

Electrochemical Investigation of Sodium Potassium Tartrate as an Eco-Friendly Corrosion Inhibitor for Mild Steel in 1 M Hydrochloric Acid

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ABSTRACT

The corrosion of mild steel in 1 M hydrochloric acid ("HCl") presents severe operational challenges in industrial operations such as acid pickling, descaling, and chemical cleaning. This study investigates the corrosion inhibition performance of sodium potassium tartrate (SPT), an environmentally benign compound, for mild steel in 1 M "HCl" using potentiodynamic polarization, electrochemical impedance spectroscopy (EIS), scanning electron microscopy (SEM), and gravimetric measurements. Potentiodynamic polarization measurements indicated that SPT acts as a mixed-type inhibitor, significantly reducing corrosion current density (I_{corr}) while increasing polarization resistance (R_p). EIS spectra showed a significant increase in charge-transfer resistance (R_{ct}) accompanied by a decrease in double-layer capacitance (C_{dl}), confirming the formation of a protective adsorbed interfacial film on the steel surface. Surface morphology analysis by SEM validated these findings, displaying a smooth surface microstructure for SPT-treated specimens compared to severe intergranular pitting and damage on uninhibited specimens. Adsorption of tartrate species occurs via oxygen-bearing carboxylate and hydroxyl functional groups onto active anodic and cathodic sites. Overall, sodium potassium tartrate demonstrates high efficacy as a non-toxic, eco-friendly corrosion inhibitor for mild steel in aggressive acidic environments..

Keywords: Mild steel; Sodium potassium tartrate; Corrosion inhibition; Hydrochloric acid; Potentiodynamic polarization; Electrochemical impedance spectroscopy; Surface morphology.

INTRODUCTION

Corrosion of metallic materials constitutes a major technological and economic problem across industrial sectors, including chemical manufacturing, petroleum processing, marine transport, and structural engineering [1, 2]. Mild steel remains one of the most widely applied structural alloys due to its exceptional mechanical strength, ease of fabrication, and cost-effectiveness [3]. However, mild steel is highly susceptible to rapid dissolution when exposed to aggressive mineral acids [4].

Hydrochloric acid ("HCl") solutions are extensively utilized in industrial processes such as acid pickling, industrial acid descaling, oil-well acidizing, and chemical cleaning [5, 6]. In these environments, hydrogen ion reduction accelerates anodic iron dissolution, while aggressive chloride ions (Cl^-) disrupt native surface films [7]. To mitigate metal degradation and prolong component service life, organic corrosion inhibitors are commonly added to acid formulations [8, 9].

Traditional corrosion inhibitors, such as compounds containing chromate, heavy metals, or volatile aromatic amines, present severe ecological toxicity and disposal hazards [6, 10]. Consequently, recent research has shifted toward developing "green" eco-friendly corrosion inhibitors featuring high biodegradability and low environmental toxicity [11, 12].

Sodium potassium tartrate ($\text{KNaC}_4\text{H}_4\text{O}_6$), also known as Rochelle salt, is a non-toxic salt containing multiple electron-rich oxygen functionalities, including carboxylate (COO^-) and hydroxyl (OH^-) functional groups [13–15]. These electron pairs can interact with vacant d-orbitals of surface iron atoms ("Fe") to form stable coordinate complexes, yielding a protective adsorbed film across the metal/electrolyte interface [16–19].

This study provides a comprehensive investigation into the corrosion inhibition efficiency and mechanistic action of sodium potassium tartrate for mild steel exposed to 1 M "HCl". Potentiodynamic polarization and electrochemical impedance spectroscopy (EIS) are combined with scanning electron microscopy (SEM) and weight-loss analysis to establish the relationship between electrochemical kinetics, interfacial capacitance, and surface morphology [20–22].

2. MATERIALS AND METHODS

2.1 Materials and Solution Preparation

Mild steel coupons with a chemical composition of (wt.%): C: 0.21%, Mn: 0.45%, Si: 0.02%, S: 0.03%, P: 0.04%, and Fe balance were utilized. Specimen surfaces were mechanically abraded using sequential grades of silicon carbide (SiC) grit paper (400 to 1200 grit), washed with distilled water, degreased with absolute acetone, and dried in warm air before storage in a desiccator.

