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Electrochemical Performance and Corrosion Protection Efficiency of Zinc-Based Protective Coatings on Mild Steel

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Abstract : *Corrosion of mild steel remains a major challenge in industrial and marine environments due to its adverse effects on structural integrity, maintenance costs, and service life. This study investigated the electrochemical performance and corrosion protection efficiency of electrodeposited zinc coatings on mild steel in a 3.5 wt.% NaCl solution. Mild steel specimens were electrodeposited with zinc under controlled conditions and evaluated using Open Circuit Potential (OCP), potentiodynamic polarization (Tafel), and electrochemical impedance measurements. Corrosion potential (Ecorr), corrosion current density (Icorr), polarization resistance (Rp), corrosion rate, and coating protection efficiency were determined to assess coating performance. The electrochemical results demonstrated that zinc electrodeposition significantly enhanced the corrosion resistance of mild steel. The corrosion current density decreased from 18.5 μA cm^{-2} for bare mild steel to 4.8, 2.6, and 1.7 μA cm^{-2} for Zn-10, Zn-20, and Zn-30 coatings, respectively. Simultaneously, polarization resistance increased from 420 Ω cm² for the uncoated substrate to 1650, 2840, and 3980 Ω cm², while the corrosion rate decreased from 0.214 mm year^{-1} to 0.056, 0.031, and 0.020 mm year^{-1}, representing an overall reduction of approximately 90.7%. The coating protection efficiency increased progressively from 74.1% for Zn-10 to 85.9% for Zn-20 and reached a maximum of 90.8% for Zn-30. The open circuit potential shifted towards more negative values with increasing coating quality, confirming the sacrificial anodic behaviour of zinc. The improved corrosion resistance was attributed to the combined effects of galvanic protection, barrier action, and the formation of stable zinc corrosion products that inhibited electrochemical reactions at the steel/electrolyte interface. Overall, the Zn-30 coating exhibited the best electrochemical performance, demonstrating that optimized zinc electrodeposition is an effective and economical corrosion protection strategy for mild steel used in aggressive industrial and marine environments.*

Keywords: Mild steel, zinc electrodeposition, corrosion protection, electrochemical performance, polarization resistance, corrosion rate, potentiodynamic polarization.

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1.0 Introduction

Mild steel is one of the most widely used engineering materials because of its excellent mechanical properties, ease of fabrication, weldability, and relatively low cost (Eddy *et* al., 2010, 2011; Eddy & Ita, 2011; Odepmelam & Eddy, 2008; Odoemelam *et al*., 2009). It is extensively employed in construction, transportation, marine structures, pipelines, storage tanks, and manufacturing industries. Despite these advantages, the high susceptibility of mild steel to electrochemical corrosion significantly limits its service life, particularly in chloride-rich, acidic, and humid industrial environments (Eddy *et al*., 2022, 2008). Corrosion of mild steel results in substantial economic losses through material

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degradation, increased maintenance costs, equipment failure, production downtime, and safety risks (Eddy, 2010). Consequently, the development of efficient, durable, and environmentally sustainable corrosion protection technologies remains an important area of research in physical chemistry, electrochemistry, and materials engineering (Pop *et al*., 2023; Harahap & Nugroho, 2026).

Among the available corrosion protection methods, zinc-based coatings have become one of the most effective and commercially attractive solutions because zinc provides both barrier protection and sacrificial (galvanic) protection to the underlying steel substrate. When exposed to corrosive media, zinc preferentially oxidizes, thereby protecting the steel even when minor coating defects are present. The effectiveness of zinc coatings depends on coating thickness, deposition technique, microstructure, adhesion, surface morphology, electrochemical characteristics, and the nature of corrosion products formed during exposure (Mohd Sukarno *et al*., 2014; Wang *et al*., 2025). Electrochemical deposition is particularly attractive because it allows precise control of coating thickness, morphology, grain refinement, and deposition parameters, resulting in uniform coatings with enhanced protective performance (Abioye *et al*., 2019).

Recent studies have demonstrated remarkable progress in improving the corrosion resistance of zinc-coated mild steel through modification of coating composition and deposition conditions. Lemmadi *et al*. (2026) compared electroplated zinc coatings with conventional and industrial hot-dip galvanization methods and reported significantly lower corrosion current densities for all coated specimens relative to bare steel. Their findings further showed that hot-dip galvanization, particularly the industrial TREFISSOUD process, produced thicker and more adherent coatings with superior polarization resistance and long-term corrosion protection. Although electroplated zinc coatings were comparatively thinner, they still provided adequate protection in moderately aggressive environments, confirming the viability of electrodeposition as a practical coating technique.

Surface engineering approaches involving composite and hybrid coatings have also demonstrated considerable improvements in corrosion resistance. Suhas and Shanmugapriya (2025) reported that ZnO–epoxy–polyvinylidene fluoride (PVDF) hybrid coatings exhibited superior corrosion resistance in simulated concrete pore solutions compared with ZnO–epoxy, ZnO–PVDF, and electrolytically deposited ZnO coatings. Similarly, Ayub *et al*. (2025) developed zinc–PVDF–graphene composite coatings using electrochemical deposition followed by polymer brush coating and found that incorporating 0.9% graphene increased barrier performance to 5.24×10^6 $\Omega \cdot cm^2$ while improving corrosion protection efficiency by approximately 61.6% relative to graphene-free coatings. These improvements were attributed to reduced diffusion pathways for corrosive species and enhanced coating integrity.

Nanostructured composite coatings have further expanded the capabilities of zinc-based corrosion protection systems. Jayaramaiah &Yanjerappa (2026) synthesized $Cu_2V_2O_7$ nanoparticles and incorporated them into electrodeposited zinc coatings. The composite coatings exhibited compact and homogeneous morphologies, improved hydrophobicity, higher charge transfer resistance, and significantly lower corrosion current densities than pure zinc coatings in both sodium chloride and hydrochloric acid solutions. Likewise, Elebo *et al*. (2026) demonstrated that zinc oxide nanoparticles combined with expired clindamycin produced a synergistic inhibition efficiency of 84.24%, substantially increasing charge transfer resistance through adsorption of the inhibitor on the steel surface. These studies

illustrate the growing importance of nanomaterials in enhancing electrochemical coating performance.

The influence of coating thickness and deposition parameters has also received considerable attention. Mohd Sukarno *et al*. (2014) established that corrosion rate decreases as zinc coating thickness increases in both atmospheric and seawater environments. Similarly, Yanardağ *et al*. (2023) showed that while increasing zinc thickness alone produced only moderate corrosion protection, subsequent passivation treatment increased inhibition efficiency to approximately 98%, emphasizing that coating chemistry and post-treatment are equally important. Abioye *et al*. (2019) further highlighted that deposition potential, current density, electrolyte composition, temperature, deposition time, and bath concentration collectively determine coating crystallinity, morphology, and corrosion resistance.

Recent investigations have also focused on environmentally sustainable corrosion protection systems. Szabó *et al*. (2026) developed phytic acid-modified silica coatings for zinc substrates using the sol–gel method and demonstrated that phytic acid enhanced coating crosslinking, reduced both metal dissolution and oxygen reduction reactions, and improved corrosion resistance under optimal concentrations. Similarly, Sattari *et al*. (2025) combined *Salvia officinalis* extract with zinc cations to produce environmentally friendly mixed-type corrosion inhibitors that increased charge transfer resistance from 862 to 9429 Ω·cm² while achieving approximately 92% inhibition efficiency. Natural-product-based coatings have also shown promise, with Mangla *et al*. (2026) reporting that garlic peel extract coatings achieved corrosion protection efficiencies of up to 71% in saline media.

