Corrosion Inhibition Study of Mixed-Type Inhibitor on Mild Steel Using HCL Acid Medium.

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Abstract:
Corrosion, which used to be a problem mainly studied by metallurgists and chemists, is now a topic that involves many different areas of study. This is because metals are used in almost every part of our lives. It's important now more than ever to pay attention to how metals corrode. The use of metals has increased a lot in all areas of technology. New types of strong alloys are being used, and these are often more likely to corrode in certain ways. Most of the chemicals used to stop corrosion are expensive and can be harmful to living things and the environment. That's why it's important to find cheaper and safer alternatives to use as corrosion inhibitors. Using natural substances to stop metal corrosion in acidic or basic conditions is a new trend. Inhibitors are crucial in slowing down the process of corrosion. There are many different types of inhibitors, including organic ones, which often contain nitrogen, oxygen, and phosphorus. Inorganic inhibitors form protective layers on the metal surface. Plant-based inhibitors, which are biodegradable, contain chemicals from plants that help slow down corrosion. These inhibitors work by slowing down either the anodic or cathodic reactions, or both. This study focuses on mixing organic, plant-based, and inorganic substances to control corrosion on mild steel in a 0.5M HCl solution. The weight loss method showed 89.39% inhibition for 4 ml, 70.06% for Tafel, and 79.75% for impedance for 4 ml at room temperature.

Keywords: Corrosion Rate; Acid Medium; Weight Loss Method; Inhibition Efficiency;

1. Introduction

"Corrosion is the process of material degradation, typically metal, due to chemical or electrochemical reactions with the surrounding environment. In the oil and gas industry, corrosion impacts pipelines, storage tanks, offshore platforms, refineries, and drilling equipment. The sector faces significant losses every year because of equipment failure, production halts, leaks, and safety issues [1].

Types of Corrosion in Oil & Gas

Type of Corrosion	Description	Occurrence
CO_2 Corrosion (Sweet Corrosion)	Reaction of CO_2 with water forms carbonic acid, leading to corrosion.	Pipelines carrying wet natural gas.
H_2S Corrosion (Sour Corrosion)	Hydrogen sulfide leads to sulfide stress cracking (SSC) and embrittlement.	Sour gas and oil wells.

Type of Corrosion	Description	Occurrence
Microbiologically Influenced Corrosion (MIC)	Caused by sulfate-reducing bacteria (SRB).	Pipelines, storage tanks, offshore rigs.
Erosion-Corrosion	Accelerated wear due to high-velocity fluids carrying sand or particles.	Flowlines and elbows in piping systems.

Pickling is a metal surface treatment process that involves the use of strong acids, such as hydrochloric acid (HCl) or sulfuric acid (H_2SO_4), to remove oxides, rust, and scale from metal surfaces, particularly in steel and stainless steel. Tanks, piping, and other infrastructure are frequently exposed to corrosive acids. Even stainless steels are susceptible to corrosion under strong acidic and high-temperature conditions. Hydrogen generated during acid-metal reactions can diffuse into steel, leading to embrittlement and structural failure. Acid vapors also corrode surrounding metal structures and instrumentation. Pitting and crevice corrosion are common in heat-affected zones and welds due to high chloride concentrations. The use of acid-resistant materials, such as PTFE-lined tanks, titanium, and high-alloy stainless steels, is essential. Acid inhibitors are also added to reduce metal attack. Ventilation and fume extraction systems are necessary to protect both equipment and workers [2]. Corrosion mitigation is critical in various industries to ensure safety, reduce costs, and extend the lifespan of infrastructure. Investing in corrosion-resistant materials, inhibitors, coatings, and monitoring systems is key to sustainable operations. Here is a detailed strategy by which a chemist and an engineer can collaborate to implement corrosion inhibition. It combines theoretical knowledge, laboratory work, field implementation, monitoring, and continuous improvement. I have included references to recent literature and best practices. If you wish, I can tailor this strategy to a specific industry, such as oil and gas or construction [3].

Strategy for Corrosion Inhibition: Chemist & Engineer Collaboration

Phase	Chemist's Role	Engineer's Role	Key Outputs / Decision Points
1. Problem Definition & Assessment	- Identify metal/alloy types, corrosive environment (chemical composition, pH, temperature, flow, oxygen, microbial presence, etc.). - Perform literature review for similar systems: look at known inhibitors, mechanisms, environmental and regulatory constraints.	- Map out where in the system corrosion is problematic (critical components, failure history). - Gather operational data: temperature, pressure, flow, cycles, mechanical stresses. - Perform risk assessment: safety, cost, downtime, environmental impact.	A comprehensive corrosion profile: what is corroding, under what conditions, to what degree. Prioritization of components or zones for inhibition.
2. Selection of Candidate Inhibitors	- From literature & database/screening, propose a set of inhibitor chemistries (organic,	- Evaluate practical constraints: compatibility with fluids / coatings;	A shortlist (say 3-5) of inhibitors that are likely to work in real

