Research Journal of Chemical Sciences ____ISSN 2231-606X
Vol. **16(2),** 11-20, June **(2026)** *Res. J. Chem. Sci.*

Inhibitive Action of *Azadirachta indica* Leaves Extract on Corrosion of Mild Steel in Acetic acid Solution

Harshida G. Chaudhari[1]*and Rajendra T. Vashi[2]
[1]Department of Chemistry, Shree Jayendrapuri Arts and Science College, Bharuch, Gujarat, India
[2]Chemistry Department, Navyug Science College, Rander Road, Surat, Gujarat, India
harshidac@yahoo.co.in

Available online at: www.isca.in, www.isca.me
Received 10th August 2025, revised 16th March 2026, accepted 11th April 2026

Abstract

The corrosion inhibition effect of Azadirachta indica (AZI) leaves extract on corrosion of mild steel (MS) in a acetic acid solution has been evaluated by weight loss (WL), potentiodynamic polarization (PDP) and electrochemical impendence spectroscopy (EIS) techniques. Corrosion rate (CR) increases with the increase in acid concentration. At constant inhibitor concentration, CR increases with increase in acid concentration, while inhibition efficiency (IE) decreases. The CR decreses as inhibitor concentration increases, while percentage of IE increases with inhibitor concentration. AZI showed maximum IE of 81.37% at 1.0g/L inhibitor concentration in 0.5 M acetic acid. Polarization measurements indicats that AZI can function as mixed-type of inhibitor. The negative value of free energy of adsorption ($\Delta G°_{ads}$) and enthaly of adsorption ($\Delta H°_{ads}$) indicated that the adsorption of inhibitor is spontenious and exothermic. The lover value of energy of activation (E_a) for the unhibited system compare to inhibited system, indicate that the inhibitors are more effective at lower temperature. The results shows that there is a good agreement between WL and elecrochemical techniques.

Keywords: Corrosion, Mild steel, Acetic acid, AZI, WL, PDP, EIS.

Introduction

Corrosion is defined as the destructive attack of a metal by chemical or electrochemical reaction with its environment, resulting in the loss of material properties. A severe corrosion of material may result in tremendous economic loss as well environmental impact to some extent. MS is considered as low carbon steel having carbon content of 0.05–0.25%. MS is most important material, extensively used in construction and industries like petroleum, chemical, petrochemical, transportation industries etc. Acetic acid is an important chemical reagent and industrial chemical, mainly used in the production of cellulose acetate, polyvinyl acetate, plastic, acetic anhydride and in textile processing industry. Diluted acetic acid is often used in descaling agents. In the food industry, acetic acid is used under the food additives as an acidity regulator and as a condiment. Many researchers had been studied the corrosion inhibition of MS in acetic acid by using various inhibitors[1-5].

In order to protect the metal from corrosion several techniques have been applied. Among these the use of inhibitors is one of the most practical and efficient methods for protection metals from corrosion. The corrosion inhibitors are substances which effectively reduce the rate of corrosion when added in very small qautnties[6].

The known hazardous effect of most synthetic corrosion inhibitors is the motivation for the use of some natural products. Nowadays there is growing attention towards eco friendly corrosion inhibitions “green corrosion inhibitors”. Such inhibitors are biodegradable, cheap, eco-friendly, readily available and renewable sources of materials, and ecologically acceptable[7].

Azadirachta indica, commonly known as neem, is a member of mahogany family, Meliaceae[8]. Neem plants grow in various countries in the world, including Asia, Africa, America, and Australia[9]. It is native to India, Bangladesh, Thailand, Nepal, Cambodia, Laos, Myanmar and Pakistan[10]. It grows well in tropical and sub-tropical regions. It has been used in Ayurvedic medicine for more than 4000 years due to its medicinal properties. In India, this tree is called Divine tree, Wonder tree, Free tree of India, Nature’s drugstore, Village Pharmacy, Panacea for all diseases[11].

Neem trees are attractive broad-leaved evergreens in all season that can grow up to 30m tall and 25m in girth. Neem leaves serve as antibacterial, antifungal, anti inflammatory, immunomodulatory, antihyperglycemic, antiulcer, antifungal, antibacterial, antimutagenic, anticancer, antimalarial, antiviral, antioxidant[12,13]. The tree is popular for its pharmacological attributes such as hypolipidemic, microbicidal, antidiabetic, hepatoprotective, insecticidal, nematicidal, neuroprotective, cardioprotective, and antileishmaniasis properties[14]. Besides these uses, there are several other reports on the biological and pharmacological actions such as antipyretic, antiseptic and antiparalitic[15,16].

Neem leaves are useful for chickenpox, increase immunity of the body; reduce fever caused by malaria, treating various foot fungi, useful against termites, used in curing neuromuscular pains. Bathing with Neem leaves is beneficial for itching and other skin diseases. Various researchers[13,17-31] studied AZI leaves extract as an green corrosion inhibitor for various metal in acidic solutions. The purpose of the present study is to investigate the corrosion inhibition ability of AZI leaves extract for MS in acetic acid solutions by using WL, PDP and EIS techniques.

Materials and Methods

Preparation of sample and solution: The size of the test specimens used for the study is 4.5×2.0×0.2cm having an effective area of 0.2097 dm^2 were prepared from MS sheet having chemical composition of (wt %) C = 0.25 Mn = 0.50, Si = 0.35, P = 0.09, S = 0.07 and Fe = 98.74. First the test specimens were cleaned by washing with distilled water and degreased by acetone and again washed with doubled distilled water then dried by air dryer and weighted by using electronic balance. The various concentration of acetic acid, 0.5, 1.0, 1.5, and 2.0 M was prepared by diluting analytical grade acetic acid in double distilled water, was used as corrosive media.