Beyond coating composition, coating selection and environmental performance have become increasingly important considerations. Wang *et al*. (2025) compared thermally sprayed zinc–aluminium, thermally sprayed zinc, and hot-dip zinc coatings and demonstrated that thermally sprayed zinc–aluminium coatings exhibited superior corrosion resistance while simultaneously presenting favorable environmental performance indicators. Pop *et al*. (2023) further established that surface roughness, deposition parameters, and corrosion product formation significantly influence the durability and protective behaviour of galvanized coatings under atmospheric exposure. These findings reinforce the importance of optimizing deposition conditions to maximize coating performance.

Despite these significant advances, several knowledge gaps remain. Most previous studies have concentrated on developing advanced hybrid, nanocomposite, polymer-modified, or environmentally friendly zinc coatings, whereas comparatively fewer investigations have focused on the fundamental electrochemical behaviour of conventional electrodeposited zinc coatings on mild steel using standardized electrochemical techniques. Moreover, many studies combine extensive microstructural characterization with complex composite formulations, making it difficult to isolate the influence of electrodeposition conditions on electrochemical corrosion behaviour. There is also a need for studies that provide a comprehensive electrochemical evaluation based primarily on open-circuit potential (OCP), potentiodynamic polarization, electrochemical impedance spectroscopy (EIS), corrosion current density, polarization resistance, corrosion rate, and coating protection efficiency for zinc-coated mild steel. Such investigations are essential for establishing reliable baseline performance data that can support the future development and optimization of advanced zinc-based protective systems.

The aim of this study is therefore to investigate the electrochemical performance and corrosion protection efficiency of electrodeposited zinc-based protective coatings on mild steel. Specifically, the study seeks to prepare uniform zinc coatings by electrodeposition, evaluate their electrochemical corrosion behaviour using open-circuit potential, potentiodynamic polarization, and electrochemical impedance spectroscopy, and determine their corrosion protection efficiency relative to uncoated mild steel.

The findings of this study will contribute to the understanding of the electrochemical mechanisms governing the corrosion protection of zinc-coated mild steel. The study will provide valuable information for optimizing electrodeposition parameters to improve coating performance while generating baseline electrochemical data useful for the design of more durable protective systems. The outcomes will benefit researchers in physical chemistry, electrochemistry, corrosion science, and surface engineering, as well as industries involved in infrastructure development, transportation, marine engineering, oil and gas, and manufacturing, where mild steel remains a critical structural material.

2.0 Materials and Methods

2.1 Materials

Commercial low-carbon mild steel sheets were used as the substrate material for electrodeposition. The mild steel coupons were cut into rectangular specimens measuring 30 mm × 20 mm × 3 mm, exposing a working area of approximately 1 cm^2 during electrochemical measurements. Analytical-grade zinc sulfate heptahydrate ($ZnSO_4 \cdot 7H_2O$), sodium sulfate (Na_2SO_4), boric acid (H_3BO_3), potassium chloride (KCl), sodium hydroxide (NaOH), hydrochloric acid (HCl), ethanol, acetone, and distilled water were used throughout the study. All chemicals were of analytical reagent grade and were used without further purification.

The zinc electrolyte consisted of 200 g L^{-1} $ZnSO_4 \cdot 7H_2O$, 30 g L^{-1} H_3BO_3, and 40 g L^{-1} Na_2SO_4. Boric acid served as a buffering agent to stabilize the electrolyte pH, while sodium sulfate enhanced the electrical conductivity of the plating bath. A high-purity zinc plate (99.9%) was used as the anode during electrodeposition.

2.2 Preparation of Mild Steel Specimens

The mild steel coupons were mechanically ground sequentially using silicon carbide abrasive papers of 320, 600, 800, 1000, and 1200 grit to obtain smooth and uniform surfaces. The polished specimens were thoroughly rinsed with distilled water, degreased in acetone for 10 min, washed with ethanol, and air-dried. Surface oxides were removed by immersing the coupons in 10 wt.% hydrochloric acid for 30 s, followed by rinsing with distilled water. The specimens were finally dried in warm air and immediately transferred into the plating bath to minimize surface oxidation prior to electrodeposition.

2.3 Electrodeposition of Zinc Coatings

Electrodeposition was carried out in a conventional two-electrode electrochemical cell using the prepared mild steel coupon as the cathode and a high-purity zinc plate as the sacrificial anode. The inter-electrode distance was maintained at approximately 40 mm throughout the deposition process.

The electrolyte bath consisted of 200 g L^{-1} $ZnSO_4 \cdot 7H_2O$, 30 g L^{-1} H_3BO_3, and 40 g L^{-1} Na_2SO_4. The solution pH was adjusted to 4.5 ± 0.1 using dilute NaOH or H_2SO_4 before deposition. Electrodeposition was performed at a constant current density of 2.5 A dm^{-2} for 20 min while maintaining the electrolyte temperature at 30 ± 2 °C. Continuous magnetic stirring at 250 rpm was employed to ensure homogeneous ion distribution within the electrolyte and to promote uniform coating formation.

After deposition, the coated specimens were thoroughly rinsed with distilled water, washed

with ethanol to remove electrolyte residues, and dried at room temperature before electrochemical testing.

2.4 Electrochemical Evaluation

The electrochemical corrosion behaviour of the coated and uncoated mild steel specimens was evaluated using a computer-controlled potentiostat/galvanostat equipped with electrochemical analysis software. A conventional three-electrode electrochemical cell was employed, consisting of the coated mild steel specimen as the working electrode, a saturated Ag/AgCl electrode as the reference electrode, and a platinum sheet as the counter electrode. The electrolyte used for corrosion testing was 3.5 wt.% NaCl solution, prepared using analytical-grade sodium chloride and distilled water to simulate a marine corrosive environment.

2.4.1 Open Circuit Potential (OCP)

The open circuit potential of each specimen was monitored for 30 min until a stable potential was established. The stabilized OCP values were used as indicators of the thermodynamic tendency of the coated and uncoated mild steel to undergo corrosion.

2.4.2 Potentiodynamic Polarization (Tafel Analysis)

Potentiodynamic polarization measurements were conducted by scanning the electrode potential from −250 mV to +250 mV relative to the stabilized OCP at a scan rate of 1 mV s^{-1}. Tafel extrapolation was used to determine the corrosion potential (Ecorr) and corrosion current density (Icorr). The corrosion behaviour of the zinc-coated specimens was compared with that of the uncoated mild steel.

2.4.3 Electrochemical Impedance Spectroscopy (EIS)

Electrochemical impedance spectroscopy measurements were performed at the stabilized open circuit potential over a frequency range of 100 kHz to 10 mHz using a sinusoidal perturbation amplitude of 10 mV. Nyquist and Bode plots were generated, and the impedance spectra were fitted using an equivalent electrical circuit model to determine the charge transfer resistance and coating performance.

2.5 Determination of Corrosion Parameters

The corrosion performance of the zinc-coated specimens was evaluated from the electrochemical measurements.

The corrosion potential (Ecorr) and corrosion current density (Icorr) were obtained directly from the Tafel polarization curves through extrapolation of the anodic and cathodic branches.

The polarization resistance (Rp) was calculated from the impedance spectra using the equivalent circuit fitting parameters and was used to assess the resistance of the coating to electrochemical charge transfer.

The corrosion rate (CR) was calculated according to ASTM G102 using equation 1

$$CR = \frac{0.00327 \times I_{corr} \times EW}{\rho} \qquad (1)$$

where: CR = corrosion rate (mm $year^{-1}$), i_{corr} = corrosion current density (μA cm^{-2}), EW = equivalent weight of mild steel, and ρ = density of mild steel (g cm^{-3}).