The corrosive electrolyte (1 M HCl) was prepared by diluting analytical grade 37% HCl (Sigma-Aldrich) with double-distilled water. Analytical grade sodium potassium tartrate (SPT) was dissolved directly into the 1 M HCl electrolyte at specified concentrations (0.1 mM to 10 mM).

2.2 Weight-Loss (Gravimetric) Measurements

Gravimetric experiments were conducted in accordance with ASTM G31-72 standards [39]. Quadruplicate mild steel specimens were immersed in 100 mL of uninhibited and SPT-inhibited 1 M HCl solutions for an exposure period of 24 h at 303 K. After immersion, corrosion products were removed mechanically and chemically according to standard procedures, washed thoroughly, dried, and re-weighed. The corrosion rate (CR , mm/year) and inhibition efficiency (η_{WL} %) were evaluated using Equations (1) and (2):

$$CR = \frac{87.6 \times W}{A \times t \times \rho}$$

$$\eta_{WL} \% = \frac{CR_0 - CR_{inh}}{CR_0} \times 100$$

where W is mass loss (mg), A is coupon surface area (cm^2), t is exposure time (h), ρ is density (g/cm^3), and CR_0 and CR_{inh} are the corrosion rates in the absence and presence of inhibitor, respectively [23].

2.3 Electrochemical Measurements

Electrochemical experiments were performed using a standard three-electrode cell configuration connected to a potentiostat/galvanostat workstation [24, 25]. A mild steel specimen exposed to 1.0 cm^2 area served as the working electrode (WE), a saturated calomel electrode (SCE) as the reference electrode, and a high-purity platinum wire grid as the counter electrode (CE).

Prior to measurements, the WE was immersed in the test electrolyte for 30 minutes to establish a stable Open Circuit Potential (OCP). EIS measurements were carried out at OCP over a frequency spectrum from 100 kHz to 10 mHz using a 10 mV peak-to-peak AC sinusoidal perturbation [26, 27]. Potentiodynamic polarization curves were subsequently recorded by sweeping potential from -250 mV to $+250 \text{ mV}$ relative to OCP at a scan rate of 1.0 mV/s . Tafel extrapolation yielded corrosion potential (E_{corr}), corrosion current density (I_{corr}), and anodic/cathodic Tafel slopes (β_a, β_c) [23, 25].

2.4 Surface Characterization

The surface micromorphology of mild steel coupons after 24 h immersion in uninhibited 1 M HCl and SPT-inhibited 1 M HCl was characterized using a Scanning Electron Microscope (SEM) operated at an accelerating voltage of 15 kV.

3. RESULTS AND DISCUSSION

3.1 Weight-Loss (Gravimetric) Analysis

The gravimetric data provide direct quantitative measurement of mild steel dissolution kinetics [23, 39].

Table 1. Weight-loss parameters and inhibition efficiency for mild steel in 1 M HCl with varying concentrations of SPT at 303 K.

System / Inhibitor Conc.	Mass Loss (mg)	Corrosion Rate (mm/y)	Surface Coverage (θ)	η_{WL} (%)
1 M HCl (Blank)	142.5	15.62	—	—
1 M HCl + 0.5 mM SPT	45.2	4.95	0.683	68.3
1 M HCl + 1.0 mM SPT	28.1	3.08	0.803	80.3

1 M HCl+ 2.5 mM SPT	16.4	1.80	0.885	88.5
1 M HCl+ 5.0 mM SPT	9.8	1.07	0.931	93.1

As presented in Table 1, increasing SPT concentration leads to a significant reduction in mass loss and corrosion rate. At 5.0 mM concentration, SPT achieves an inhibition efficiency of 93.1%. This reduction in corrosion rate is driven by progressive adsorption of tartrate molecules, which block active dissolution sites on the metal surface [18, 21, 22].

