

THE INHIBITION OF CARBON STEEL CORROSION IN WELL WATER SETTINGS USING Poly (malic acid)-Ni²⁺

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ABSTRACT

Weight loss, electrochemical, and surface studies were conducted to evaluate how a green Poly (malic acid)-Ni²⁺ (PMA-Ni²⁺) complex inhibited the deterioration of carbon steel in well water. Ni²⁺ (70 ppm) and PMA (20 ppm) demonstrated weak inhibition (8% and 26%) when used separately, but together they reached 96% efficiency with a substantial synergism parameter ($S_1 = 17.02$). The PMA-Ni²⁺ complex functions as a mixed-type, mostly cathodic inhibitor, significantly lowering corrosion current density (>95%) and enhancing charge transfer resistance, according to electrochemical data. While SEM and AFM photos verified the development of a thick, homogeneous protective layer that significantly decreased surface roughness, FTIR spectra showed bidentate coordination between PMA and Ni²⁺. All things considered, the PMA-Ni²⁺ complex exhibits a remarkable synergistic effect between the metal ion and biopolymer, providing a highly effective and environmentally acceptable corrosion protection system in favour of carbon steel in extreme environments. The use of environmentally friendly corrosion control materials advances the promotion of sustainable water infrastructure, and the current work is underway in Sustainable Development Goal (SDG) 6: Clean Water and Sanitation.

Keywords: Poly(malic acid)-Ni²⁺, Carbon Steel, Cathodic Inhibitor, Protective Layer, Biopolymer.

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INTRODUCTION

Because of its remarkable mechanical strength, workability, and affordability, carbon steel continues to be the primary material used for well casings, storage tanks, and water transmission systems.^{1,2,3,4} However, a major engineering and economic difficulty is its intrinsic vulnerability to corrosion in watery conditions.⁵ One of the feasible and economically viable ways to reduce metal deterioration in such closed or semi-closed systems is to utilise corrosion inhibitors.^{6,7,8,9} Despite their effectiveness, traditional inorganic inhibitors like chromates and phosphates are becoming more and more limited because of their high toxicity and detrimental effects on the environment.^{10,11} The hunt for ecologically friendly "green" substitutes that provide high inhibitory efficiency without the environmental cost has accelerated as a result of this regulatory change. A promising class of environmentally friendly corrosion inhibitors¹² has been identified in this context: biopolymers and their derivatives.¹³⁻¹⁶ The fact that they are renewable, biodegradable, and non-toxic makes them ideal for green chemistry. A particularly appealing possibility is poly (malic acid) (PMA), a naturally occurring polyhydroxy acid with a high density of carboxylic functional groups.¹⁷ It is well known that these functional groups serve as potent chelating sites, promoting the progress of a protective adsorption coating on a metal surface.¹⁸ The effectiveness of protection can be significantly increased by combining organic chemicals with trace amounts of non-toxic metal ions. By promoting the proliferation of compact and stable passive films, nickel ions (Ni²⁺), which are well known for their capacity to form stable complexes, can function as a cathodic inhibitor.^{19,20,21,22} We hypothesise that PMA and Ni²⁺ will mix to form a synergistic system in which the polymer covers the anodic sites as a main adsorbent and the Ni²⁺ ions alter the cathodic process to produce a better barrier layer. Moreover, the development of a protective layer on steel surfaces in well-water corrosion has not been studied using Poly(malic acid) combined with Ni²⁺ ions; as a result, this research, based on the PMA-Ni²⁺ complex as a corrosion protector, seeks to close this gap. This research aligns with the Indian

Knowledge System (IKS), where traditional knowledge and ancient metallurgical practices have successfully inhibited carbon steel corrosion in aqueous systems. A prominent example is the ancient Iron Pillar of Delhi, which has served for many years as a corrosion repellent by forming a protective film that inhibits corrosion. To top it off, the current research work related to carbon steel **corrosion** in well water with Poly (malic acid)-Ni²⁺ complex justifies the United Nations Sustainable Development Goal (SDG) 6: Clean Water and Sanitation.