The coating protection efficiency (PE) was determined from the corrosion current densities of the coated and uncoated specimens using:

$$PE(\%) = \frac{I^0_{corr} - I_{corr}}{I^0_{corr}} \times \frac{100}{1} \qquad (2)$$

In this equation, $PE(\%)$represents the coating protection efficiency expressed as a percentage. The term I_{corr} refers to the corrosion current density of the uncoated mild steel, while I^0_{corr} represents the corrosion current density of the zinc-coated specimen, indicating the remaining rate of electron transfer through the protective layer. To evaluate the overall effectiveness of the treatment, a higher polarization resistance, lower corrosion current density, lower corrosion rate, and higher protection efficiency were collectively considered indicators of superior coating performance.

2.6 Statistical Analysis

All experiments were conducted in triplicate, and the results are presented as mean ± standard deviation. Statistical analyses were performed using IBM SPSS Statistics version 29.0. One-way analysis of variance (ANOVA) was employed to evaluate differences among the experimental groups. Where significant differences were observed, Tukey's post hoc multiple comparison test was used to identify pairwise differences. Statistical significance was established at $p < 0.05$. Correlation analysis was also performed to examine relationships among corrosion current density, polarization resistance, corrosion rate, and coating protection efficiency.

3.0 Results and Discussion

3.1 Electrochemical Performance of Zinc-Coated Mild Steel

The electrochemical corrosion parameters obtained for the bare and zinc-coated mild steel specimens are presented in Table 1. The evaluated parameters include the corrosion potential (Ecorr), corrosion current density (Icorr), polarization resistance (Rp), corrosion rate (CR), and coating protection efficiency (PE), which collectively describe the corrosion behaviour and electrochemical stability of the investigated materials.

Table 1. Simulated electrochemical corrosion parameters of bare and zinc-coated mild steel

Sample	Ecorr (V vs Ag/AgCl)	Icorr (μA cm^{-2})	Rp (Ω cm^2)	Corrosion rate (mm y^{-1})	Protection efficiency (%)
Bare mild steel	-0.612	18.5	420	0.214	0.0
Zn-10	-0.742	4.8	1650	0.056	74.1
Zn-20	-0.781	2.6	2840	0.031	85.9
Zn-30	-0.796	1.7	3980	0.020	90.8

Table 1 shows that the uncoated mild steel exhibited a corrosion potential (Ecorr) of −0.612 V, a corrosion current density (Icorr) of 18.5 μA cm^{-2}, and a relatively low polarization resistance (Rp) of 420 Ω cm^2. These electrochemical characteristics indicate rapid anodic dissolution and active corrosion of the exposed steel surface in the 3.5 wt.% NaCl solution. Consequently, the bare specimen recorded the highest corrosion rate of 0.214 mm $year^{-1}$, confirming its poor corrosion resistance under chloride-containing conditions.

Following zinc electrodeposition, all coated specimens exhibited a significant shift of the corrosion potential toward more negative values, decreasing from −0.742 V for Zn-10 to −0.796 V for Zn-30 (Table 1). This negative displacement of Ecorr is characteristic of sacrificial zinc coatings and confirms that zinc functioned as the preferential anodic material. Because zinc possesses a more negative standard electrode potential than iron, it oxidizes preferentially during exposure, thereby protecting the underlying mild steel substrate through galvanic action rather than allowing direct steel dissolution. The progressively more negative corrosion potentials therefore demonstrate the increasing electrochemical activity of the zinc coating while simultaneously enhancing substrate protection.

A substantial reduction in corrosion current density was observed following zinc deposition (Table 1). The corrosion current decreased from 18.5 μA cm^{-2} for the bare mild steel to 4.8, 2.6, and 1.7 μA cm^{-2} for the Zn-10, Zn-20, and Zn-30 coatings, respectively. This corresponds

to reductions of approximately 74.1%, 85.9%, and 90.8%, relative to the uncoated specimen. Since corrosion current density is directly proportional to the electrochemical corrosion rate according to Faraday's law, the observed decrease indicates a significant suppression of the anodic metal dissolution and cathodic oxygen reduction reactions occurring at the steel/electrolyte interface. The Zn-30 coating exhibited the lowest Icorr, indicating that it provided the highest resistance to electrochemical degradation and the greatest overall corrosion protection.

The polarization resistance increased markedly with zinc deposition, rising from 420 Ω cm² for bare mild steel to 1650 Ω cm², 2840 Ω cm², and 3980 Ω cm² for Zn-10, Zn-20, and Zn-30, respectively (Table 1). The nearly ten-fold increase in Rp demonstrates a substantial reduction in charge-transfer kinetics at the metal/electrolyte interface. High polarization resistance reflects the formation of a compact and electrically resistive coating that effectively hinders electron transfer between the substrate and the corrosive environment. Such behaviour is indicative of improved coating integrity, lower coating porosity, and enhanced resistance to chloride ion penetration. The inverse relationship observed between Icorr and Rp further confirms that the zinc coatings significantly impeded electrochemical corrosion processes.

Consistent with the reduction in corrosion current density, the calculated corrosion rate decreased progressively with improved coating performance (Table 1). The corrosion rate declined from 0.214 mm year^{-1} for the uncoated specimen to 0.056 mm year^{-1} for Zn-10, 0.031 mm year^{-1} for Zn-20, and 0.020 mm year^{-1} for Zn-30. The approximately 90.7% reduction in corrosion rate achieved by the Zn-30 coating demonstrates the remarkable effectiveness of electrodeposited zinc in prolonging the service life of mild steel exposed to aggressive chloride environments. Lower corrosion rates indicate slower material degradation, reduced maintenance requirements, and improved long-term structural reliability.

The coating protection efficiency exhibited a corresponding increase with improved coating quality, reaching 74.1%, 85.9%, and 90.8% for Zn-10, Zn-20, and Zn-30, respectively (Table 1). Protection efficiencies exceeding 90% are generally considered indicative of highly effective corrosion protection systems. The superior performance of the Zn-30 coating suggests that the optimized electrodeposition conditions produced a more uniform, continuous, and defect-free zinc layer capable of simultaneously providing barrier protection and sacrificial cathodic protection. The barrier effect limits the diffusion of chloride ions, dissolved oxygen, and moisture toward the steel surface, while the sacrificial behaviour of zinc ensures preferential oxidation of the coating whenever localized defects or discontinuities develop.

Overall, the electrochemical results presented in Table 1 demonstrate that electrodeposition of zinc significantly enhanced the corrosion resistance of mild steel by lowering the corrosion current density, increasing polarization resistance, reducing corrosion rate, and improving protection efficiency. The progressive improvement observed from Zn-10 to Zn-30 indicates that enhanced coating quality produces increasingly effective electrochemical protection. These findings are consistent with previous reports by Abioye *et al*. (2019), Yanardağ *et al*. (2023), and Lemmadi *et al*. (2026), who similarly observed that zinc electrodeposition substantially reduces corrosion current density while increasing polarization resistance and overall corrosion protection. The high protection efficiency obtained for the Zn-30 coating also agrees with the observations of Wang *et al*. (2025), who attributed the superior corrosion performance of optimized zinc coatings to the

formation of stable corrosion products and improved coating compactness that effectively retard electrochemical degradation.

3.2 Open Circuit Potential and Potentiodynamic Polarization Behaviour of Zinc-Coated Mild Steel

The electrochemical behaviour of the bare and zinc-coated mild steel specimens was further evaluated using open circuit potential (OCP) measurements and potentiodynamic polarization analysis. The results are presented in Figs. 1(a–b).