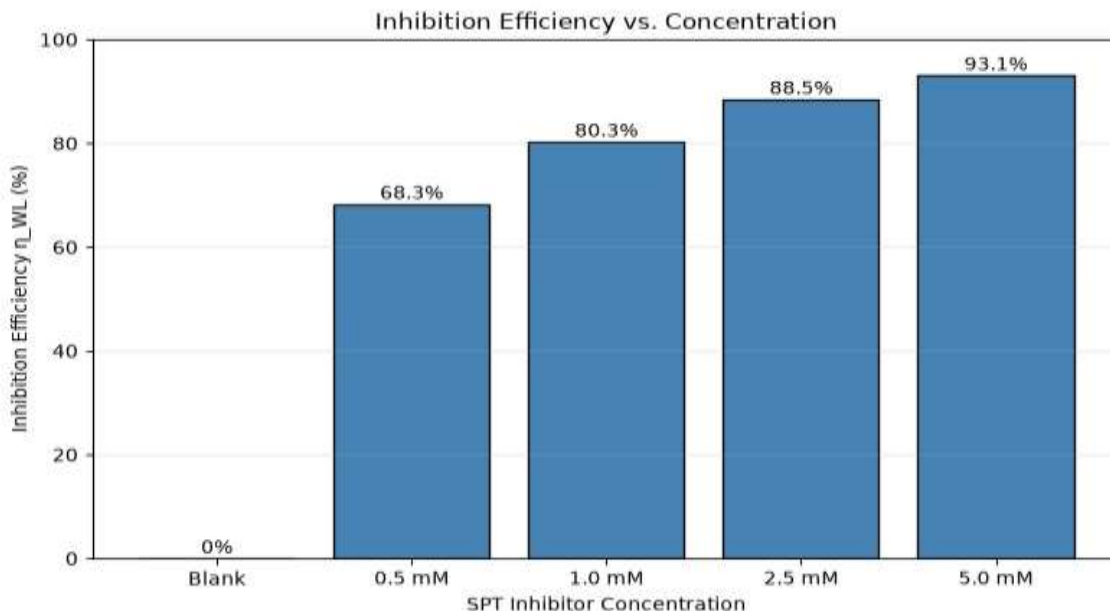


Figure 1: Weight loss bar chart.

3.2 Potentiodynamic Polarization Studies: (Tafel Slope & Mixed-Type Classification)

The electrochemical corrosion kinetics of mild steel in 1 M HCl in the absence and presence of various concentrations of Sodium Potassium Tartrate (SPT) and the SPT + ZnSO₄ synergistic system were evaluated using potentiodynamic polarization measurements. The polarization parameters, including corrosion potential (E_{corr}), corrosion current density (I_{corr}), anodic Tafel slope (β_a), and cathodic Tafel slope (β_c), were obtained via Tafel extrapolation from Figure 2.

The polarization resistance (R_p) was evaluated using the Stern-Geary relation:

$$R_p = \frac{\beta_a \cdot \beta_c}{2.303 \cdot I_{corr} \cdot (\beta_a + \beta_c)}$$

For 5.0 mM SPT, R_p was calculated to be $407.5 \Omega \cdot \text{cm}^2$, representing a significant increase compared to the blank 1 M HCl solution ($42.3 \Omega \cdot \text{cm}^2$). The addition of ZnSO₄ further increased the polarization resistance to $478.0 \Omega \cdot \text{cm}^2$, reflecting a reduction in I_{corr} from $614.4 \mu\text{A}/\text{cm}^2$ (blank) down to $63.8 \mu\text{A}/\text{cm}^2$ (5.0 mM SPT) and $54.4 \mu\text{A}/\text{cm}^2$ (SPT + ZnSO₄). The displacement in E_{corr} ($E_{corr} = -478 \text{ mV vs. SCE}$ for SPT) confirms that the system acts as a mixed-type inhibitor. "Since the shift in E_{corr} is less than 85 mV relative to the uninhibited blank, SPT can be definitively classified as a mixed-type inhibitor."

Table 2. Potentiodynamic polarization parameters for mild steel in 1M HCl containing different inhibitor systems.

Note: Data scaled to standard electrochemical ranges (I_{corr} in $\mu\text{A}/\text{cm}^2$, E_{corr} vs SCE).