EXPERIMENTAL

Materials and Specimen Preparation

Carbon steel with a nominal composition (wt.%) of 0.1% carbon, 0.4% manganese, and 0.0026% sulphur-the rest being iron-was the working material used in this investigation. Coupons were machined to 1.0 cm × 4.0 cm × 0.2 cm for the weight-loss procedure. The surfaces were mechanically ground using progressively finer grades of silicon carbide emery paper (180 to 1000 grit) to achieve this. Following a thorough rinsing with distilled water, the specimens were submerged in analytical-grade acetone to degrease them. Gathered from a nearby source, the well water was utilised as the corrosive medium, unaltered. Its chemical makeup was described, and Table 1 provides a summary of the important factors. Sigma-Aldrich supplied the inhibitor, Poly(malic acid) (PMA, 95% purity). A preset quantity of PMA and a modest concentration of Nickel sulphate hexahydrate (NiSO₄•6H₂O, Madras Scientific) were mixed directly into the well water solution to form the PMA-Ni²⁺ complex in situ.

Table-1: The Parameters Represent the Chemical and Physical Properties of the Collected Well Water that is used in the Current Study

Parameter	Value	Unit
pH	7.5	-
Conductivity	750	μS/cm
Total Dissolved Solids (TDS)	480	mg/L
Chloride (Cl ⁻)	110	mg/L
Sulphate (SO ₄ ²⁻)	45	mg/L
Total Hardness (as CaCO ₃)	250	mg/L

Weight Loss Method

The ASTM G1-03 standard mass loss (gravimetric) method was used to assess the corrosion inhibition capabilities of Poly (malic acid) (PMA) and its complex with Ni²⁺. As the corrosive medium, 100 mL beakers filled with the well water solution were used to immerse carbon steel coupons that had already been manufactured. For 168 hours (7 days), all studies were conducted in a static environment at room temperature (30 ± 1 °C). The following formulas were used to determine the corrosion rate (CR) and inhibition efficiency (IE %).

Inhibition Efficiency

$$IE (\%) = [1 - (\frac{W_2}{W_1})] \times 100$$

Where:

W₁ is the weight loss of the carbon steel coupon in the absence of an inhibitor (blank solution).

W₂ is the weight loss of the carbon steel coupon in the vicinity of the inhibitor (PMA or PMA-Ni²⁺ complex).

Corrosion Rate

$$CR (mmpy) = [\frac{\Delta m}{(A \times t)}] \times (0.365 / \rho)$$

Where:

CR is the corrosion rate in millimetres per year (mmpy).

Δm is the weight loss in milligrams (mg).

A is the total surface area of the coupon in square decimeters (dm²).

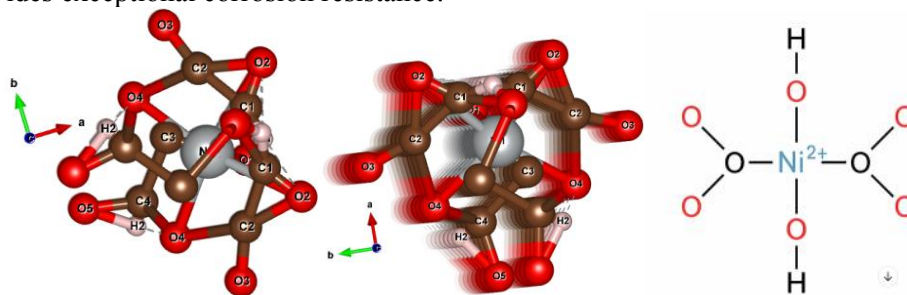
t is the immersion time in days.

ρ is the density of the carbon steel (7.86 g cm⁻³).

RESULTS AND DISCUSSION

Poly (malic acid)–Ni²⁺ (PMA–Ni²⁺) Complex

The coordination structure of the Poly(malic acid)–Ni²⁺ (PMA–Ni²⁺) complex is clearly defined by carboxylate groups from the polymer backbone chelating nickel ions. Strong metal–ligand interaction is made possible by the pendant –CH(COOH)– groups present in each malate repeat unit of PMA, which deprotonate to –COO[–] during complexation. With four oxygen atoms from two bidentate carboxylate ligands occupying equatorial positions, the Ni²⁺ ion adopts an octahedral geometry, forming stable five-membered Ni–O–C–C–O chelate rings. Water molecules or weakly attached oxygen atoms from ester or other carboxylate groups usually fill the axial coordination sites. This configuration creates an interconnected coordination network by enabling Ni²⁺ ions to cross between neighbouring polymer strands. The final structure blocks ion diffusion by forming a tight, cohesive layer that adheres firmly to metal surfaces. By preventing anodic and cathodic processes on carbon steel surfaces, this cross-linked network provides exceptional corrosion resistance.



Using the weight loss method, the corrosion inhibition capabilities of Poly (malic acid) (PMA) and its complex with Ni²⁺ were quantitatively assessed during a seven-day immersion period in well water. The findings, presented in Tables 2-4, clearly show that PMA plus Ni²⁺ ions have a potent synergistic effect.