Phase	Chemist's Role	Engineer's Role	Key Outputs / Decision Points
	inorganic, green / natural, synthetic). Consider adsorption mechanisms, ability to scavenge oxygen, passivate surfaces, resist biofouling, etc. - Consider environmental toxicity, availability, cost.	dilution; injection feasibility; handling & safety; workplace / environmental regulations.	operational conditions.
3. Laboratory Testing & Mechanism Elucidation	- Test the inhibitors under simulated conditions: pH, temperature, flow, presence of aggressive ions (chloride, hydrogen sulfide, CO_2 etc.). Use electrochemical methods (polarisation, impedance spectroscopy), weight-loss, surface characterisation (SEM, XPS, etc.). - Investigate mechanism: adsorption (physical/chemical), complex formation, passivation film formation, oxygen scavenging etc. Use computational methods (DFT, molecular dynamics) to support experiments.	- Ensure that lab tests mimic field conditions as far as possible: shear/stress, real fluid composition, temperature, pressure. Determine the required dosage, frequency of reapplication / replenishment.	Lab-validated inhibitor(s) with known efficacy, mechanism, required dosage, and expected longevity.
4. Field Trials / Pilot Implementation	- Support in formulation (e.g. inhibitors + adjuvants), monitoring criteria.	- Implement a pilot/in-service test on selected components or zones. Monitor corrosion rates, operational effects, any undesired side effects (clogging, interactions, deposition, toxicity).	Data from real system: how well inhibitor works, what modifications needed (dosage, delivery, formulation). Decision to scale up or discard.
5. Full Scale Implementation	- Ensure production or procurement of the inhibitor at required purity etc. - Provide guidelines / SOPs for handling, mixing, injecting, safety.	- Integrate the inhibitor system into existing operations: injection systems, flow, sensors, shut-downs if needed. Ensure compatibility with coatings, protection	Operational deployment: system functioning with inhibitor, staff trained, safety in place.

Phase	Chemist's Role	Engineer's Role	Key Outputs / Decision Points
		systems.	
6. Monitoring, Maintenance & Review	- Design testing / sampling schedule: electrochemical measurements, corrosion probes, coupons, non-destructive inspection. Analyze failures or loss of performance.	- Set up instrumentation / sensors for continuous monitoring (temperature, pH, dissolved gases, etc.). Maintain records. Schedule maintenance: reapplication of coatings, replacement of sacrificed materials, topping up inhibitor etc.	Metrics of performance (rate of corrosion, downtime, cost), feedback into the system to adjust or change inhibitor or operating conditions.
7. Environmental, Regulatory & Economic Evaluation	- Assess environmental impact of the inhibitor (toxicity, biodegradability). Ensure compliance with local / international regulations. - Consider "green inhibitors" or natural extracts if possible.	- Cost-benefit analysis: initial investment, chemical costs, maintenance, failures avoided. - Ensure disposal / waste handling is compliant.	

Corrosion happens through two types of reactions: anodic, where metal breaks down, and cathodic, where oxidizers like hydrogen ions or oxygen are reduced. Inhibitors slow down corrosion by affecting one or both of these reactions. Anodic inhibitors reduce metal breakdown by creating insoluble substances on the metal surface, such as chromates or phosphates [4]. Cathodic inhibitors slow the cathodic reaction by stopping oxidizers from reaching the metal. Mixed-type inhibitors affect both reactions. Corrosion inhibitors work by either forming a protective layer on the metal or changing how the electrochemical reactions happen. The choice of inhibitor type—organic, inorganic, or plant-based— depends on several factors, like the type of metal being protected, the environment it's in, the cost, the environmental impact, and how long the protection is needed [5]. Organic inhibitors are commonly used because they can stick to metal surfaces and form a protective film. These inhibitors often have atoms like nitrogen, oxygen, sulfur, or phosphorus, and/or structures like aromatic rings that help them chemically bond to the metal. This bonding blocks the places on the metal where corrosion can start. Some alter the double layer at the metal-solution interface, inhibiting both anodic and cathodic reactions (mixed-type inhibitors). Inorganic inhibitors have been widely used, especially in industrial and marine environments [6]. They function primarily by forming insoluble precipitates or passive oxide films on the metal surface. Some precipitate with metal ions to create a barrier, such as chromates, while others promote or maintain passivation, like phosphates and silicates. Anodic inhibitors mainly protect against metal dissolution. These are natural, biodegradable compounds extracted from plants (leaves, bark, peels, seeds). They serve as a sustainable alternative to synthetic inhibitors. They contain bioactive molecules like alkaloids, flavonoids, tannins, and amino acids, which adsorb onto the metal surface via physisorption or chemisorption [7]. Organic inhibitors offer high efficiency and molecular tunability, though they may be expensive or toxic. Inorganic inhibitors are cost-effective and robust for industrial use but may pose environmental risks. Plant extract inhibitors provide a green, low-cost alternative, suitable for less aggressive environments and eco-sensitive applications [8].

Recent Key Developments in Corrosion / Corrosion Inhibitors (2022-2025)

Year	**Research Highlight**	**Findings / Novelty**	**Metals / Environment**	**Reference**
2025	Use of safflower plant extract as sustainable inhibitor for carbon steel in HCl	Achieved ~89.6% inhibition at 2.5 g/L. Mixed-type inhibitor (both anodic & cathodic), adsorption follows Langmuir isotherm. Computational DFT used to identify active compounds.	Carbon steel in HCl (acidic)	Yousif et al., *RSC Advances*, 2025 RSC Publishing [9]
2024	Bio-based ionic liquid (IL) corrosion inhibitor	Choline hexanoate showed inhibition efficiency (IE) ≈ 98.16% at 3.3×10^{-3} M at 60 °C. Studied via polarization, Raman, XPS, and molecular dynamics simulation. Acts as mixed-type inhibitor.	Mild steel in 5 % HCl	*Sustainable Chemistry and Pharmacy*, 2024 ScienceDirect [10]
2024	Corrosion inhibition of AA2024-T3 aluminium alloy by molybdate	Molybdate provides mixed inhibition. Notable increase in breakdown potential against pitting (~+250 mV), decrease in open circuit potential. Proposed two-step mechanism: formation of intermediate molybdenum oxides and suppression of intermetallic particle activity.	Aluminium alloy (AA2024-T3)	*Journal of the Electrochemical Society*, 2024 IOPscience [11]
2023	Highly efficient green inhibitor	Combined experimental + DFT approach; showed	Mild steel, acidic medium	*Colloids and Surfaces:*