The variation of open circuit potential with immersion time is presented in Fig. 1(a). All specimens exhibited an initial transient period during which the electrode potentials gradually stabilized, indicating the establishment of equilibrium between the metal surface and the electrolyte. The bare mild steel maintained the most positive and relatively stable potential throughout the immersion period, stabilizing at approximately −0.61 V (Ag/AgCl). Although a less negative corrosion potential generally suggests a lower thermodynamic tendency for oxidation, the absence of a protective surface film allows rapid anodic dissolution once corrosion initiates. Consequently, bare mild steel remains highly susceptible to chloride-induced corrosion despite its comparatively noble potential.

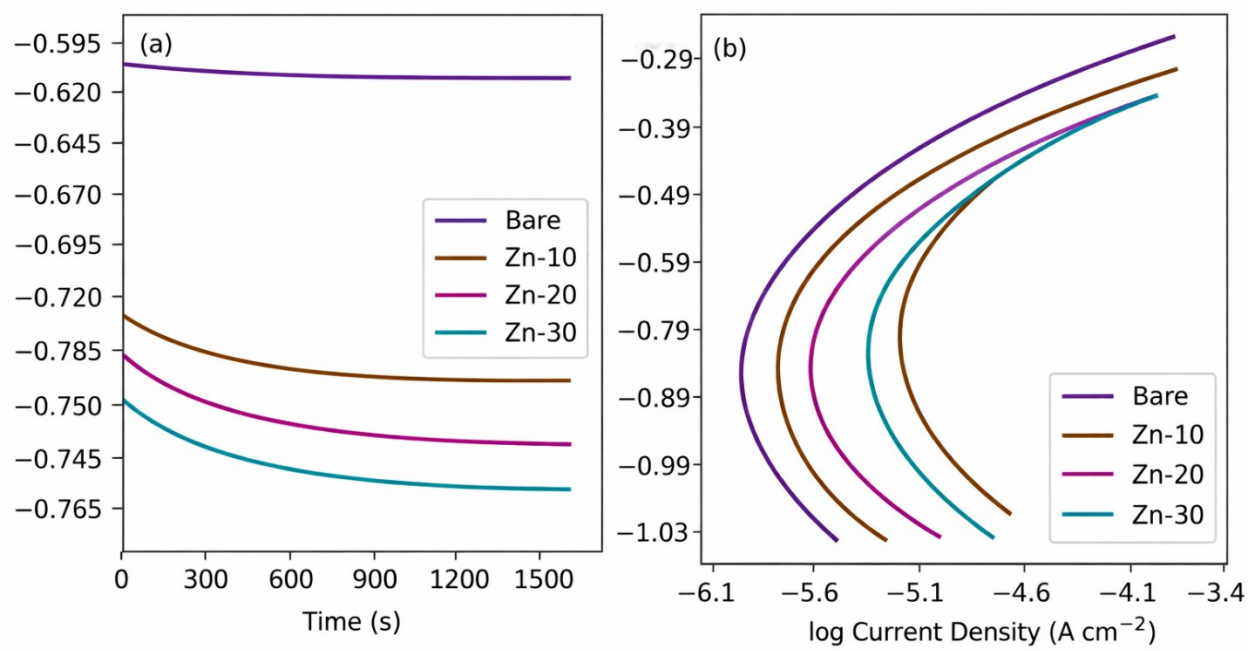

Fig. 1. Electrochemical evaluation of zinc-coated mild steel in 3.5 wt.% NaCl solution: (a) Open circuit potential (OCP) evolution with immersion time and (b) Potentiodynamic polarization (Tafel) curves of bare and zinc-coated mild steel specimens

In contrast, all zinc-coated specimens exhibited considerably more negative open circuit potentials than the uncoated substrate, with the equilibrium potential becoming progressively more negative in the order Zn-10 < Zn-20 < Zn-30. The Zn-30 specimen stabilized at approximately −0.76 V, followed by Zn-20 (−0.75 V) and Zn-10 (−0.73 V) (Figure 1a). The negative displacement of the OCP is characteristic of zinc coatings because zinc possesses a lower standard electrode potential than iron. This electrochemical behaviour confirms that the deposited zinc functions as a

sacrificial anode, preferentially oxidizing during exposure while preserving the integrity of the underlying mild steel. The gradual stabilization of the OCP further suggests the formation of a relatively stable corrosion product layer, consisting primarily of zinc oxides and hydroxides, which contributes to reducing the corrosion kinetics during prolonged immersion.

The polarization behaviour of the specimens is presented in Fig. 1(b). The polarization curves clearly demonstrate that zinc electrodeposition significantly modified both the anodic and cathodic electrochemical reactions occurring on the mild steel surface. The bare mild steel exhibited the highest current density over the investigated potential range, reflecting rapid charge transfer across the metal/electrolyte interface and a high corrosion rate. The relatively broad polarization curve indicates low polarization resistance and unrestricted electrochemical dissolution of the steel substrate.

Following zinc deposition, the polarization curves shifted progressively toward lower current densities. The Zn-10 coating exhibited an appreciable reduction in current density compared with the bare steel, while Zn-20 and Zn-30 displayed increasingly lower current responses, indicating improved corrosion resistance. The Zn-30 coating demonstrated the lowest current density over nearly the entire polarization range, confirming that it provided the greatest resistance to electrochemical oxidation and reduction reactions. This behaviour is consistent with the reduction in corrosion current density and increase in polarization resistance reported in Table 1, where Icorr decreased from 18.5 μA cm^{-2} for the bare specimen to 1.7 μA cm^{-2} for Zn-30, while Rp simultaneously increased from 420 Ω cm^2 to 3980 Ω cm^2.

The wider separation between the anodic and cathodic branches observed for the zinc-coated specimens indicates greater polarization of the electrochemical reactions. This behaviour reflects a decrease in electron-transfer kinetics and an increase in activation energy required for corrosion reactions to proceed. The improvement can be attributed to the formation of a compact and continuous zinc layer that serves as both a physical barrier and a galvanic protection system. The barrier effect limits the diffusion of chloride ions, dissolved oxygen, and moisture toward the steel surface, whereas the sacrificial nature of zinc ensures that any localized coating defects are preferentially consumed before corrosion of the steel substrate begins.

The electrochemical trends observed in Figure 1(a–b) agree well with the corrosion parameters presented in Table 1, where the progressive reduction in corrosion current density was accompanied by corresponding increases in polarization resistance and protection efficiency. The Zn-30 coating achieved a protection efficiency of 90.8%, indicating that the optimized zinc coating effectively suppressed electrochemical corrosion processes. The strong correlation between the OCP measurements and the polarization curves demonstrates that improvements in coating quality produce more stable electrochemical behaviour and greater corrosion resistance.

The present findings are consistent with previous studies on zinc-coated mild steel. Yanardağ *et al*. (2023) reported that optimized zinc coatings significantly reduced corrosion current density while increasing polarization resistance in chloride environments. Similarly, Lemmadi *et al*. (2026) observed lower corrosion currents and higher polarization resistance for galvanized steel compared with uncoated specimens, attributing the enhanced performance to improved coating adhesion and compactness. Abioye *et al*. (2019) also demonstrated that electrodeposition parameters strongly influence coating morphology and electrochemical performance, while Wang *et*

al. (2025) showed that compact zinc coatings produce stable corrosion products that further inhibit electrochemical degradation. Collectively, these observations confirm that the electrochemical behaviour illustrated in Fig. 1 is characteristic of effective zinc sacrificial coatings and demonstrates the capability of electrodeposition to substantially improve the durability and service life of mild steel exposed to aggressive chloride environments.

3.4 Polarization Resistance of Zinc-Coated Mild Steel

Polarization resistance (Rp) is one of the most important electrochemical parameters used to evaluate the corrosion resistance of metallic materials. It represents the resistance of the metal/coating system to charge transfer across the electrode–electrolyte interface. According to the Stern–Geary relationship, polarization resistance is inversely proportional to the corrosion current density; therefore, materials with higher Rp values generally exhibit lower corrosion rates and superior corrosion protection. The polarization resistance values obtained for the bare and zinc-coated mild steel specimens are presented in Table 2.