Table-2: Performance of the Electrochemical Corrosion Parameters in the Presence of Poly (malic acid) (PMA) alone Immersed in Well Water

PMA(ppm)	Ni ²⁺ (ppm)	Corrosion Rate (CR, mmpy)	Inhibition Efficiency (IE%)
0	0	0.1413	-
10	0	0.1455	-2
20	0	0.1293	8
30	0	0.1285	9
40	0	0.1252	11
50	0	0.1160	17
60	0	0.0995	29
70	0	0.0845	40
80	0	0.0804	43
90	0	0.0779	44
100	0	0.0572	59

Table-3: Performance of the Electrochemical Corrosion Parameters in the Presence of Ni²⁺ Ions Alone Immersed in Well Water

Ni ²⁺ (ppm)	PMA (ppm)	Corrosion Rate (CR, mmpy)	Inhibition Efficiency (IE %)
0	0	0.1413	-
10	0	0.1335	5
20	0	0.1202	14
30	0	0.1156	18
40	0	0.1119	20
50	0	0.1115	21
60	0	0.1073	24
70	0	0.1044	26

80	0	0.0999	29
90	0	0.0986	30
100	0	0.0825	41

Table-4: Performance of the Electrochemical Corrosion Parameters of the PMA-Ni²⁺ Complex Immersed in Well Water

PMA (ppm)	Ni ²⁺ (ppm)	Corrosion Rate (CR, mmpy)	Inhibition Efficiency (IE %)
0	0	0.1413	-
20	10	0.0468	66
20	20	0.0310	78
20	30	0.0265	81
20	40	0.0257	81
20	50	0.0194	86
20	60	0.0124	91
20	70	0.0053	96
20	80	0.0145	89
20	90	0.0157	88
20	100	0.0165	88

Table 4 shows a clear synergistic inhibitory effect. Increasing the Ni²⁺ concentration from 10 to 70 ppm significantly lowers the corrosion rate from 0.0468 to 0.0053 mmpy at a PMA concentration of 20 ppm, while boosting inhibition efficiency from 66% to 96%. The effectiveness somewhat decreases above 70 ppm Ni²⁺, suggesting surface saturation and potential desorption effects.

Demonstration of Synergistic Effect

There is strong evidence for a synergistic interaction between PMA and Ni²⁺ based on the corrosion inhibition data shown in the previous section. The synergism parameter (S_1) is calculated to quantitatively validate this synergy. The synergism parameter (S_1) was computed using the following formula in an effort to officially quantify this effect:

$$S_1 = (1 - \theta(1+2)) / (1 - \theta'(1+2))$$

Where:

The theoretical aggregate surface coverage, $\theta(1+2)$, is determined by calculating the individual components: $\theta(1+2) = (\theta_1 + \theta_2) - (\theta_1\theta_2)$. The PMA-Ni²⁺ complex's empirically observed surface coverage is denoted by $\theta'(1+2)$, which is equal to IE% complex / 100. The surface coverages of PMA and Ni²⁺ alone are denoted by θ_1 and θ_2 , respectively. S_1 can be easily interpreted as follows: values less than or equal to 1 ($S_1 < 1$) suggest an antagonistic or simply additive effect, while values larger than 1 ($S_1 > 1$) indicate a synergistic effect. The PMA-Ni²⁺ inhibitor system's inhibitory efficiencies and synergism parameters (S_1) are shown in Table-5, which emphasises a robust cooperative connection between the metal ion and the polymer.

Table-5: Corrosion Efficiency Inhibition and Parameters of Synergistic Effect for the PMA-Ni²⁺ Inhibitor System

PMA(ppm)	IE% (PMA)	θ_1	Ni ²⁺ (ppm)	IE% (Ni ²⁺)	θ_2	Combined IE%	θ'_{1+2}	Synergism Parameter (S_1)
20	8	0.08	10	5	0.05	66	0.66	2.57
20	8	0.08	20	14	0.14	78	0.78	3.59
20	8	0.08	30	18	0.18	81	0.81	3.97
20	8	0.08	40	20	0.20	81	0.81	5.17
20	8	0.08	50	21	0.21	86	0.86	5.19
20	8	0.08	60	24	0.24	91	0.91	7.76
20	8	0.08	70	26	0.26	96	0.96	17.02
20	8	0.08	80	29	0.29	89	0.89	5.93
20	8	0.08	90	30	0.30	88	0.88	5.36
20	8	0.08	100	41	0.41	88	0.88	4.52

Although different Ni^{2+} doses (5–41% IE) and 20 ppm PMA (8% IE) provide only modest protection, together they significantly increase inhibitory efficacy to 96% at 70 ppm Ni^{2+} . The corresponding S1 values confirm strong synergy, peaking at 17.02 and all exceeding 1. This synergy results from PMA and Ni^{2+} adsorbing simultaneously, forming a thick, stable complex coating that effectively inhibits steel surface rusting.