Year	Research Highlight	Findings / Novelty	Metals / Environment	Reference
	from B. glabra petal extract	strong adsorption; good anti-pitting and anti-cracking behavior; strong performance in sulphuric acid.		*Physicochemical and Engineering Aspects*, 2023 ScienceDirect [12]
2023-2024	Functionalization of plant extracts with nanomaterials	E.g. Tikoua (a plant extract) functionalised with nanomaterials significantly enhanced inhibition against carbon steel in sulphuric acid. Efficiency up to ~95.8 %. The use of nanomaterials improves adsorption, possibly stability.	Carbon steel, acidic medium	From "Utilizing nanomaterials to functionalize the Tikoua extract…" SpringerLink [13]
2024	Use of plant extracts as sustainable inhibitors for cultural heritage alloys	Focus on copper or bronze type alloys; exploring non-toxic agents to preserve heritage metals, avoiding traditional toxic chromates etc.	Alloys in heritage/conservation context (bronze, copper etc.)	González-Parra & Di Turo, *Sustainability*, 2024 MDPI [14]
2022-2023	Review papers on plant-based and "green" inhibitors	Systematic surveys showing: most work still focused on mild/carbon steel in acidic media; many plant extracts show >80% inhibition; increasing use of computational methods (DFT, MD) alongside experimental. Also reviews identifying gaps (e.g. in realistic exposure conditions).	Multiple metals/environments, with focus on steel & acid; also aluminium alloy in NaCl etc.	de Souza Morais et al., *Applied Sciences*, 2023 MDPI; Sheydaei, *Surfaces*, 2024 MDPI; [15] reviews on aluminium alloys in NaCl environments (Lavanya & Kumari, 2022) JCC HeMS [16]
2022	Advances in inhibitors for reinforced concrete / chloride-induced	Mainly exploring non-nitrite alternatives (organic & inorganic) in concrete rebar corrosion,	Steel reinforcement in concrete with chloride exposure	*Cement & Conc* [17]

Year	Research Highlight	Findings / Novelty	Metals / Environment	Reference
	corrosion	to avoid environmental & health issues associated with nitrites.		

Key Themes & Trends Emerging

- Green / Natural Inhibitors: There is a growing number of studies utilizing plant extracts, bio-based ionic liquids, and similar materials, driven by environmental regulations. These inhibitors show strong performance, achieving inhibition rates of 80-95% in many cases.
- Hybrid & Functionalized Systems: The combination of plant extracts with nanomaterials, or the use of coatings containing graphene oxide and similar functional fillers, is improving barrier properties, stability, and adhesion.
- Milder Conditions & Realistic Environments: More research is now being conducted in NaCl (chloride) environments, in concrete, or at elevated temperatures. This approach moves beyond traditional lab-based acid testing.
- Computational & Theoretical Support: There is an increased use of DFT, molecular dynamics, adsorption isotherms, and quantum computational methods to better understand molecular interactions and aid in the design of improved inhibitors [18].
- Inorganic vs. Organic Alternatives: Some studies, such as those involving molybdate with aluminum, show that non-toxic inorganic alternatives remain relevant.
- There is also a focus on understanding underlying mechanisms, such as pitting and intermetallic behavior.
- Protective Coatings & Barrier Systems: Self-healing coatings and coatings doped with nanoscale fillers like graphene, GO/rGO, and ceramics are being explored to enhance protection [19, 20].

2. Materials

2.1. Preparation of Acid

Collecting 0.5 M (43.1 ml) of hydrochloric acid from the flask, it was properly added to a volumetric flask and diluted with 1000 ml of double-distilled water. Using phenolphthalein indicator, the 0.5 M HCl was standardized by a 0.5 M NaOH solution (standardized by oxalic acid).

2.2. Preparation of specimen

Table 1 Chemical composition of investigated of steel.

Metals	C	Si	Mn	P	S	Cr	Ni	Fe
% composition	0.024	0.377	1.210	0.024	0.002	18.790	8.250	Balance

2.3 Weight loss method

The steel panels' surface was prepared for the weight loss testing by first using acetone to clean the sheets (2x2 cm^2), and then polishing them with 400, 600, 800, 1200, and 2000 sandpapers to get rid of any oxidized layers. They were then dried at 50 °C after being cleaned again with acetone.

2.4 Electrochemical method

A variety of sandpaper grades, ranging from rougher to finer, were used to polish the metal bars after the steel was cut into a cylinder form with dimensions of 5 X 0.032 cm^2 (the exposed part was 0.032 cm^2).

The metal bars were meticulously cleaned with acetone and deionized water before being left to dry.

2.5 Preparation of mixed type inhibitor

2.5.1 Preparation of plant extract

About two to three kilograms of leaves were collected, rinsed with tap water, and then left in distilled water for a day. The leaves were dried for two days at room temperature after the water was removed. After cutting the leaves into small pieces, 100 milliliters of distilled water were added, and the mixture was heated to between 55 and 58 degrees Celsius until a greenish color emerged in the beaker. Let it cool entirely for four to five hours. Whitman filter paper was used to filter it off, and it was left for a day to settle completely. Take the filter and store it for two days in a cool refrigerator (15–20°C).

2.5.2 Preparation of organic solution

70% ethanol was added to a saturated solution of potassium nitrate and glycerol. Allow it to sit for a day after gently mixing it for 20 to 30 minutes.

2.5.3 Preparation of inhibitor

Glycerol, 70% ethanol, plant extract solution, and an equal amount of saturated potassium nitrate (20 ml each) were poured into a separating funnel and shaken rapidly for 10 minutes, removing gases with each shake. To obtain the whole mixture, let the solution sit for a day. Consider this entire residue to be an inhibitor.