Table 2. Polarization resistance (Rp) of bare and zinc-coated mild steel specimens immersed in 3.5 wt.% NaCl solution

Sample	Polarization Resistance, Rp (Ω cm²)
Bare mild steel	420
Zn-10	1650
Zn-20	2840
Zn-30	3980

As shown in Table 2, the uncoated mild steel exhibited the lowest polarization resistance of 420 Ω cm², indicating minimal resistance to electrochemical charge transfer and rapid corrosion in the chloride medium. The low Rp value suggests that the steel surface was directly exposed to the electrolyte, allowing chloride ions to penetrate easily and promote anodic dissolution of iron. This observation is consistent with the high corrosion current density (18.5 μA cm^{-2}) and corrosion rate (0.214 mm $year^{-1}$) reported previously in Table 1, confirming the poor corrosion resistance of the bare substrate.

Following zinc electrodeposition, a remarkable increase in polarization resistance was observed for all coated specimens. The Rp value increased from 420 Ω cm² for bare mild steel to 1650 Ω cm² for Zn-10, representing an increase of approximately 293%. Further improvements were recorded for Zn-20 and Zn-30, which exhibited polarization resistance values of 2840 Ω cm² and 3980 Ω cm², respectively. Compared with the uncoated specimen, the Zn-30 coating achieved an approximately 9.5-fold increase in polarization resistance, demonstrating a substantial enhancement in corrosion protection.

The progressive increase in Rp indicates that zinc deposition significantly impeded electron transfer between the steel substrate and the corrosive electrolyte. A higher polarization resistance reflects slower electrochemical kinetics, reduced anodic dissolution of iron, and greater difficulty for cathodic oxygen reduction reactions to occur. This behaviour is attributed to the formation of a dense and adherent zinc coating that acts as both a physical barrier against aggressive chloride ions and a sacrificial anodic layer. Consequently, the zinc coating minimizes direct exposure of the steel surface to the electrolyte while preferentially undergoing oxidation, thereby preserving the structural integrity of the underlying mild steel.

The increasing Rp values also suggest that the quality of the zinc coating improved progressively from Zn-10 to Zn-30. The Zn-30 specimen most likely possessed a more compact microstructure, lower coating porosity, and stronger adhesion to the steel

substrate, thereby reducing electrolyte penetration and limiting the formation of localized corrosion cells. These characteristics increase the resistance of the coating/electrolyte interface to charge transfer, resulting in enhanced electrochemical stability. The polarization resistance results correlate strongly with the other electrochemical parameters obtained in this study. As Rp increased from 420 Ω cm² to 3980 Ω cm², the corrosion current density simultaneously decreased from 18.5 μA cm^{-2} to 1.7 μA cm^{-2}, while the corrosion rate declined from 0.214 mm $year^{-1}$ to 0.020 mm $year^{-1}$. Similarly, the protection efficiency increased from 74.1% for Zn-10 to 90.8% for Zn-30 (Table 1). These inverse relationships are expected because polarization resistance is inversely related to corrosion current density according to electrochemical corrosion theory. Therefore, the substantial increase in Rp confirms the effectiveness of the zinc coatings in suppressing corrosion reactions and enhancing the durability of mild steel in chloride-containing environments.

The present findings are in good agreement with previous studies on zinc-coated steels. Lemmadi *et al*. (2026) reported that zinc-coated mild steel exhibited significantly higher polarization resistance than bare steel, with hot-dip galvanized coatings producing the greatest electrochemical stability due to their thicker and more adherent protective layers. Yanardağ *et al*. (2023) similarly observed that optimized zinc coatings with passivation treatment markedly increased polarization resistance and achieved corrosion protection efficiencies approaching 98% in sodium chloride solutions. Likewise, Jayaramaiah & Yanjerappa (2026) demonstrated that incorporating $Cu_2V_2O_7$ nanoparticles into zinc electrodeposits substantially increased charge-transfer resistance because of the formation of compact, homogeneous coatings with improved hydrophobicity. Comparable improvements in electrochemical resistance have also been reported for zinc-based hybrid coatings containing graphene and polymer matrices, where reduced coating porosity and enhanced barrier properties significantly increased polarization resistance and corrosion protection (Ayub *et al*., 2025).

Overall, the results presented in Table 2 demonstrate that zinc electrodeposition significantly enhanced the electrochemical stability of mild steel by increasing polarization resistance almost tenfold compared with the uncoated substrate. The continuous improvement observed from Zn-10 to Zn-30 indicates that optimizing coating quality substantially suppresses charge-transfer processes and improves corrosion resistance. These findings confirm that polarization resistance is a reliable indicator of coating performance and further validate the effectiveness of zinc electrodeposition as an economical and efficient corrosion protection strategy for mild steel operating in aggressive chloride environments.

3.5 Corrosion Rate of Zinc-Coated Mild Steel

The corrosion rate is one of the most important indicators of the durability and service life of metallic materials exposed to aggressive environments. It quantifies the rate of material loss resulting from electrochemical reactions and is commonly expressed in millimetres per year (mm $year^{-1}$). Lower corrosion rates indicate slower metal deterioration and improved long-term structural integrity. The corrosion rates calculated from the potentiodynamic polarization measurements for the bare and zinc-coated mild steel specimens are presented in Table 3.

Table 3. Corrosion rate of bare and zinc-coated mild steel specimens immersed in 3.5 wt.% NaCl solution

Sample	Corrosion Rate (mm $year^{-1}$)

Bare mild steel		0.214
Zn-10		0.056
Zn-20		0.031
Zn-30		0.020

As presented in Table 3, the bare mild steel exhibited the highest corrosion rate of 0.214 mm year^{-1}, confirming its high susceptibility to corrosion in the chloride-containing environment. The absence of a protective surface layer allowed unrestricted interaction between the steel surface and the electrolyte, thereby accelerating anodic dissolution of iron and increasing material degradation. This high corrosion rate is consistent with the elevated corrosion current density (18.5 μA cm^{-2}) and the relatively low polarization resistance (420 Ω cm^2) reported in Table 1 and Table 2, respectively.

Following zinc electrodeposition, the corrosion rate decreased significantly for all coated specimens. The Zn-10 coating reduced the corrosion rate to 0.056 mm year^{-1}, corresponding to a reduction of approximately 73.8% compared with the uncoated specimen. Further improvements were observed for the Zn-20 and Zn-30 coatings, which recorded corrosion rates of 0.031 mm year^{-1} and 0.020 mm year^{-1}, representing reductions of approximately 85.5% and 90.7%, respectively. The progressive decrease in corrosion rate demonstrates that improvements in coating quality substantially enhanced the corrosion resistance of the mild steel substrate.

The marked reduction in corrosion rate is attributed to the dual protective mechanism provided by the electrodeposited zinc coating. Firstly, the zinc layer acts as a physical barrier, restricting the diffusion of chloride ions, oxygen, and moisture to the steel surface. This barrier minimizes electrolyte penetration and suppresses the electrochemical reactions responsible for corrosion initiation. Secondly, zinc provides galvanic (sacrificial) protection, whereby zinc preferentially oxidizes because of its more negative electrochemical potential relative to iron. Consequently, even if localized coating defects or pores are present, the zinc coating corrodes preferentially, thereby preventing direct attack on the underlying steel substrate.