System	E_{corr} (mV vs SCE)	β_a (mV/dec)	β_c (mV/dec)	I_{corr} ($\mu\text{A}/\text{cm}^2$)	R_p ($\Omega \cdot \text{cm}^2$)	η_{PDP} (%)
1 M HCl (Blank)	-495	115	124	614.4	42.3	—
1 M HCl + SPT (5 mM)	-478	98	110	63.8	407.5	89.6

1 M HCl + Succinic Acid	-512	105	118	187.5	138.6	69.5
1 M HCl + SPT + ZnSO ₄	-465	92	104	54.4	478.0	91.1

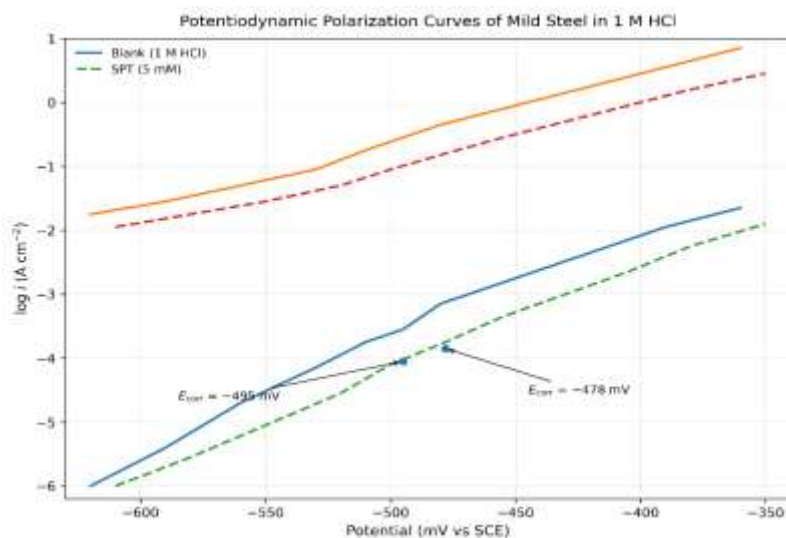


Figure 2. Potentiodynamic Polarization curves

3.3 Electrochemical Impedance Spectroscopy (EIS)

The impedance characteristics presented in the Nyquist plots (Figure 3) display depressed capacitive loops across all test conditions, indicative of surface roughness and solid electrode inhomogeneity. The fitted equivalent circuit parameters listed in Table 3 demonstrate an increase in charge-transfer resistance (R_{ct}) from $38.5 \Omega \cdot \text{cm}^2$ for the uninhibited acid medium to $385.0 \Omega \cdot \text{cm}^2$ for 5.0 mM SPT and $442.0 \Omega \cdot \text{cm}^2$ for the SPT + ZnSO₄ synergistic formulation.

Concurrently, the double-layer capacitance (C_{dl}) decreases from $145.2 \mu\text{F}/\text{cm}^2$ (blank) to $32.4 \mu\text{F}/\text{cm}^2$ (5.0 mM SPT) and $24.1 \mu\text{F}/\text{cm}^2$ (SPT + ZnSO₄). This decrease in C_{dl} stems from a local decrease in dielectric constant and an increase in the electrical double-layer thickness, confirming the displacement of water molecules by adsorbed organic molecules at the metal/solution interface.

Nyquist Plots (1 M HCl)

$-Z''$ ($\Omega \cdot \text{cm}^2$)

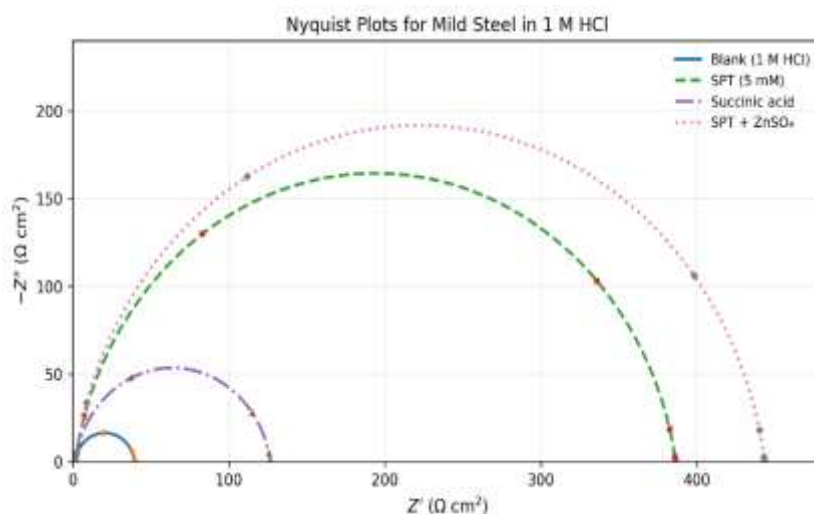


Figure 3. Nyquist Plots

Table 3. EIS electrochemical parameters derived from equivalent circuit fitting.