3. Methods

3.1 Weight loss measurements

After being polished and degreased, the steel specimens are weighed and submerged in 150 ml beakers filled with 100 ml of 0.5M HCl. Following that, weight loss is measured once every 24 hours for five days, on the fifteenth day, and on the thirtieth day. The specimen is washed with distilled water, rinsed in acetone, and dried before the subsequent measurement. Different known amounts of inhibitor in the range of 1 ml, 2 ml, 3 ml, 4 ml, 5 ml, and 10 ml are used to repeat the experiment.

3.2 Electrochemical measurements

Measurements of all electrochemical tests, which employ three electrodes, were conducted using EmStat 4STM. The standard calomel electrode (SCE) and platinum served as the reference and counter electrodes, respectively, while a mild steel rod served as the working electrode. In relation to the reference electrode, the potential was measured and reported. The working electrode was polished and submerged in the media until a steady-state open circuit voltage was reached prior to each trial. Following electrochemical impedance spectroscopy (EIS) investigations on the same electrode in the same medium without any additional surface treatment, electrochemical impedance and Tafel were carried out right away.

3.2.1 Potentiodynamic polarization studies

A mild steel specimen with a working electrode area of 0.032 cm² was subjected to a 0.5 M HCl solution. The reference electrode is a calomel electrode, and 100 milliliters of 0.5 M HCl were used for all electrochemical tests, which were conducted at room temperature. In potentiodynamic experiments, the electrode was held in solution at open circuit voltage for 30 minutes prior to each EIS technique for achieving a stable state. At a scan rate of 1 mV/sec, potentiodynamic polarization curves were acquired around the OCP from -0.50 mV to +0.50 mV. Every possibility that was looked into has to do with SCE.

By extrapolating polarization curves, the values of related electrochemical corrosion kinetic parameters, such as corrosion current density (i_{corr}), corrosion potential (E_{corr}), cathodic and anodic Tafel slopes (b_c-barrier potential of the cathode & b_a-barrier potential of the anode-V/decade), I corr/surface area (A/cm^2), and polarization resistance (Ω), were determined.

3.2.2 Electrochemical impedance studies (EIS)

Using a potentiostat connected to a computer that displayed OCP vs. time, the electrochemical measurement and EIS were carried out. EmStat 4STM was used to report potentiodynamic polarization curves in acceptance. Before starting the EIS, which was conducted at a frequency range of 10 µHz to 200 kHz and a potential range of -0.50 mV to +0.50 mV around the OCP with a scan rate of 1 mV/sec, the OCP was measured for 800 seconds. Lastly, the potential was scanned from negative to positive OCP to create the impedance graphs.

4. Result and discussion

4.1. Weight loss method

Mild steel specimens when immersed in 0.5M HCl solution in the presence and absence of different dosages from 1 ml to 10 ml were recorded in Tab. 1 at room temperature for different periods of immersion.

The percentage of inhibition efficiency was evaluated from the weight loss measurement using the formula.

$$\%\,IE = \frac{Wo - Wi}{Wo} \times 100$$

Where IE is inhibition efficiency, Wo & Wi is weight loss in ‘g’. Wo is absence of inhibitor; Wi is presence of inhibitor.

as shown in Table 1. When compared to blank (without inhibitor), inhibition efficiency increases daily when the inhibitor is present. A range of inhibitor dosages, from 1 ml to 10 ml, is used in the average weight reduction approach. An increase in inhibitor dosage reduces the rate of steel corrosion; the inhibitor's saturation point has a maximum dosage range of 4 ml during a 30-day period. It has been found that 4 milliliters of inhibitor provides the highest corrosion protection for steel, at around 89.39%. Due to the enhanced adsorption of extract molecules, a large amount of accessible surface area is covered, which results in an inhibition efficiency that is directly proportional to a graded increase in inhibitor dosage [21]. If too much inhibitor is added after saturation, it will not contribute to the adsorption process and may result in a drop in inhibition efficiency, as shown in Table 1.

It is clear that the protection efficiency was concentration-dependent because it rose as the inhibitor concentration increased and the corrosion rate decreased in Table 1. Figure 1 also shows this relationship. Increased protection performance is the result of a significant number of inhibitor molecules being adsorbed on the tested steel surface as the inhibitor concentration rises [22]. The steel surface is shielded from the corrosive solution by the adsorbed inhibitor molecules, which regulate and/or block the reaction sites. The inhibitor may slow corrosion because it contains important ion pairs of electrons, including ion pairs on nitrogen and sulfur atoms and pi-electrons, that are coordinately bound with iron atoms on the coupon surface [23].

Figure:1- Inhibition efficiency plot with different time period by weight loss method