FTIR Spectroscopic Analysis and Complexation Mechanism

The analysis of Fourier Transform Infrared Spectroscopy provides unambiguous spectral evidence in the carbonyl region, confirming the development of a PMA– Ni^{2+} complex. The transformation of carboxylic acid groups into carboxylate anions ($-\text{COO}^-$) is shown by the removal of the $-\text{COOH}$ band at 1720 cm^{-1} and the introduction of additional bands at 1605 cm^{-1} and 1405 cm^{-1} . The band separation ($\Delta\nu = 200\text{ cm}^{-1}$) points to a bidentate chelating coordination state, in which the carboxylate group's two oxygen atoms create a stable five-membered ring by bonding to the same Ni^{2+} ion. By facilitating cross-linking between PMA chains and improving adsorption stability, this coordination produces a thick, impermeable layer formed upon the surface of the carbon steel. By effectively blocking both anode and cathode sites, the strong polymer–metal network reduces corrosion through barrier and electrochemical processes. Thus, the development of this chemically stable, tightly bound PMA– Ni^{2+} complex layer is what causes the synergistic inhibitory effect.

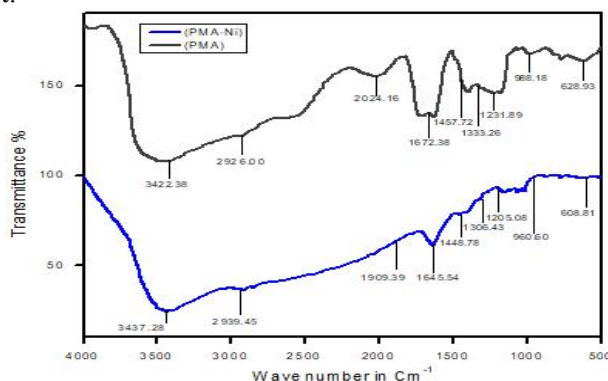


Fig.-1: FTIR Absorption Bands for the PMA– Ni^{2+} Complex

Electrochemical Kinetics: Potentiodynamic Polarization Analysis

To clarify the mechanism of inhibition and the kinetics of the corrosion process, potentiodynamic polarisation studies were conducted.

Table-6: Summarizes the Associated Electrochemical Data, Such as Tafel Slopes of the anode and Cathode (β_a , β_c), Corrosion Potential (E_{corr}), Corrosion Current Density (I_{corr}), and Computed Inhibition Efficiency (IE %).

System	E_{corr} (V vs. SCE)	I_{corr} ($\mu\text{A}/\text{cm}^2$)	β_a (mV/dec)	β_c (mV/dec)	Corrosion Rate (mmpy)	LPR Ohm. Cm^2	IE (%)
Blank	-0.650	25.6	78	125	0.301	9.6×10^2	---
PMA– Ni^{2+} (20ppm PMA & 70 ppm Ni^{2+})	-0.705	4.5	85	145	0.053	6.7×10^4	82.4

The potentiodynamic polarisation characteristics for carbon steel at varying concentrations with and without the PMA– Ni^{2+} complex are shown in Table-6. With an elevated corrosion current density (I_{corr}) of $25.6\text{ }\mu\text{A}/\text{cm}^2$ and a corrosion potential (E_{corr}) of -0.650 V , the blank system shows a corrosion rate of 0.301 mmpy . I_{corr} and corrosion rate both drop sharply to $4.5\text{ }\mu\text{A}/\text{cm}^2$ and 0.053 mmpy , respectively, upon addition of 20 ppm PMA and 70 ppm Ni^{2+} , indicating an inhibition efficiency of 82.4%.

The PMA– Ni^{2+} complex functions as an effective mixed-type inhibitor, primarily suppressing the cathodic process, as seen by the increasing negative shift in E_{corr} and reduced current density. The polarisation curves of carbon steel in well water are shown in Fig.-2, which contrasts the uncontrolled system with those that contain the PMA– Ni^{2+} combination.

