant Extracts. International Journal of Corrosion Volume 2012, Article ID 897430.
- 73) Rukaiyat MS, Abubakar GS, Fatima MK. Corrosion inhibition of mild steel using alkaloids and tannins extracts of *Jatropha curcas* in acidic media. Bayero J Pure Appl Sci. 2017;10(1):311–7.
- 74) Shakeel Ahmed, Saifullah, Mudasir Ahmad, Babu Lal Swami, Saiqa Ikram. Green synthesis of silver nanoparticles using *Azadirachta indica* aqueous leaf extract. Journal of Radiation Research and Applied Sciences Volume 9 (2016).
- 75) Bentiss, M. Lebrini, M. Lagrenée, Thermodynamic characterization of metal dissolution and inhibitor adsorption processes in mild steel/2,5-bis(n-thienyl)-1,3,4-thiadiazoles/hydrochloric acid system, Corrosion Science Volume 47, Issue 12, December 2005, Pages 2915-2931.
- 76) Ikenna B. Onyeachu, Ime Bassey Obot, Ahmad A. Sorour, Mohammed I. Abdul-Rashid, Green corrosion inhibitor for oilfield application I: Electrochemical assessment of 2-(2-pyridyl) benzimidazole for API X60 steel under sweet environment in NACE brine ID196, Corrosion Science Volume 150, 15 April 2019, Pages 183-193.
- 77) Orhororo, E.K., Erameh, A.A. and Adingwupu, A.C, EVALUATION OF THE EFFECT OF TEMPERING ON THE CORROSION SUSCEPTIBILITY OF LOW CARBON STEEL IN SEA WATER, Nigerian Research Journal of Engineering and Environmental Sciences 3(1) 2018 pp. 409-415.

- 78) Moses M. Solomon, Husnu Gerengi, Tugce Kaya, Saviour A. Umoren, Performance Evaluation of a Chitosan/Silver Nanoparticles Composite on St37 Steel Corrosion in a 15% HCl Solution, Research Article November 7, 2016.
- 79) M. Aliasghari, M. Iranpoor, Application of composite conducting polymers for improving the corrosion behavior of various substrates: a Review, J. Compos. Compd. 2 (2020) 228–240.
- 80) S.R. Al-Mhyawi, Green synthesis of silver nanoparticles and their inhibitory efficacy on corrosion of carbon steel in hydrochloric acid solution, Int. J. Electrochem. Sci. 18 (2023) 100210.
- 81) Bhoomika R. Holla, R. Mahesh, H.R. Manjunath, Plant extracts as green corrosion inhibitors for different kinds of steel: A review, Heliyon 10 (2024) e33748.
- 82) Hemalatha Parangusan, Mostafa H. Sliem, Aboubakr M. Abdullah, Muhsen Elhaddad, Noora Al-Than, Jolly Bhadra, Plant extract as green corrosion inhibitors for carbon steel substrate in different environments: A systematic review, International Journal of Electrochemical Science Volume 20, Issue 4, April 2025, 100919.
- 83) Rafael Marinho Bandeira, Fernando Pereira Lima, Maelson Sousa Nunes, Evania Carvalho dos Santos, Jose Ribeiro dos Santos Junior, Jose Milton Elias de Matos, Chistiane M. Feitosa, Mahendra Rai, Shandesh Bhattarai and Deependra Das Mulmi, The green plant-based corrosion inhibitors—a sustainable strategy for corrosion protection, Surface Science and Technology (2025) 3:19.
- 84) A.M. Jabbar and A.S. Abdalnabi. Effect of organic corrosion inhibitors functional groups (azo and azomethine) on carbon steel N80 alloy corrosion using the electrochemical polarization technique. *Int. J. Corros. Scale Inhib.*, 2024, 13.
- 85) K.K. Kennedy, K.J. Maseka, M. Mbulo, K.K. Kennedy, K.J. Maseka, M. Mbulo, Selected adsorbents for removal of contaminants from wastewater: towards engineering clay minerals, Open J. Appl. Sci. 8 (8) (2018) 355–369.