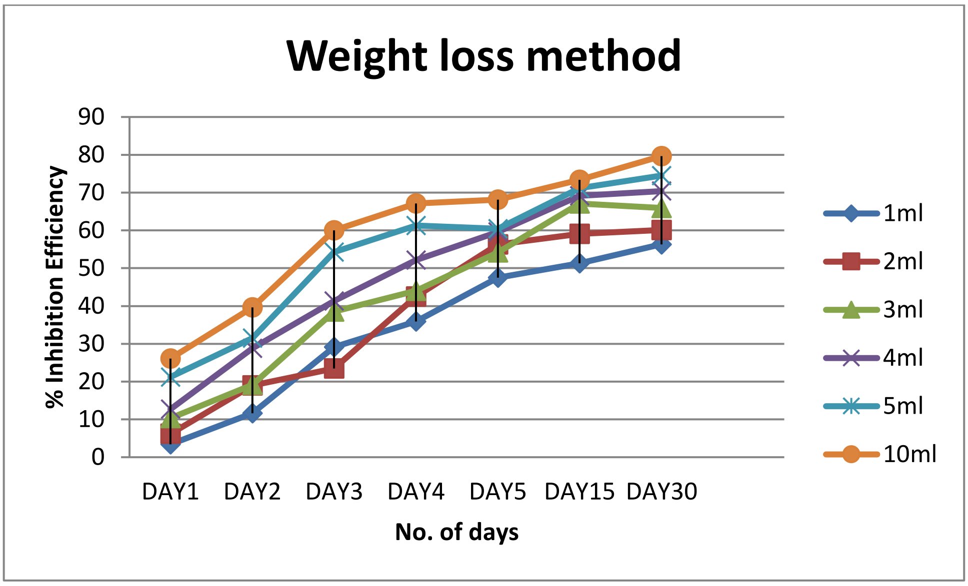

Table: 1- Steel surface exposed in 0.5M HCl solution

SI. No	Dosage of inhibitor in 'ml'	% Inhibition efficiency						
		DAY1	DAY2	DAY3	DAY4	DAY5	DAY15	DAY30
1	1	3.41	11.62	29.17	35.89	47.46	51.32	56.33
2	2	6.17	18.96	23.46	42.48	56.31	59.12	60.11
3	3	10.32	19.14	38.49	44.01	54.16	67.1	65.96
4	4	12.69	28.77	41.36	52.11	59.57	69.17	89.39
5	5	21.22	31.47	54.29	61.32	60.46	71.21	74.5
6	10	26.1	39.64	60	67.1	68.14	73.35	64.2

4.2. Potentiodynamic polarization studies

The Corrosion rate was calculated using formula,

$$\% \, CR = \frac{k \times E \times icorr}{\rho}$$

CR indicates the rate of corrosion in mm/y (mill meter per year), k is a constant that refers the unit of corrosion rate and has a constant value, where E is the equivalent weight of the corroding alloy, I_{corr} which implies the corrosion current density in μA cm^2 and finally ρ is the density of the alloy in kg m^{-3}. The following equation is used for IE with different concentrations of inhibitor

$$IE = \frac{icorr - i * corr}{icorr} \times 100$$

Where I_{corr} and i^*_{corr} are corrosion current in the absence and presence of plant extract.

Surface Coverage $\theta = \frac{icorr - i*corr}{icorr}$

Percentage IE = $\theta \times 100$ 100, Where I_{corr} and $i^*_{corr(inh)}$ are corrosion rates in the absence and presence of inhibitor respectively.
At room temperature, polarization curves are recorded in a 0.5M HCl solution with and without different inhibitor concentrations. The experimental polarization curves are displayed in Fig. 2, and the various extracted parameters, including cathodic and anodic Tafel slopes (βc,βa), polarization (βc, βa), inhibition efficiency (IE%) corrosion current densities (I_{corr}), and corrosion potential (E_{corr}), are shown in Table 2. Origin software was used to fit the experimental curves [24] (Tafel extrapolation) in order to obtain these parameters. I_{corr} and E_{corr} without inhibitor ar%), an inhibitor 4466 μA/cm^2 and -0.407 mV/SCE, respectively, as shown in Table 2 and Fig. 2. Additionally, the cathodic and anodic current densities are reduced when varying extract dosages are present. The findings in Table 2 demonstrate that when inhibitor concentrations rise, the corrosion current density decreases (1337 μA/cm^2 for 4 ml),ml), and the E_{corr} value shifts in the direction of a positive value. Even at low dosages, it is evident that the addition of an inhibitor significantly reduces current density values and increases inhibition efficiency, reaching a maximum of 70.06% (4ml). (4 ml) additionally, the data shows that the rate of corrosion increases with excessive inhibitor addition, and the inhibition efficiency decreases from 70.06% to 61.64%. This study shows that the inhibitor's saturation point is 4 ml, with a maximum inhibition of roughly 70.06%.

Table-2: Polarization study when steel is exposed to 0.5M HCl solution

Dosage	**Ecorr/SCE (mV)**	**Icorr (μA/cm2)**	**βa (mV/dec)**	**βc (mV/dec)**	**Icorr/A cm2**	**CR**	**η (%)**
Blank	-0.407	4466	0.479	0.599	0.092	1769	-
1ml	-0.405	2949	0.405	0.523	0.065	1168	33.96
2ml	-0.404	2065	0.3	0.415	0.06	817.8	53.76
3ml	-0.4	1911	0.281	0.439	0.045	757	57.21
4ml	-0.4	1337	0.224	0.414	0.054	529	70.06
5ml	-0.398	1437	0.257	0.435	0.224	569.1	67.82
10ml	-0.395	1713	0.224	0.353	0.054	678.4	61.64

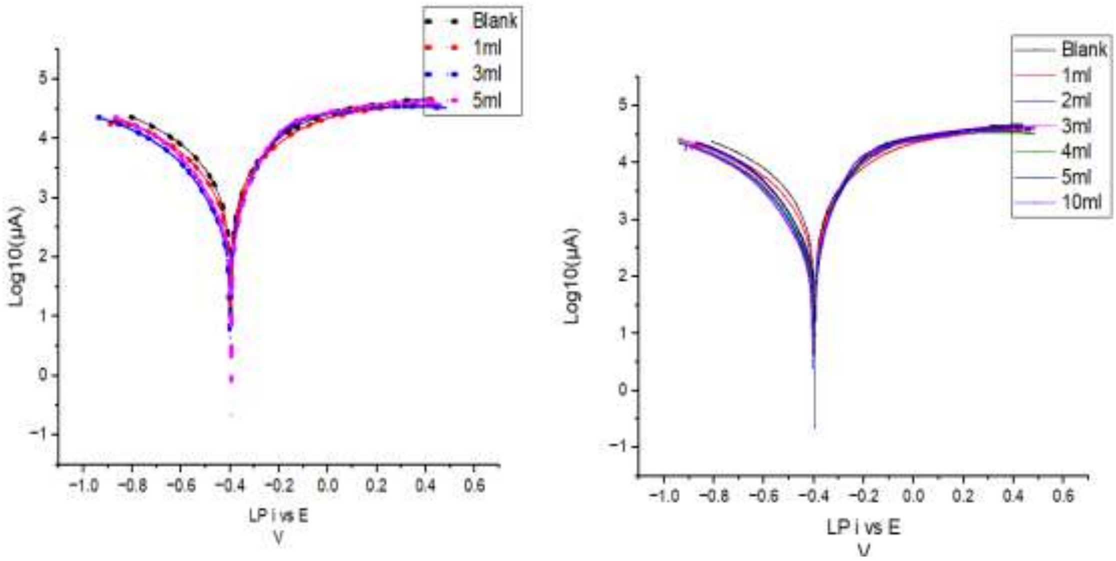

Figure-2 Poarization study of steel exposed to 0.5M HCl solution with different dosage of inhibitor