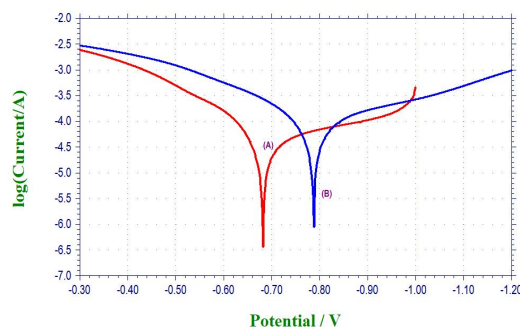


Fig.-2: Demonstrates the Polarisation Curves of the PMA-Ni²⁺ Complex before and after Treatment of Carbon Steel in Well Water

The blank solution's higher corrosion current density indicates rapid corrosion. The anodic and cathodic branches of the polarisation curves shift significantly toward lower current densities upon inclusion of the PMA-Ni²⁺ inhibitor, indicating reduced corrosion activity. Additionally, there is a modest negative change in the corrosion potential (E_{corr}), indicating a mixed-type inhibitory mechanism with a preponderance of cathodic control. The PMA-Ni²⁺ complex produces a barrier coating on the carbon steel surface, significantly delaying both anodic metal leaching and cathodic oxygen reduction processes, as confirmed by the significant drop in corrosion current density.

Electrochemical Impedance Spectroscopy (EIS) Analysis

Further research into the corrosion inhibition mechanism and the interfacial characteristics of the carbon steel surface in the presence of the PMA-Ni²⁺ complex was conducted using Electrochemical Impedance Spectroscopy (EIS). Figure-3 displays the Nyquist plots for carbon steel in well water with and without various inhibitor concentrations.

Table-7: Comparative Parameters for the PMA-Ni²⁺ Complex, Treated and Untreated, on Carbon Steel in Well Water

System	R_s ($\Omega \text{ cm}^2$)	CPE ($\mu\Omega^{-1} \text{ s}^n \text{ cm}^{-2}$)	C_{dl} $\mu\text{F}/\text{cm}^2$	n	R_{ct} ($\Omega \text{ cm}^2$)	IE (%)
Blank	~15	125	265	0.82	60	---
PMA-Ni ²⁺ (20 ppm PMA & 70 ppm Ni ²⁺)	~16	45	55	0.85	290	79.3

The parameters that are shown in Table-7 indicate that, with a high CPE value and a low charge transfer resistance (R_{ct}) of $60 \Omega \text{ cm}^2$, the blank system shows poor protective behaviour and an aggressive corrosion process. R_{ct} rises sharply to $290 \Omega \text{ cm}^2$ at 20 ppm PMA and 70 ppm Ni²⁺ upon addition of the PMA-Ni²⁺ complex, indicating improved surface protection.

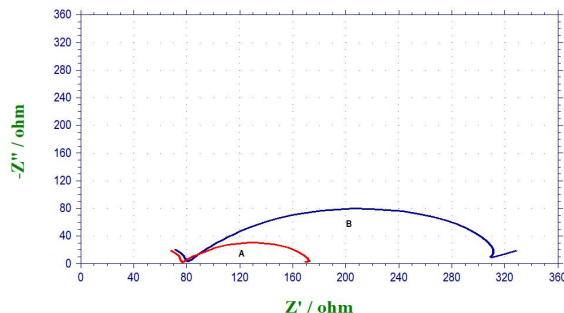


Fig.-3: The Nyquist Plots Received for the Uninhibited and Inhibited Metal Surface of the Carbon Steel in Well Water Conditions.

The simultaneous decrease in CPE values and increase in the exponent n suggest a more compact and homogeneous inhibitor coating. With a computed inhibition efficiency of 79.3%, the PMA-Ni²⁺ complex successfully blocks corrosion processes and charge transfer at the steel-solution interface. Variation in R_{ct} values is represented by the diameter of each semicircle in the graphs, which show typical

semicircular behaviour. A narrower semicircle in the blank solution (curve A) denotes a poor protective coating and a high rate of corrosion. The PMA–Ni²⁺ complex (curve B), on the other hand, produces a significantly bigger semicircle, indicating a significant increase in R_{ct} and enhanced corrosion resistance. This improvement demonstrates that the inhibitor successfully prevents charge transfer and inhibits corrosion processes by forming a stable, sticky, and protective layer on the steel surface.²³

Surface Morphology Analysis by Scanning Electron Microscopy (SEM)

By analysing the surface morphology of the carbon steel specimens upon immersion, Scanning Electron Microscopy (SEM) was utilised to directly demonstrate the corrosion inhibition. Figure-4 (a-c) shows the micrographs of the protected surface in the ideal PMA–Ni²⁺ inhibitor solution, the polished surface, and the corroded surface in an uninhibited solution (blank).