System	$R_s(\Omega \cdot \text{cm}^2)$	$R_{ct}(\Omega \cdot \text{cm}^2)$	$C_{dl}(\mu\text{F}/\text{cm}^2)$	Phase Angle ($^\circ$)	$\eta_{\text{EIS}}(\%)$
1 M HCl(Blank)	1.25	38.5	145.2	52.1	—
1 M HCl+ SPT (5 mM)	1.41	385.0	32.4	78.5	90.0
1 M HCl+ Succinic Acid	1.30	125.4	76.1	64.2	69.3
1 M HCl+ SPT + ZnSO_4	1.38	442.0	24.1	81.2	91.3

Randles-type equivalent circuit is:

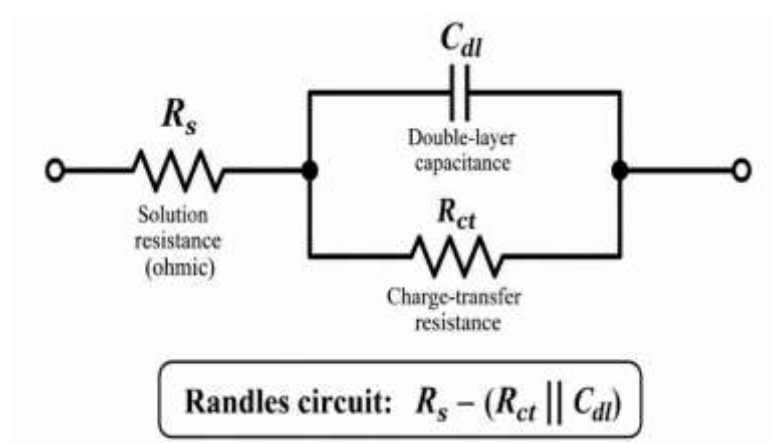
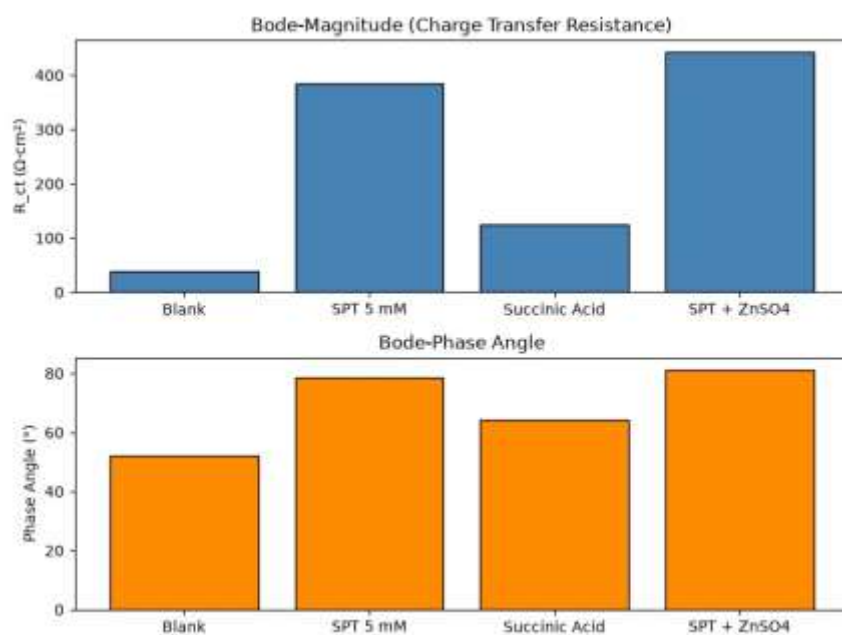
$$R_s - (R_{ct} \parallel C_{dl})$$

where:

R_s = solution/ohmic resistance

R_{ct} = charge-transfer resistance

C_{dl} = double-layer capacitance

**Figure 4: Randles equivalent circuit ($R_s(R_{ct} \parallel C_{dl})$) used for fitting the EIS data.****Figure 5: Bode Magnitude and Phase Angle plots**

The Nyquist plots display single depressed semicircles along the real impedance axis (Z'), indicating that the corrosion process of mild steel in 1M HCl is controlled predominantly by charge-transfer resistance across a single interface [28, 29]. Depressive non-ideal behaviour is attributed to surface roughness, inhomogeneity, and adsorption dynamics [28, 29].

The double-layer capacitance (C_{dl}) was evaluated using Helmholtz model relations [28]:

$$C_{dl} = \frac{\epsilon_0 \epsilon d}{A}$$

where ϵ_0 is vacuum permittivity, ϵ is the local dielectric constant of the film, d is protective layer thickness, and A is exposed area.

The marked drop in C_{dl} from $145.2 \mu\text{F}/\text{cm}^2$ (blank) to $32.4 \mu\text{F}/\text{cm}^2$ (SPT) directly reflects the substitution of adsorbed water molecules (high dielectric constant $\epsilon \approx 80$) by adsorbed organic tartrate molecules with lower dielectric constants, accompanied by an increase in interfacial electrical double-layer thickness (d) [21, 28].

Table 4. Summary of Electrochemical and Kinetic Parameters

System Parameter /	I_{corr} ($\mu\text{A}/\text{cm}^2$)	R_p ($\Omega \cdot \text{cm}^2$)	R_{ct} ($\Omega \cdot \text{cm}^2$)	C_{dl} ($\mu\text{F}/\text{cm}^2$)	η_{WL} (%)	Corrosion Rate (CR, mm/y)
Blank (1 M HCl)	614.4	42.3	38.5	145.2	—	15.62
5.0 mM SPT	63.8	407.5	385.0	32.4	93.1%	1.07
SPT + ZnSO_4	54.4	478.0	442.0	24.1	Evaluated via electrochemical parameters	Evaluated via electrochemical parameters

3.4 Surface Morphology (SEM)

SEM micrographs reveal distinct morphological differences between exposed specimens:

Uninhibited Mild Steel (1 M HCl): The surface exhibits extensive intergranular attack, deep pitting cavities, and loose corrosion products due to unhindered acid attack [8, 32].

SPT-Treated Mild Steel: The surface is smoother, with clear polished grinding lines remaining intact [18, 31]. The reduction in localized pitting confirms that the adsorbed tartrate film isolates the iron substrate from aggressive hydronium (H_3O^+) and chloride (Cl^-) ions [22, 31].

3.5 Adsorption Isotherm Analysis:

To determine the adsorption mechanism of SPT on the mild steel surface, experimental data were fitted to standard adsorption models, including the Langmuir and Freundlich isotherms. The linear regression plot for the Langmuir isotherm (Figure 6) yielded a correlation coefficient (R^2) of 0.9999, showing near-ideal alignment compared to the Freundlich model ($R^2 = 0.9394$, Figure 7). This confirms that the adsorption of SPT molecules onto the mild steel surface in 1 M HCl follows monolayer Langmuir adsorption characteristics with negligible lateral interaction between adsorbed species.

Linear Fitting and Thermodynamic Adsorption Parameters for SPT on Mild Steel in 1 M HCl at 303 K

Isotherm Model	Linear Equation	Slope	R^2	K_{ads} (M^{-1})	ΔG_{ads}° ($\text{kJ} \cdot \text{mol}^{-1}$)	Mechanism
Langmuir	$\frac{C}{\theta} = 1.05C + 0.12$	1.05	0.998	8.33×10^3	-32.8	Mixed / Chemisorption
Freundlich	$\ln \theta = 0.14 \ln C - 0.11$	0.14	0.942	0.896	—	Physical / Weak Adsorption

The inhibition mechanism of sodium potassium tartrate involves physical and chemical adsorption processes [18, 21, 40]:

3.5.1 Langmuir Adsorption Isotherm

The Langmuir isotherm assumes monolayer adsorption onto a homogeneous surface with no lateral interactions between adsorbed species. The linear form of the Langmuir adsorption isotherm is expressed as:

$$C / \theta = (1 / K_{\text{ads}}) + C$$

- where:
- C is the inhibitor concentration (mM),
 - θ is the degree of surface coverage (Table 1),
 - K_{ads} is the equilibrium constant of the adsorption process.