The E_{corr} values vary somewhat from negative to positive values (inhibitor influencing both anodic and cathodic curves), but there is no discernible trend [25]. Conveniently, the emergence of parallel Tafel lines does not significantly alter the slope of cathodic Tafel lines (βc), indicating that the hydrogen evolution mechanism is activated. The hydrogen reduction mechanism that occurs at the mild steel surface through charge transfer is unaffected by the presence of an inhibitor. The inhibitor's organic and plant-based inhibitor chemicals enable the metal surface to be adsorbed and a protective coating to develop [26].

4.3 Electrochemical impedance spectroscopy (EIS) studies

The mechanism of corrosion and inhibition can be carried out a powerful technique is an EIS. The impedance spectra of steel in HCl medium in the absence and presence of various concentrations of mixed type inhibitor. For impedance study, the following equation is used to calculate the IE,

$$IE(\%) = \frac{Rct - Rct*}{Rct} \times 100$$

Where Rct and R*ct represent the charge transfer resistances with and without of the inhibitor respectively.

In the study of mild steel corrosion, EIS is seen to be a useful and nondestructive technique that supports the potentiodynamic polarisation method. Figure 3 displays the Nyquist and Bode graphs obtained at the corrosion potential (Ecorr) for various inhibitor dosages at ambient temperature. Figure 3 makes it clear that when the concentration of leaf extract increases, the diameter of the impedance spectra also increases [27]. This can be explained by the fact that leaf extract adsorbs on reactive sites, increasing the protection of mild steel.

In order to derive the electrochemical parameters, the electrical equivalent circuits depicted in Figure 4b were used to fit experimental data. Capacitance (C) is substituted by CPE to account for impurities, surface roughness, and in homogeneity on mild steel. Alternatively, the equivalent circuit of Fig. 4b was employed to account for the flattening of the steel's EIS spectra obtained with inhibitor. The Bode diagram (Fig. 4c) provides a clear description of this flattening and validates the existence of two time constants. The reactions of the leaf extract deposited on the mild steel are responsible for R2 and CPE2 in this instance, whereas charge-transfer [28] resistance and double layer capacitance are responsible for R3 and CPE3, respectively.

By examining the impedance data and comprehending the electrochemical processes taking place at the coating/metal interface, electrochemical impedance spectroscopy (EIS) with an equivalent circuit model R(QR(RC)(RC)) can be utilized to investigate the protective qualities of coatings. A system with a solution resistance (R), a constant phase element (Q) connected in parallel with a resistor (R) and capacitor (C) to represent the coating, and another parallel RC circuit to represent the metal/electrolyte interface is represented by the circuit R(QR(RC)(RC)). Examining these elements aids in determining the barrier qualities and corrosion resistance of the coating [29,30].

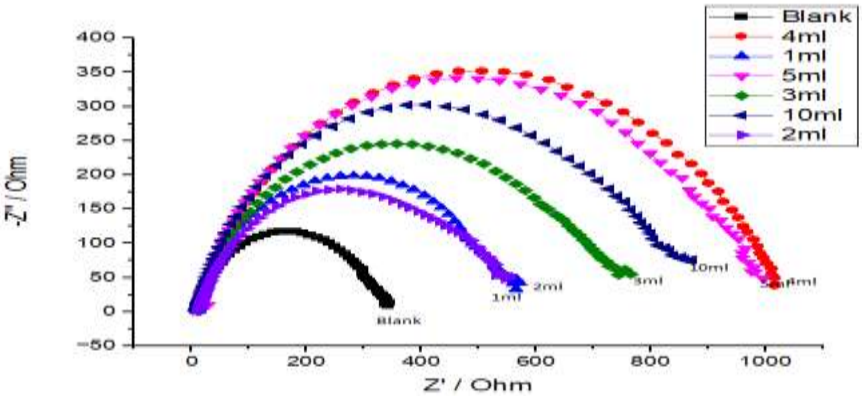

Figure 4a. Impedance spectroscopy graph blank wit different dosage of inhibitor.