- 86) Uwah IE, Okafor PC, Ebiekpe VE, Inhibitive action of ethanol extracts from *Nauclea latifolia* on the corrosion of mild steel in H₂SO₄ solutions and their adsorption characteristics. Arab J Chem (2013), 6(3):285–293.
- 87) Zhou X, Yang H, Wang F, Investigation on the inhibition behavior of a pentaerythritol glycoside for carbon steel in 3.5% NaCl saturated Ca(OH)₂ solution. Corrosion (2012) Sci 54:193–200.
- 88) Casaletto MP et al, Inhibition of Cor-Ten steel corrosion by “green” extracts of *Brassica campestris*. Corros (2018) Sci 136:91–105.
- 89) Shakeel Ahmed, Saifullah, Mudasir Ahmad, Babu Lal Swami, Saiqa Ikram. Green synthesis of silver nanoparticles using *Azadirachta indica* aqueous leaf extract. Journal of Radiation Research and Applied Sciences Volume 9, Issue 1, January 2016.
- 90) Naba Jasim Mohammed, Muhammad Rahimi Yusop & Norinsan Kamil Othman, Green and nano-based strategies for controlling mild steel corrosion in acidic media: a systematic review, npj Materials Degradation, (2026) 10:16.
- 91) Singh H, Desimone MF, Pandya S, Jasani S, George N, Adnan M et al., Revisiting the green synthesis of nanoparticles: uncovering influences of plant extracts as reducing agents for enhanced synthesis efficiency and its biomedical applications. Int J Nanomedicine 18: 4727–4750 (2023). <https://doi.org/10.2147/IJN.S419369>.
- 92) Md Ishak NAI, Kamarudin SK and Timmiati SN, Green synthesis of metal and metal oxide nanoparticles via plant extracts: an overview. Mater Res Express 6:112004 (2019).
- 93) Ahmad Royani, Muhammad Hanafi, Nabisab Mubarak, Gadang Priyotomo, Victor Sunday Aigbodion, Siti Musabikha, Azwar Manaf, Unveiling green corrosion inhibitor of Aloe vera extracts for API 5L steel in seawater environment, Scientific Reports | (2024) 14:14085.
- 94) Zhifeng Zhang, Fengjuan Wang, Yao Liu, Shengping Wu, Weihua Li, Wei Sun, Dong Guo and Jinyang Jiang, Molecule adsorption and corrosion mechanism of steel under protection of inhibitor in a simulated concrete solution with 3.5% NaCl, RSC Adv., 2018, 8, 20648-20654
- 95) Victoria Vorobyova, Margarita Skiba, Elena Gnatko, Agri-food wastes extract as sustainable-green inhibitors corrosion of steel in sodium chloride solution: A close look at the mechanism of inhibiting action, South African Journal of Chemical Engineering Volume 43, January 2023, Pages 273-295.

- 96) Shasanowar H Fakir, K Chaitanya Kumar, Hamid Ali, Jaya Rawat, Izharul Haq Farooqi, Synthesis and evaluation of green corrosion inhibitor from rice husk to mitigate corrosion of carbon steel in NaCl environment, *Materials Today: Proceedings* Volume 82, 2023, Pages 29-37.
- 97) Rania Farouq, Eman Hamdy, Moustafa M. S. Abbassy, H. A. Farag, Utilizing nanomaterials to functionalize the Tikoua extract as a powerful green anti-corrosion inhibitor for carbon steel, *Journal of Petroleum Exploration and Production Technology* (2025) 15:143.
- 98) Chandrabhan Verma, Eno E. Ebenso, M. A. Quraishi and Chaudhery Mustansar Hussain, Recent developments in sustainable corrosion inhibitors: design, performance and industrial scale applications, *Mater. Adv.*, 2021, 2, 3806.
- 99) Abdulkareem Mohammed Ali Al-Sammarraie, Khulood Abid Al-Saade, Mohammed H. A. Al-Amery, Synthesis and Characterization of Benzothiazol Derivative as a Corrosion Inhibitor for Carbon Steel in Seawater, *Materials Sciences and Applications*, Vol.6 No.7, July 30, 2015.