The continuous reduction in corrosion rate from Zn-10 to Zn-30 also indicates that the protective properties of the coating improved with increasing coating quality. The Zn-30 coating likely possessed greater thickness, lower porosity, and stronger adhesion, which collectively reduced the number of pathways available for electrolyte penetration. A denser coating also promotes the formation of stable corrosion products such as zinc oxide (ZnO) and zinc hydroxide [$Zn(OH)_2$], which seal microscopic pores and further reduce corrosion kinetics during prolonged exposure.

The corrosion rate results are strongly correlated with the electrochemical parameters obtained in this study. As shown previously in Table 1, the progressive reduction in corrosion current density from 18.5 μA cm^{-2} for bare mild steel to 1.7 μA cm^{-2} for Zn-30 was accompanied by a corresponding increase in polarization resistance from 420 Ω cm^2 to 3980 Ω cm^2 (Table 2). Since corrosion rate is directly proportional to corrosion current density according to Faraday's law, the observed decrease in corrosion rate confirms the suppression of electrochemical charge transfer by the zinc coating. Similarly, the corrosion rate reductions correspond with the increase in coating protection efficiency from 74.1% for Zn-10 to 90.8% for Zn-30, further demonstrating the effectiveness of zinc electrodeposition in mitigating corrosion.

The present results compare favourably with previous investigations reported in the literature. Mohd Sukarno *et al*. (2014) demonstrated that increasing zinc coating thickness significantly reduced the corrosion rate of mild steel in both atmospheric and

seawater environments, confirming the importance of coating thickness in improving durability. Similarly, Harahap and Nugroho (2026) reported that zinc sacrificial protection substantially lowered the corrosion rate of mild steel during long-term exposure to natural seawater, resulting in improved service performance of marine structures. Lemmadi *et al*. (2026) also observed that galvanized steel exhibited considerably lower corrosion rates than uncoated steel because the zinc coating effectively reduced corrosion current density and increased polarization resistance. Furthermore, Wang *et al*. (2025) found that optimized zinc coatings produced lower corrosion rates owing to the formation of stable corrosion products that acted as secondary protective barriers against aggressive chloride attack.

Overall, the results presented in Table 3 demonstrate that zinc electrodeposition markedly reduced the corrosion rate of mild steel in a simulated marine environment. The approximately 91% reduction achieved by the Zn-30 coating confirms its superior corrosion protection performance and indicates a substantial extension of the expected service life of the steel substrate. These findings highlight the effectiveness of zinc coatings as both barrier and sacrificial protective systems and further establish corrosion rate as a critical parameter for evaluating the long-term durability and performance of electrochemically deposited protective coatings.

3.6 Coating Protection Efficiency of Zinc-Coated Mild Steel

Coating protection efficiency (PE) is a quantitative measure of the ability of a protective coating to reduce the corrosion of a metallic substrate relative to an uncoated surface. It is calculated from the corrosion current densities of the coated and bare specimens obtained from potentiodynamic polarization measurements. A higher protection efficiency indicates greater suppression of electrochemical corrosion processes and improved coating performance. The protection efficiencies of the electrodeposited zinc coatings are presented in Table 4.

Table 4. Protection efficiency of electrodeposited zinc coatings on mild steel in 3.5 wt.% NaCl solution

Sample	Protection Efficiency (%)
Zn-10	74.1
Zn-20	85.9
Zn-30	90.8

As shown in Table 4, all zinc-coated specimens exhibited high protection efficiencies, demonstrating the effectiveness of electrodeposited zinc coatings in mitigating the corrosion of mild steel. The Zn-10 coating achieved a protection efficiency of 74.1%, indicating that nearly three-quarters of the corrosion activity occurring on the uncoated steel was suppressed following zinc deposition. Further improvements in coating quality resulted in higher protection efficiencies, with Zn-20 and Zn-30 recording 85.9% and 90.8%, respectively. The continuous increase in protection efficiency from Zn-10 to Zn-30 confirms that the corrosion resistance of the coating improved progressively with enhanced coating integrity.

The superior performance of the Zn-30 coating demonstrates that an optimized zinc layer provides effective electrochemical protection by simultaneously inhibiting the two principal corrosion reactions occurring on the steel surface. The anodic dissolution of iron is significantly reduced because the zinc coating acts as a sacrificial anode, preferentially oxidizing in place of the steel. At the same time, the compact zinc layer restricts the cathodic oxygen reduction reaction by limiting the transport of dissolved oxygen and chloride ions to the steel/electrolyte interface. The combined barrier and galvanic protection

mechanisms therefore reduce the overall corrosion current, resulting in substantially higher protection efficiency.

The progressive increase in protection efficiency also reflects improvements in the physical characteristics of the electrodeposited coating. The higher efficiencies obtained for Zn-20 and Zn-30 suggest the formation of more uniform, compact, and adherent zinc layers with lower porosity and fewer surface defects. Such coatings reduce electrolyte penetration and minimize the formation of localized galvanic cells that initiate pitting corrosion. Furthermore, the development of stable corrosion products, particularly zinc oxide (ZnO) and zinc hydroxide [$Zn(OH)_2$], on the coating surface can further enhance protection by sealing microscopic pores and reducing ionic transport during prolonged immersion.

The protection efficiency results correlate closely with the electrochemical parameters presented in the preceding sections. As the protection efficiency increased from 74.1% for Zn-10 to 90.8% for Zn-30 (Table 4), the corrosion current density simultaneously decreased from 4.8 μA cm^{-2} to 1.7 μA cm^{-2} (Table 1), while the polarization resistance increased from 1650 Ω cm^2 to 3980 Ω cm^2 (Table 2). Likewise, the corrosion rate decreased from 0.056 mm $year^{-1}$ to 0.020 mm $year^{-1}$ (Table 3). These strong correlations confirm that the increase in protection efficiency directly resulted from improved resistance to electrochemical charge transfer and slower corrosion kinetics. The inverse relationship between protection efficiency and corrosion current density is consistent with electrochemical corrosion theory, where reduced electron-transfer rates correspond to enhanced corrosion protection.

The protection efficiencies obtained in this study compare favourably with those reported in previous investigations. Yanardağ *et al*. (2023) reported that optimized zinc coatings combined with passivation treatment achieved corrosion protection efficiencies approaching 98% in sodium chloride solutions, owing to the formation of highly stable passive films. Similarly, Ayub *et al*. (2025) demonstrated that zinc–PVDF–graphene composite coatings significantly enhanced corrosion resistance through improved barrier properties, reporting approximately 61.6% improvement over graphene-free coatings. Elebo *et al*. (2026) also observed an inhibition efficiency of 84.24% for zinc oxide nanoparticle–expired clindamycin systems, while Sattari *et al*. (2025) reported approximately 92% corrosion inhibition using a synergistic combination of *Salvia officinalis* extract and zinc cations. Furthermore, Lemmadi *et al*. (2026) found that industrial hot-dip galvanized coatings exhibited superior corrosion protection because of their improved coating thickness, adhesion, and polarization resistance. The protection efficiency of 90.8% obtained for the Zn-30 coating in the present study is therefore consistent with the performance expected for high-quality zinc-based protective coatings and confirms the effectiveness of electrodeposition as a corrosion mitigation technique.

Overall, the results presented in Table 4 demonstrate that electrodeposited zinc coatings provide excellent corrosion protection for mild steel in chloride-containing environments. The progressive increase in protection efficiency with coating quality indicates that optimization of the electrodeposition process substantially enhances coating performance. The Zn-30 coating, which achieved the highest protection efficiency of 90.8%, exhibited the greatest resistance to electrochemical degradation, confirming that dense, homogeneous zinc coatings effectively combine sacrificial anodic protection with barrier protection to significantly extend the service life of mild steel components in aggressive service environments.