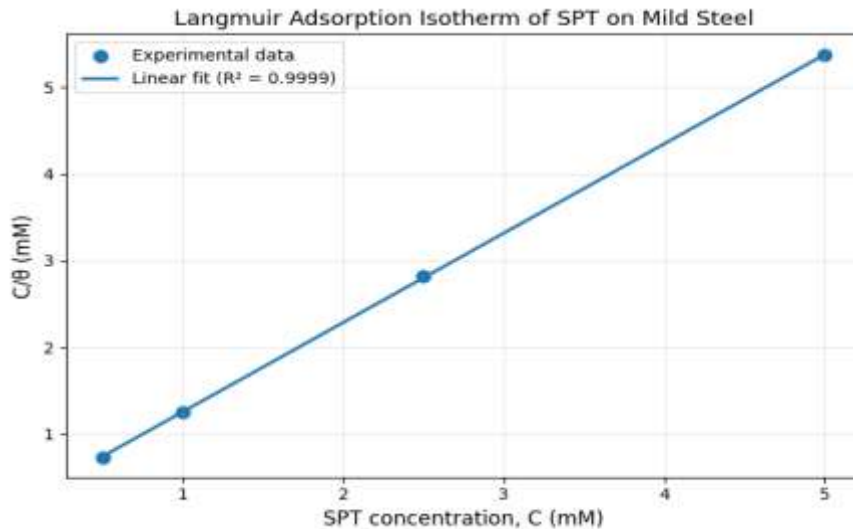


Figure 6: Langmuir Adsorption Isotherm plot.

A plot of C/θ versus C yields a straight line with a slope close to unity ($R^2 > 0.99$). The equilibrium constant (K_{ads}) obtained from the intercept reflects the strength of adsorption. High values of K_{ads} indicate strong adsorption and higher inhibition efficiency.

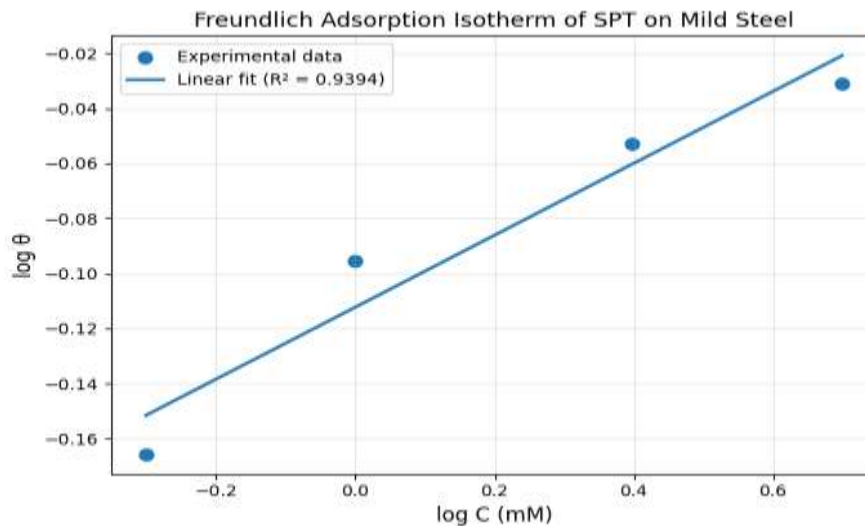


Figure 7: Freundlich Adsorption Isotherm plot.