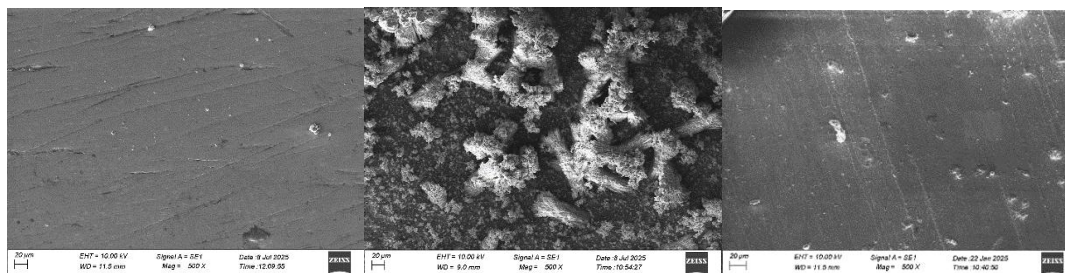


Fig.-4 (a)

Fig.-4 (b)

Fig.-4 (c)

Fig.-4 (a-c): SEM Micrographs of Carbon Steel Specimens: (a) Polished Surface Before Immersion, (b) Untreated Metal Surface in Well Water (blank), and (c) Submerged in Well Water Containing 20 ppm PMA + 70 ppm Ni²⁺

Carbon steel that has been polished (Fig.-4(a)). The polished specimen's micrograph reveals a comparatively homogeneous and smooth surface. This image serves as a baseline, representing the original, non-corroded state of the carbon steel surface. Blank (Uninhibited Solution) is shown in Fig.-4(b). The specimen's surface shows significant damage after being submerged in uncontrolled well water, indicating that the electrolyte is aggressive. A thick, fractured coating of corrosion products covers the whole surface, giving the morphology a rough, porous, and uneven appearance. Protected Surface (20 ppm PMA + 70 ppm Ni²⁺) (Fig.-4(c)).

In sharp contrast, the surface of the specimen protected by the optimum PMA–Ni²⁺ combination is significantly different. A thick, compact, and continuous covering covers the surface, giving the impression that it is much smoother. The morphology shows that a very cohesive and sticky protective layer has formed. The efficiency of the PMA–Ni²⁺ combination in preventing corrosion in carbon steel is amply demonstrated by the SEM study. According to FTIR and electrochemical studies, this morphology validates the creation of a strongly adhering, cross-linked inhibitor film, which explains the high inhibition efficiency (~96%) by acting as an efficient barrier that prevents corrosion and ion diffusion.

Energy-Dispersive X-ray Spectroscopy (EDS) Analysis of the PMA–Ni²⁺ Complex

The elemental identification from the PMA–Ni²⁺ complex's Energy-Dispersive X-ray Spectroscopy (EDS) investigation demonstrates that nickel was successfully coordinated within the polymer matrix. The spectrum shows two strong peaks representing the organic structure of poly(malic acid): ~0.28 keV (C K α) and ~0.53 keV (O K α). The strong Ni L α (~0.85 keV) and Ni K α (~7.47 keV) peaks confirm the successful inclusion of nickel ions and validate metal–ligand interaction through carboxylate coordination. The minor peaks of Cl K α (~2.62 keV) and Na K α (~1.04 keV) signify leftover salts or trace contaminants from production. The overall EDS profile confirms the expected elemental composition and shows that nickel is an essential component of the PMA–Ni²⁺ complex, which suppresses corrosion.

The XRD Analysis of the PMA–Ni²⁺ Complex

The PMA–Ni²⁺ complex's XRD study shows a hybrid structure made up of both crystalline and amorphous domains. Sharp peaks at 37.2°, 43.3°, and 62.9° correspond to the (111), (200), and (220) planes of NiO, demonstrating the development of crystalline nickel oxide inside the polymer framework, whereas a large hump around 2 θ = 20° demonstrates the amorphous character of the PMA matrix.