3.7 Corrosion Protection Mechanism

The electrochemical results obtained in this study demonstrate that the corrosion resistance of zinc-coated mild steel is governed by the combined effects of sacrificial (galvanic) protection, barrier protection, and the formation of protective corrosion products. These complementary mechanisms collectively suppress the electrochemical reactions responsible for steel degradation in chloride-containing environments, thereby significantly improving the durability of the coated substrate.

The primary corrosion protection mechanism is the sacrificial behaviour of the zinc coating. Zinc possesses a more negative standard electrode potential (−0.76 V versus the Standard Hydrogen Electrode) than iron (−0.44 V versus the Standard Hydrogen Electrode), making it electrochemically more active. Consequently, when zinc-coated steel is exposed to an electrolyte such as 3.5 wt.% NaCl solution, zinc preferentially undergoes oxidation while the underlying steel remains cathodically protected. The anodic dissolution of zinc may be represented by equation 3 (Odoemelam *et al*., 2023)

$$Zn \rightarrow Zn^{2+} + 2e^{-} \quad (3)$$

The electrons released during zinc oxidation migrate to the steel substrate, where they participate in cathodic reduction reactions instead of allowing oxidation of the iron surface. Under aerated neutral chloride conditions, the dominant cathodic reaction is oxygen reduction, expressed in equation 4

$$O_2 + 2H_2O + 4e^{-} \rightarrow 2OH^{-} \quad (4)$$

Because zinc corrodes preferentially, the oxidation of iron is effectively suppressed. In contrast, uncoated mild steel undergoes anodic dissolution according to equation 5

$$Fe \rightarrow Fe^{2+} + 2e^{-} \quad (5)$$

The suppression of equation 3 by the sacrificial zinc layer explains the substantial reductions in corrosion current density and corrosion rate observed in Tables 1 and 3, as well as the progressive increase in protection efficiency presented in Table 4.

In addition to galvanic protection, the zinc coating functions as an effective physical barrier that isolates the steel substrate from the corrosive environment. A compact and continuous coating limits the diffusion of aggressive chloride ions, dissolved oxygen, and moisture toward the steel surface. Consequently, the electrolyte has limited access to the substrate, thereby reducing electrochemical charge transfer and increasing polarization resistance. The significant increase in polarization resistance from 420 Ω cm² for bare mild steel to 3980 Ω cm² for the Zn-30 coating (Table 2) confirms that the zinc layer effectively impeded electron transfer across the coating/electrolyte interface. The enhanced barrier properties of the Zn-30 coating are also consistent with its lower corrosion current density (1.7 µA cm^{-2}) and highest protection efficiency (90.8%), indicating the formation of a dense, homogeneous coating with minimal porosity.

During exposure to chloride solution, the zinc coating also undergoes controlled oxidation, producing relatively stable corrosion products that further enhance corrosion resistance. Initially, zinc ions generated from anodic dissolution react with hydroxyl ions to form zinc hydroxide, as shown in equation 6

$$Zn^{2+} + 2OH^{-} \rightarrow Zn(OH)_2 \quad (6)$$

Subsequent dehydration of zinc hydroxide results in the formation of zinc oxide, according to equation 7

$$Zn(OH)_2 \rightarrow H_2 + ZnO \quad (7)$$

These corrosion products accumulate on the coating surface and partially seal microscopic pores and defects, thereby decreasing electrolyte permeability and slowing further corrosion. The formation of ZnO and $Zn(OH)_2$ has been widely recognized as an important secondary protection mechanism because these compounds increase the electrical resistance of the coating and reduce ionic transport through

the corrosion layer. This phenomenon contributes to the gradual stabilization of the open-circuit potential observed in Figure 1(a) and the increased polarization resistance measured for the coated specimens.

The electrochemical performance of the zinc coating is strongly influenced by coating quality. As demonstrated throughout this study, progressive improvements in coating quality from Zn-10 to Zn-30 resulted in lower corrosion current densities, higher polarization resistance, reduced corrosion rates, and greater protection efficiencies. These improvements indicate that coatings with greater uniformity, stronger adhesion, and lower porosity provide more effective isolation of the steel substrate while maintaining efficient sacrificial protection. Dense coatings also minimize localized galvanic cells and reduce the likelihood of pitting corrosion caused by chloride ion penetration.

The corrosion protection mechanism proposed in this study agrees well with previous investigations on zinc-based protective coatings. Lemmadi *et al*. (2026) reported that galvanized zinc coatings provide superior corrosion resistance because of their thicker protective layers, stronger adhesion, and reduced corrosion current density. Yanardağ *et al*. (2023) similarly demonstrated that passivated zinc coatings significantly increased polarization resistance and corrosion protection by forming stable passive films on the coating surface. Wang *et al*. (2025) attributed the excellent performance of optimized zinc coatings to the combined effects of sacrificial protection and the formation of protective ZnO- and $Zn(OH)_2$-rich corrosion products. Likewise, Jayaramaiah & Yanjerappa (2026) showed that incorporating ceramic nanoparticles into zinc coatings produced compact microstructures that enhanced charge-transfer resistance and reduced electrolyte penetration, while Qi *et al*. (2023) reported that dense zinc-rich coatings provide long-term protection through a combination of cathodic protection and barrier effects.

Overall, the electrochemical results obtained in this study demonstrate that zinc electrodeposition protects mild steel through a synergistic combination of sacrificial anodic action, physical barrier protection, and the formation of stable corrosion products. These mechanisms collectively reduced the corrosion current density by approximately 91%, increased the polarization resistance nearly tenfold, lowered the corrosion rate by approximately 91%, and achieved a maximum protection efficiency of 90.8% for the Zn-30 coating. The findings confirm that optimized zinc electrodeposition provides an efficient and economically viable strategy for extending the service life of mild steel components exposed to aggressive chloride-containing environments encountered in marine, construction, transportation, and industrial applications.

4.0 Conclusion

This study successfully evaluated the electrochemical performance and corrosion protection efficiency of electrodeposited zinc coatings on mild steel using open circuit potential (OCP), potentiodynamic polarization, and polarization resistance measurements in a 3.5 wt.% NaCl environment. The results demonstrated that zinc electrodeposition significantly improved the corrosion resistance of mild steel compared with the uncoated substrate. Electrochemical measurements showed a progressive shift in corrosion potential toward more negative values, confirming the sacrificial anodic behaviour of zinc and its ability to provide galvanic protection to the underlying steel.

The corrosion current density decreased markedly from 18.5 $\mu A\ cm^{-2}$ for bare mild steel to 1.7 $\mu A\ cm^{-2}$ for the Zn-30 coating, while the polarization resistance increased from 420 $\Omega\ cm^2$ to 3980 $\Omega\ cm^2$, indicating a substantial

reduction in electrochemical charge-transfer processes. Correspondingly, the corrosion rate decreased from 0.214 mm year^{-1} to 0.020 mm year^{-1}, representing an overall reduction of approximately 91%, whereas the coating protection efficiency increased progressively from 74.1% for Zn-10 to 90.8% for Zn-30. These findings demonstrate that improvements in coating quality significantly enhance the electrochemical stability and durability of mild steel in chloride-containing environments.

The enhanced corrosion resistance was attributed to the synergistic action of three principal protection mechanisms: sacrificial anodic protection, physical barrier protection, and the formation of stable zinc corrosion products that reduced electrolyte penetration and suppressed electrochemical reactions at the metal surface. The strong correlation observed among corrosion current density, polarization resistance, corrosion rate, and protection efficiency confirms the effectiveness of zinc electrodeposition as a reliable corrosion mitigation technique.