- 100) Y. Chen, T. Hong, M. Gopal, W.P. Jepson, EIS studies of a corrosion inhibitor behavior under multiphase flow conditions, *Corrosion Science* 42 (2000) 979±990.
- 101) Jinrong Yang, Bosheng Zhao, Jilagamazhi Fu, Long Zhao, Xiaoqing Yue, Yujie Pang, Huihu Shi, Jianbin Zhang, Reply to “Comments on measurement and relationships of density and viscosity of 1,2 propylene glycol + dimethyl sulfoxide mixtures and spectral insight, *Journal of Molecular Liquids* Volume 296, 15 December 2019, 111745.
- 102) José A Rodríguez, Julián Cruz-Borbolla, Pablo A Arizpe-Carreón, Evelin Gutiérrez, Mathematical Models Generated for the Prediction of Corrosion Inhibition Using Different Theoretical Chemistry Simulations, *Materials (Basel)*, 2020 Dec 11;13(24):5656.
- 103) Yakun Zhu, Michael L. Free, Gaosong Yi, The effects of surfactant concentration, adsorption, aggregation, and solution conditions on steel corrosion inhibition and associated modeling in aqueous media, *Corrosion Science* Volume 102, January 2016, Pages 233-250.
- 104) A.S. Sowmyashree, Amita Somya, C.B. Pradeep Kumar, Srilatha Rao, Novel nano corrosion inhibitor, integrated zinc titanate nano particles: Synthesis, characterization, thermodynamic and electrochemical studies, *Surfaces and Interfaces* Volume 22, February 2021, 100812.
- 105) S. S. Abd El Rehim, S. M. Sayyah, M. M. El-Deeb, S. M. Kamal, R. E. Azooz, Adsorption and corrosion inhibitive properties of P(2-aminobenzothiazole) on mild steel in hydrochloric acid media, *Int J Ind Chem* (2016) 7:39–52.
- 106) Kalaiselvi Kathirvel, Brindha Thirumalairaj, Mallika Jaganathan, Quantum Chemical Studies on the Corrosion Inhibition of Mild Steel by Piperidin-4-One Derivatives in 1 M H₃PO₄, *Open Journal of Metal*, Vol.4 No.4, October 30, 2014.
- 107) M.P. Desimone, G. Gordillo, S.N. Simison, The effect of temperature and concentration on the corrosion inhibition mechanism of an amphiphilic amido-amine in CO₂ saturated solution, *Corrosion Science* Volume 53, Issue 12, December 2011, Pages 4033-4043.
- 108) Juan Du, Ce Li, Jinming Liu, Xiang Chen, Guan Wang, Zixuan Zuo, Chengxi Huang, Fengcheng Lou, and Ming Wang, Inhibition effect of nano-silica synergistic corrosion inhibitor on 110SSsteel in ultra-high temperature organic acidic environment, Volume 58 Issue 8, December 2023.
- 109) Awwal Abdullahi Adamu, Ogunkemi Risikat Agbeke Iyun and James Dama Habila, Adsorption and thermodynamic studies of the corrosion Inhibition effect of *Desmodium adscendens* (Swartz) extract on carbon steel in 2 M HCl, Adamu *et al. BMC Chemistry* (2025) 19:163.
- 110) Bhawna Chugh, Ashish K. Singh, Sanjeev Thakur, Balaram Pani, Hassane Lgaz, Ill-Min Chung, Ranjana Jha, Eno E. Ebenso, Comparative Investigation of Corrosion-Mitigating Behavior of Thiadiazole-Derived Bis-Schiff Bases for Mild Steel in Acid Medium: Experimental, Theoretical, and Surface Study, *ACS Omega* 2020 5 (23), 13503-13520.
- 111) Giselle Gómez-Sánchez, Octavio Olivares-Xometl, Paulina Arellanes-Lozada, Natalya V. Likhanova, Irina V. Lijanova, Janette Arriola-Morales, Víctor Díaz-Jiménez and Josué López-Rodríguez, Temperature Effect on

the Corrosion Inhibition of Carbon Steel by Polymeric Ionic Liquids in Acid Medium, Int. J. Mol. Sci. 2023, 24(7), 6291.