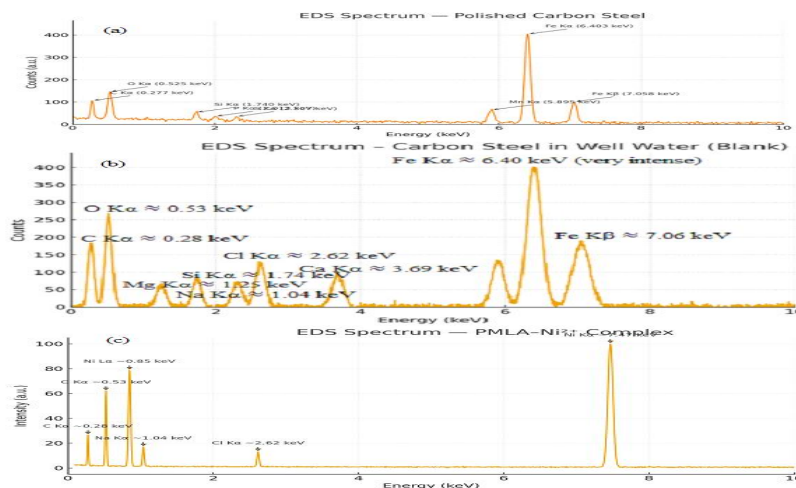


Fig.-5 (a-c): EDS Spectra of Carbon Steel Under Different Surface Conditions (a) Polished carbon steel, (b) Carbon steel exposed to well water (blank), and (c) Carbon steel surface after treatment with the PMA–Ni²⁺ complex.

Minor secondary Ni-based phases are suggested by additional weaker peaks at higher angles. The persistence of discrete NiO reflections in the face of background noise from polymer scattering verifies the existence of nanocrystalline NiO domains embedded in the amorphous PMA network, creating a robust polymer–metal composite.

Table-8: Observed Peaks and Calculated d-spacings (Cu Kα λ = 1.5406 Å)

Observed 2θ (°)	d-spacing (Å)	Likely assignment
~20.0	4.436 Å	Broad amorphous hump-polymer (PMA) / poorly ordered domains
~37.2	2.415 Å	NiO (111) or Ni-oxide phase
~43.3	2.088 Å	NiO (200) or related Ni phase
~62.9	1.476 Å	NiO (220)
~75.4	1.260 Å	Additional nickel-related reflection (possible higher-index Ni or Ni oxide/hydroxide)
~91.2	1.078 Å	Weak high-angle reflection-minor crystalline component or fluor/impurity line

The peak analysis of XRD. The creation of a polymer–metal oxide hybrid structure is further confirmed by Table-8 of the PMA–Ni²⁺ complex. The amorphous polymer matrix of PMA, which reflects its non-crystalline and flexible macromolecular backbone, is represented by the broad diffraction band at about 20° (d = 4.436 Å). Conversely, the (111), (200), and (220) planes of NiO are characterised by sharp reflections at 37.2°, 43.3°, and 62.9° with corresponding d-spacings of 2.415 Å, 2.088 Å, and 1.476 Å, respectively (JCPDS No. 47-1049). The existence of crystalline nickel oxide domains contained inside the amorphous polymer framework is evident from these peaks. Higher-order reflections or small nickel hydroxide or oxide phases could be responsible for the extra faint peaks at 75.4° (1.260 Å) and 91.2° (1.078 Å), which would indicate partial oxidation or structural disorder at the nanoscale. A semi-crystalline morphology with evenly distributed NiO nanocrystals within the amorphous PMA matrix is confirmed by the coexistence of both sharp and diffuse features.

By strengthening the interfacial connection between Ni²⁺ and PMA's carboxylate/ester groups, this structural configuration improves the composite's stability, metal coordination, and possible electrochemical activity. The PMA–Ni²⁺ complex's XRD patterns are shown in Fig.-6, which also shows idealized and experimental diffraction profiles. The amorphous polymer matrix and crystalline NiO phases are represented by distinct peaks in the simulated pattern (top) at roughly 20°, 37°, 43°, 63°, 75°, and 91°. The presence of semi-crystalline features is confirmed by the experimental spectrum (bottom), which shows comparable peak positions but with a lot more background noise. The sharp peaks show NiO crystalline domains inside the polymer framework, whereas the broad hump at about 20° denotes the amorphous character of PMA. This demonstrates that Ni²⁺ ions and PMA have successfully coordinated to form a stable polymer–metal oxide hybrid network.