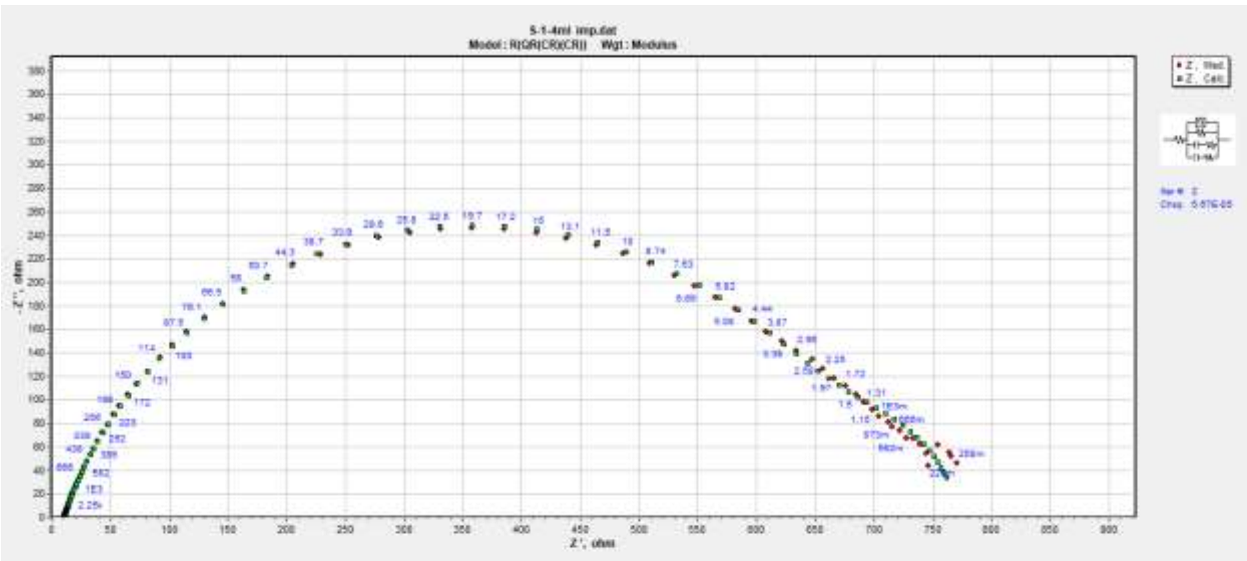

Figure 4b. Impedance spectroscopy graph 4ml dosage of inhibitor fitted with R(RQ(RC)(RC) circuit using Zsim sofware.

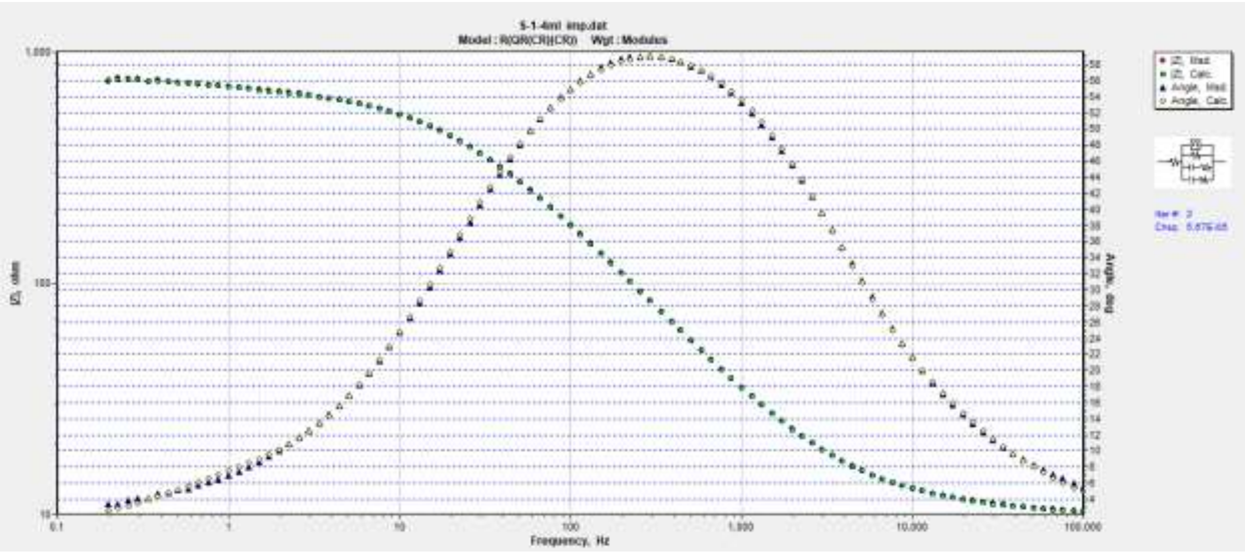

Figure 4c. Impedance spectroscopy graph 4ml dosage of inhibitor bode potential sample using Zsim sofware.

Table: 4- Impedance spectroscopy of steel with blank and different dosage of inhibitor at 0.5M HCl solution.

Dosage	R1 (Ωcm2)	R_{ct} (Ωcm2)	C_{dl} (Ωcm2)	IE (%)
Blank	24.64	253.04	6.34X10-6	
1ML	15.25	331.84	7.21X10-6	23.74
2ML	11.94	346.6	7.9X10-6	26.99
3ML	8.36	426.71	8.3X10-6	40.69
4ML	5.17	1250.17	9.6X10-6	79.75
5ML	6.12	898.6	8.32X10-6	71.84
10ML	7.65	504.8	8.14X10-6	49.8

Table 4 provides a summary of the derived and fitted parameters. When 4 ml of the inhibitor is added to the HCl aggressive solution, the polarisation resistance increases from 253.04 to 1250.17 Ωcm^2. This rise is more noticeable with 4 ml of leaves, which is explained by the organic molecules and plant extract replacing the water and HCl at the mild teel/solution interface. The creation of a thick protective layer and the adsorption of the inhibitor chemicals on the mild steel surface are suggested by the increase in Rct values with the amount of inhibitor. As the inhibitor is added, the inhibition efficiency rises to 79.75% for 4 millilitres.

Conclusion

Corrosion inhibitors play a crucial role in mitigating the degradation of metals and alloys in various environments. They function by forming a protective film, altering the electrochemical reactions, or interfering with the diffusion of corrosive agents. Inhibitors are widely used in industries such as oil and gas, water treatment, chemical processing, and infrastructure maintenance. As corrosion continues to be a significant economic and safety concern, the development and application of effective inhibitors remain essential. Traditional inorganic inhibitors like chromates are highly effective but pose environmental and health hazards. Consequently, the focus has shifted toward:

- Environmentally friendly ("green") inhibitors derived from plant extracts and biodegradable compounds
- Smart inhibitors that release protective agents in response to corrosion triggers
- Nano-engineered inhibitors for targeted and long-lasting protection

The future of corrosion inhibition lies in sustainable, smart, and adaptive technologies that integrate with real-time monitoring systems, offering more precise and environmentally responsible protection strategies.