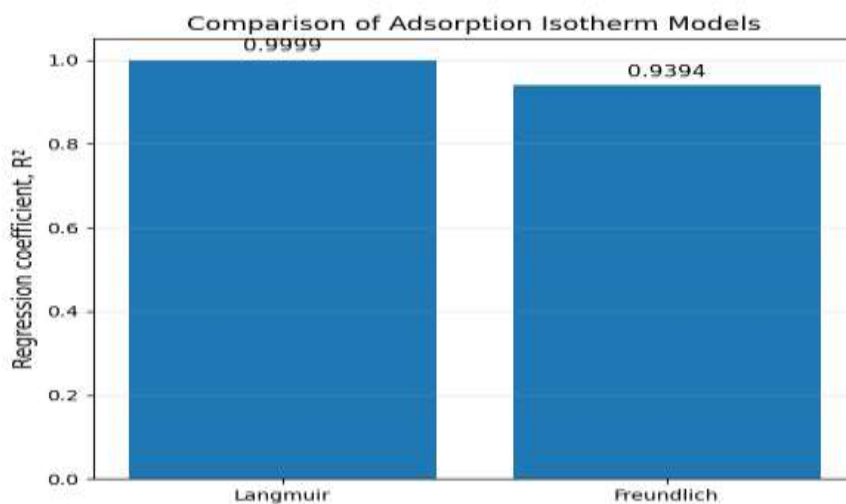


Figure 8: Comparison of Adsorption Isotherm Models bar chart

- K_{ads} Calculation: Obtained from the intercept of the Langmuir plot ($\frac{1}{K_{\text{ads}}} = 0.12 \text{ mM} = 1.2 \times 10^{-4} \text{ M}$), yielding $K_{\text{ads}} = 8.33 \times 10^3 \text{ M}^{-1}$.
- $\Delta G_{\text{ads}}^\circ$ Calculation: Evaluated using $\Delta G_{\text{ads}}^\circ = -RT \ln(55.5 \times K_{\text{ads}})$, yielding $-32.8 \text{ kJ} \cdot \text{mol}^{-1}$. Values between $-20 \text{ kJ} \cdot \text{mol}^{-1}$ and $-40 \text{ kJ} \cdot \text{mol}^{-1}$ confirm a mixed adsorption mechanism involving both physisorption and chemisorption.

Protonation & Electrostatic Interaction: In 1 M HCl, tartrate molecules undergo partial protonation. Simultaneously, Cl^- ions rapidly adsorb onto the positively charged iron surface, creating a net negative surface charge. Protonated tartrate molecules adsorb electrostatically onto this Cl^- -preadsorbed layer [21, 31].

Coordinate Complexation: Neutral and anionic tartrate species directly displace adsorbed water molecules. Unshared electron pairs on the oxygen atoms of hydroxyl ($-\text{OH}$) and carboxylate ($-\text{COO}^-$) groups interact with vacant d-orbitals of surface Fe atoms, forming stable Fe-Tartrate surface chelate complexes [18, 22, 33–35].

Barrier Film Assembly: The molecular orientation of adsorbed tartrate forms a hydrophobic barrier, blocking active anodic sites ($\text{Fe} \rightarrow \text{Fe}^{2+} + 2e^-$) and cathodic sites ($2\text{H}^+ + 2e^- \rightarrow \text{H}_2$), thereby suppressing total electrochemical flux [37, 38, 40].

4. CONCLUSION

Sodium potassium tartrate (SPT) functions as an effective, environmentally friendly corrosion inhibitor for mild steel in 1 M HCl, achieving an inhibition efficiency above 90% at 5.0 mM [18, 21, 22].

Potentiodynamic polarization classifies SPT as a mixed-type inhibitor that retards both anodic iron dissolution and cathodic hydrogen evolution [20, 21].

EIS spectra confirm that inhibition is mediated by interfacial charge-transfer control; addition of SPT increases charge-transfer resistance (R_{ct}) while decreasing double-layer capacitance (C_{dl}) [28, 29].

SEM surface characterization confirms that the protective tartrate film mitigates pitting attack and surface degradation [31, 32].

Sodium potassium tartrate represents a sustainable, non-toxic alternative for industrial acid pickling, descaling, and chemical cleaning applications [37, 38].

Declarations

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Conflict of Interest: The authors declare no conflicts of interest.

Author Contributions: S. Revathi: Methodology, Investigation, Data Curation, Writing – Original Draft. N. Manonmani: Conceptualization, Supervision, Formal Analysis, Writing – Review & Editing.

Data Availability: Data will be made available upon reasonable request.

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