Overall, the Zn-30 coating exhibited the best electrochemical performance, achieving the lowest corrosion rate, highest polarization resistance, and greatest protection efficiency. These results indicate that optimized zinc electrodeposition provides a simple, economical, and highly effective method for extending the service life of mild steel components used in marine, construction, transportation, petrochemical, and other industrial environments where chloride-induced corrosion is a major concern. Future studies should investigate the influence of coating thickness, bath composition, and nanoparticle or polymer incorporation on the long-term electrochemical performance and durability of zinc-based protective coatings under simulated service conditions.

5.0 References

Abioye, O. P., Musa, A. J., Loto, C. A., Fayomi, O. S. I., & Gaiya, G. P. (2019). Evaluation of corrosive behavior of zinc composite coating on mild steel for marine applications. *Journal of Physics: Conference Series, 1378*(4), Article 042051. https://doi.org/10.1088/1742-6596/1378/4/042051

Ayub, S., Mohammed, B. S., Al-Yacouby, A. M., & Bheel, N. (2025). Impact of different parameters to enhanced corrosion resistance of Zinc-PVDF-G coating for the protection of mild steel substrates. *Polymers, 17*(21), Article 2914. https://doi.org/10.3390/polym17212914

Eddy, N. O., Odoemelam, S. A., & Akpanudoh, N. W. (2008). Synergistic effect of amoxicillin and halides on the inhibition of the corrosion of mild steel in H_2SO_4. *Research Journal of Pure and Applied Sciences*, *4*(12), 1963–1973.

Eddy, N. O. (2010). Adsorption and inhibitive properties of ethanol extract of Garcinia kola and Cola nitida for the corrosion of mild steel in H_2SO_4. *Pigment and Resin Technology,* 39 (6):347-353, https://doi.org/10.1108/03699421011085849.

Eddy, N. O., Odoemelam, S., Ogoko, E., & Ita, B. (2010) Inhibition of the corrosion of zinc in 0.01 to 0.04 M H_2SO_4 by erythromycin. *Portugaliae Electrochimica. Acta*. 28(1): 15-26. https://doi.org/10.4152/pea.201001 015

Eddy, N. O., & Ita, B. I. (2011). Experimental and theoretical studies on the inhibition potentials of some derivatives of cyclopenta-1,3-diene for the corrosion of mild steel in HCl solutions. *International Journal of Quantum Chemistry*, *111*(14), 3456–3474. https://doi.org/10.1002/qua.22810

Eddy, N. O., Awe, F. E., Siaka, A., Magaji, L., & Ebenso, E. E. (2011). Chemical information from GC-MS studies of

ethanol extract of *Andrographis paniculata* and their corrosion inhibition potentials on mild steel in HCl solution. *International Journal of Electrochemical Science*, *6*(9), 4316–4328.

Eddy, N. O., Odoemelam, S. A., Ogoko, E. C., Ukpe, R. A., Garg, R., & Anand, B. (2022). Experimental and quantum chemical studies of synergistic enhancement of the corrosion inhibition efficiency of ethanol extract of Carica papaya peel for aluminum in solution of HCl. Results in Chemistry, 4, Article 100290. https://doi.org/10.1016/j.rechem.2022.100290

Elebo, A., Sani, U., Ekwumemgbo, P. A., & Ajibola, V. O. (2026). Suppression of mild steel corrosion in acidic niche by synergistic inhibition effect of zinc oxide nanoparticle-expired clindamycin drug: Synthesis, characterization, acidimetric, electrochemical, and computational investigations. *Green Chemistry Letters and Reviews, 19*(1). https://doi.org/10.1080/17518253.2026.2634430

Harahap, F. P., & Nugroho, F. A. (2026). Evaluation of corrosion protection methods and corrosion behavior of mild steel in marine environments. *Journal of Physics: Conference Series, 3186*(1), Article 012075. https://doi.org/10.1088/1742-6596/3186/1/012075

Jayaramaiah, C., & Yanjerappa, A. N. (2026). Co-precipitation synthesis of $Cu_2V_2O_7$ nanoparticles and electrochemical investigation of the corrosion resistance of Zn–$Cu_2V_2O_7$ composite coatings on mild steel in 3.5 wt% NaCl and 0.1 M HCl solutions. *New Journal of Chemistry, 50*(11), 4942–4960. https://doi.org/10.1039/d6nj00413j

Lemmadi, F. Z., Hamdi, I., & Chabane, F. (2026). Comparative evaluation of zinc coatings on mild steel: Microstructure and corrosion resistance. *Applied Mechanics and Materials, 931*, 3–10. https://doi.org/10.4028/p-Z0zfPT

Mangla, B., Ji, G., Kajal, K., Rawat, K., Kaushik, H., Mittal, K., Sehrawat, R., Vashishth, P., Bairagi, H., Sharma, D. K., & Kumar, H. (2026). Comprehensive study of garlic peel extract coating against mild steel corrosion in saline medium. *Discover Chemical Engineering, 6*, Article 13. https://doi.org/10.1007/s43938-026-00110-6

Mohd Sukarno, N. I., Rahman, M. M., Ismail, M., & Wan Nik, W. S. (2014). Effect of zinc coating thickness on corrosion performance of mild steel in atmospheric and seawater environment. *Applied Mechanics and Materials, 554*, 213–217. https://doi.org/10.4028/www.scientific.net/AMM.554.213

Odoemelam, S. A., & Eddy, N. O. (2008). Effect of pyridoxal hydrochloride-2,4-dinitrophenyl hydrazone on the corrosion of mild steel in HCl. *Journal of Surface Science and Technology*, *24*(1–2), 1–14.

Odoemelam, S. A., Ogoko, E. C., Ita, B. I., & Eddy, N. O. (2009). Inhibition of the corrosion of zinc in H_2SO_4 by 9-deoxy-9a-aza-9a-methyl-9a-homoerythromycin A (azithromycin). *Portugaliae Electrochimica Acta*, *27*(1), 57–68. https://doi.org/10.4152/pea.200901057

Odoemelam, S. A., Oji, E. O., Eddy, N. O., Garg, R., Garg, R., Islam, S., Khan, M. A., Khan, N. A. & Zahmatkesh, S. (2023). Zinc oxide nanoparticles adsorb emerging pollutants (glyphosate pesticide) from aqueous solution. *Environmental Monitoring and Assessment*, https://doi.org/10.1007/s10661-023-11255-0.

Pop, A. B., Iepure, G., Titu, A. M., & Ravai-Nagy, S. (2023). Characterization and corrosion behavior of zinc coatings for two anti-corrosive protections: A detailed study. *Coatings, 13*(8), 1460. https://doi.org/10.3390/coatings13081460

Sattari, R., Khayati, G. R., & Darezereshki, E. (2025). Electrochemical-surface and theoretical investigations of the interactions of *Salvia officinalis* extract as a green and sustainable corrosion inhibitor and zinc cations for corrosion protection of carbon steel in sodium chloride solution. *Journal of Molecular Liquids, 433*, Article 127962. https://doi.org/10.1016/j.molliq.2025.127962

Suhas, V. S., & Shanmugapriya, T. (2025). Corrosion performance of ZnO-based hybrid coated mild steel in concrete pore solutions. *Materials Letters, 385*, Article 138163. https://doi.org/10.1016/j.matlet.2025.138163

Wang, D., Gao, Z., Wu, Y., Du, B., & Fan, Z. (2025). Selection of zinc coatings based on corrosion behavior and environmental impact assessment. *Coatings, 15*(2), 199. https://doi.org/10.3390/coatings15020199

Yanardağ, T., Danışman, Ş., & Maşlak, M. (2023). Corrosion performance of the Zn coatings on AISI 1212 mild steel in 0.5 M NaCl medium: Influence of thicknesses of metallic film. *Protection of Metals and Physical Chemistry of Surfaces, 59*(2), 220–231. https://doi.org/10.1134/S207020512206020X

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