References

1. Revie, R. W., & Uhlig, H. H. (2008). *Corrosion and Corrosion Control: An Introduction to Corrosion Science and Engineering* (4th ed.). Wiley.
2. Schutt, H. U. (2006). *Corrosion and Corrosion Control in Oil and Gas Industry*. Wiley-VCH.
3. Koch, G. H., et al. (2002). *Corrosion Cost and Preventive Strategies in the United States*. FHWA-RD-01-156.
4. Schweitzer, P. A. (2006). *Fundamentals of Metallic Corrosion: Atmospheric and Media Corrosion of Metals*. CRC Press.
5. Zaki, N. N., & El-Taher, A. M. (2002). "Corrosion Inhibition of Steel During Acid Pickling." *Corrosion*, 58(9), 758–764.
6. ASM International. (2001). *Corrosion: Materials Performance and Testing*. ASM Handbook, Vol. 13B.
7. Dominik Legut et al., Inhibition of steel corrosion with imidazolium-based compounds – Experimental and theoretical study, Corrosion Science 191, 109716 (2021) https://doi.org/10.1016/j.corsci.2021.109716
8. Tidke et al. Discover Electrochemistry (2025) 2:40 https://doi.org/10.1007/s44373-025-00055-5
9. Qahtan A. Yousif et al., Safflower plant extract as a sustainable corrosion inhibitor for carbon steel in acidic media: a combined electrochemical and computational study, RSC Adv., 2025, 15, 21006. DOI: 10.1039/d5ra03333k rsc.li/rsc-advances
10. Bio-based ionic liquid (IL) corrosion inhibitor , Effect of ionic liquid as a surfactant in hydroxyapatite coatings for improvement corrosion resistance of Ti-6Al-4V substrates for implant applications , *Sustainable Chemistry and Pharmacy*, 2024 ScienceDirect
11. Ingrid Milo˘sev, Corrosion inhibition of aluminium alloys by molybdate ions: A critical review of the chemistry, mechanisms and applications, Volume 229, 1 April 2024, 111854, *Journal of the corrosion science*.
12. Harish Kumar et al., Highly efficient green corrosion inhibitor for mild steel in sulfuric acid: Experimental and DFT approach *Colloids and Surfaces: Physicochemical and Engineering Aspects*, 2023 Volume 675, 20 October 2023, 132039.
13. Rania Farouq et al., Utilizing nanomaterials to functionalize the Tikoua extract as a powerful green anti-corrosion inhibitor for carbon steel, Journal of Petroleum Exploration and Production Technology (2025) 15:143 https://doi.org/10.1007/s13202-025-02060-1
14. Jesús Rafael González-Parra The Use of Plant Extracts as Sustainable Corrosion Inhibitors for Cultural Heritage Alloys: A Mini-Review , Mini-Review. Sustainability 2024, 16, 1868. https://doi.org/10.3390/ su16051868

15. de Souza Morais et al., *Applied Sciences*, 2023 MDPI; Sheydaei, *Surfaces*, 2024 MDPI; reviews on aluminium alloys in NaCl environments (Lavanya & Kumari, 2022) JCC HeMS
16. Popova, A. (2007). *Effect of the molecular structure on the inhibition efficiency of azoles as corrosion inhibitors for metals in acidic media. Corrosion Science*, 49(2), 653–662. https://doi.org/10.1016/j.corsci.2006.05.011
17. Verma, C. et al. (2017). *Molecular dynamics and quantum chemical studies on organic inhibitors. Journal of Molecular Liquids*, 225, 517–533.
18. Jones, D. A. (1996). *Principles and Prevention of Corrosion.* Prentice Hall. ISBN: 9780133599930
19. Umoren, S. A. & Solomon, M. M. (2019). *Green corrosion inhibitors from natural sources: A review. Journal of Environmental Chemical Engineering*, 7(3), 103102. https://doi.org/10.1016/j.jece.2019.103102
20. Yu-Min Tzou et al., Redox reactions between chromium(VI) and hydroquinone: Alternative pathways for polymerization of organic molecules, Environmental PollutionVolume 261, June 2020, 114024-https://doi.org/10.1016/j.envpol.2020.114024
21. Mingyong Chao et al., Electrochemical determination of maltol in food products using a poly(L-tryptophan) modified glassy carbon electrode, Russian Journal of ElectrochemistryVolume 50, pages 1065–1071, (2014)
22. P. Bhattacharyya, B.E. Volcani, Isolation of silicate ionophore(s) from the apochlorotic diatom nitzschia,alba, Biochemical and Biophysical Research Communications, Volume 114, Issue 1, 18 July 1983, Pages 365-372
23. Magda Moner-Girona et al., Prioritisation of clean energy interventions in Sub-Saharan Africa: A geospatial multi-criteria decision support tool, Energy for Sustainable Development, Volume 86, June 2025, 101709-https://doi.org/10.1016/j.esd.2025.101709
24. Rajesh Haldhar et al., Myristica fragrans extract as an eco-friendly corrosion inhibitor for mild steel in 0.5 M H2SO4 solution, Journal of Environmental Chemical Engineering, Volume 6, Issue 2, April 2018, Pages 2290-2301-https://doi.org/10.1016/j.jece.2018.03.023
25. A. Lanzutti et al., Microstructural and local electrochemical characterisation of Gr. 91 steel-welded joints as function of post-weld heat treatments, Corrosion Science, Volume 148, March 2019, Pages 407-417-https://doi.org/10.1016/j.corsci.2018.12.042
26. www.dx.doi.org
27. Article.sciencepublishinggroup.net
28. Digital.lib.washington.edu
29. Asbmr.onlinelibrary.wiley.com
30. www.freepatentsonline.com