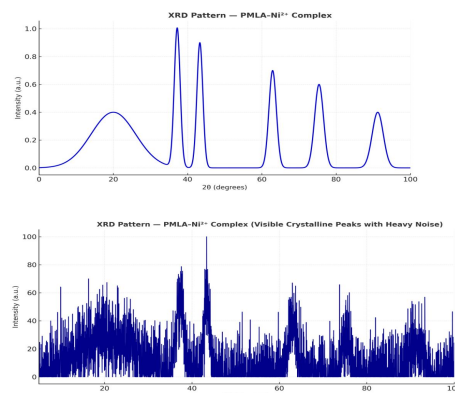


Fig.-6: XRD pattern ($2\theta = 5-100^\circ$) for the PMA- Ni^{2+} Complex Showing Visible Crystalline Peaks with Heavy Background Noise

Atomic Force Microscopy (AFM) Analysis of the PMA- Ni^{2+} Complex

To give quantitative, nanoscale insight into the surface shape and protective properties of the film generated by the PMA- Ni^{2+} complex, Atomic Force Microscopy (AFM) was utilised. Figure-7 (a-c) displays the three-dimensional topographs for the polished carbon steel, the specimen protected by the ideal inhibitor concentration, and the specimen following immersion in unfettered well water (blank).

Table-9: Comparison of AFM Parameters of Carbon Steel Submerged in Well Water Under Treated and Untreated Conditions

Samples	RMS Roughness (Rq) (nm)	Average Roughness (Ra) (nm)	Maximum Height (Ry) (nm)
Polished	71.349	56.367	401.84
Well Water (Blank)	911.7	756.66	3412.1
Well Water + 20 ppm PMA+ 70 ppm Ni^{2+}	100.59	89.944	408.05

Both with and without the PMA- Ni^{2+} inhibitor combination, the AFM values shown in Table-9 show notable surface morphological changes of carbon steel following exposure to well water. Roughness readings ($R_q = 911.7$ nm, $R_a = 756.66$ nm, $R_y = 3412.1$ nm) dramatically increase in the blank sample submerged in well water, showing significant surface corrosion and pit development. On the other hand, the inhibited surface (20 ppm PMA+ Ni^{2+}) more nearly resembles the polished metal ($R_q = 71.349$ nm) with significantly lower roughness values ($R_q = 100.59$ nm, $R_a = 89.944$ nm, $R_y = 408.05$ nm). The creation of a consistent, protective PMA- Ni^{2+} coating that successfully reduces corrosion attack and surface degradation is confirmed by this significant reduction in roughness.

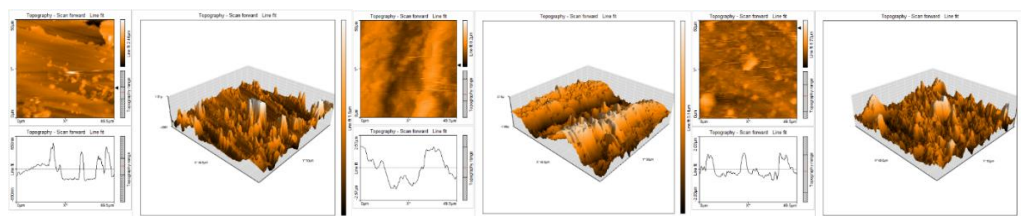


Fig.-7(a)

Fig.-7(b)

Fig.-7(c)

Fig.-7: AFM Analysis: (a) Polished Carbon Steel, (b) Well Water Blank, and (c) 20 ppm of PMA+ 70 ppm of Ni^{2+}

Safeguarding the steel surface in harsh well-water settings using Poly(malic acid)- Ni^{2+} complex as a non-toxic corrosion inhibitor to control the steel surface without degrading the material's properties. With the advantages of the current research work, it falls under the United Nations Sustainable Development Goal (SDG) 6: Clean Water and Sanitation scope.

CONCLUSION

The present investigation demonstrates that the sustainable development of the complex Poly (malic acid - Ni^{2+}) acts as an eco-friendly, benign, and highly efficient synergistic system for controlling the corrosion

of carbon steel in well water conditions, possessing 96% IE in well water environments. The Inhibition efficiency was verified using a weight-loss study conducted during the experiment. Electrochemical analysis revealed an impressive reduction in corrosion current density and an increase in charge-transfer resistance, indicating effective inhibition of the corrosion process. Moreover, FTIR, SEM, AFM, and XRD confirm the stable protective film formed on the steel surface by the poly (malic acid) – Ni²⁺ complex. The synergistic inhibition of the polymer-metal complex has shown the potential of biodegradable polymer-based inhibitors as sustainable alternatives for natural well water corrosion protection. Future studies may contribute to long-term immersion and large-scale industrial applications in various corrosion environments.

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CONFLICT OF INTERESTS

The authors had no conflicts of interest related to the current research.

AUTHOR CONTRIBUTIONS

This work relates to *SDG-6: Clean Water and Sanitation*. All the authors contributed significantly to this manuscript, participated in reviewing/editing and approved the final draft for publication. The research profile of the authors can be verified from their ORCID ids, given below:

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