Extraction of plants: Leaves of AZI were collected and dried in oven, grounded to powder. 10 g of the powder was refluxed in 500 ml double distilled water for 3h. The reflux obtained was allowed to stand for 24 h, then filtered and stored. This filtrate was reducing to 100ml. This extract so obtained were used in preparing 0.1, 0.25, 0.5 and 1.0g/L of the extract solutions[31].

Weight loss (WL) measurement: For WL measurement, previously weighed MS specimens were each suspended and completely immersed in 230 ml of 0.5, 1.0, 1.5 and 2.0 M acetic acid solution as corrosive medium in absence and presence of different concentrations of AZI leaves extract for 24h immersion period at 303±1 K. Only one specimen was suspended in each glass beaker of 250 ml capacity. After 24 hours (1 day) of immersion period, each samples were withdrawn from the test solution and were cleaned by using Clark's solution, prepared by dissolving 2% Sb_2O_3 and 5% $SnCl_2$ in 100 ml concentrated HCl at room temperature with constant stirring for about 15-20 minutes[32,33]. After cleaning the test specimens were washed with distilled water followed by acetone and then dried with air dryer and re-weighted. The difference in weight before and after immersion period was taken as WL. Thereafter, CR was calculated from WL data by using following equation-1.

$$\text{CR (mg/ dm}^2\text{d)} = \frac{(\text{Weight loss in gram x 1000})}{Area\ in\ dm^2.\ day} \quad (1)$$

Where: dm^2 = exposed area in desimeter^2, (dm^2 = 100 cm^2)

From the WL measurements, the % IE of the inhibitor were calculated using following equations

$$\text{IE}(\%) = \frac{Wu-Wi}{Wu} \times 100 \quad (2)$$

Where: W_u and W_i are the weight loss (mg/dm^{-2}) of MS in the uninhibited and inhibited acid solution, respectively.

The same WL measurements were also carried out at different temperatures like 313 323 and 333 K in 200 ml 1.0 M acetic acid as corrosive medium by using thermostat with an accuracy of ± 0.5°C for an immersion period of 2 h. After exposure period, the test specimens were removed form soltions and CR was determined. The experiment was carried out without and with the inhibitor having concentration of 0.1, 0.25, 0.50 and 1.00 g/L. From the WL data at different temperature, inhibition efficiency (% IE) and thermodynamic parameters like Energy of activation (E_a), Free energy of adsorption ($\Delta G°_{ads}$), Enthalpy of adsorption ($\Delta H°_{ads}$) and Entropy of adsorption ($\Delta S°_{ads}$) were calculated.

Potentiodynamic polarization (PDP) measurements: For polarization study, the test specimens having an area of 1 cm^2 were immersed in 200ml of 0.5M acetic acid at constant temperature of 298 K without and with 1.0g/L of AZI leaves extract as inhibitor. A platinum electrode used as auxiliary electrode and Ag/AgCl electrode was used as a reference electrode. The MS specimens act as a working electrode. Initially OCP was measured as a function of time, and after the stabilization of the electrode at OCP, the polarization measurements were carried out. The change in potential was measured by potentiostate (CH instrument model- CHI608C, made in USA). Polarization curves were plotted as potential against log current density (called Tafel plots). Cathodic and anodic polarization curves corresponds to cathodic and anodic Tafel lines. From the intersect point of cathodic and anodic Tafel lines the value of corrosion current (I_{corr}) and the corrosion potential (E_{corr}) can be measured[34]. Cathodic Tafel slope (β_c) and anodic Tafel slope (β_a) were calculated directly from the software installed in the instrument.

The % IE from I_{corr} was calculated from the following equation[35];

$$\text{I.E. \%} = \frac{I_{corr\ ,u} - I_{corr\ ,i}}{I_{corr\ ,u}} \times 100 \quad (3)$$

Where: $I_{corr(u)}$ and $I_{corr(i)}$ are the corrosion current density for uninhibited and in inhibited system respectively.

Electrochemical Impedance Spectroscopy (EIS) measurements: The EIS measurements were carried out by using CH instrument (model- CHI608C, made in USA) at room temperature of 298 K, at frequency range of 1 KHz to 100 KHz with a AC amplitude of 5 mV. By ploting the real impedence (Z') versus imaginary impedence (-Z''). The Nyquist plots were obtained in absence and presence of 1.0 g/L concentrations of AZI leaves extract using 0.5 M acetic acid as corrosive medium. From the Nyquest plots the charge transfer resistance (R_{ct}) and double layer capacitance (C_{dl}) were calculated.

To calculate the value of 'C_{dl}' the frequency at which the imaginary component of impedance (–Z''max) is maximum was found as presented in following equation[36,37].

$$C_{dl} = \frac{1}{2\pi F_{max}\, R_{ct}} \tag{4}$$

Where, 'F_{max}' is the frequency at the maximum height of the semicircle on the imaginary axis and 'R_{ct}' is the charge transfer resistance.

% IE was calculated by EIS method using following equation-5.

$$\text{I.E.}(\%) = \frac{\text{Rct (i)} - \text{Rct (u)}}{\text{Cdl (uninhi .)}} \text{ x } 100 \tag{5}$$

Where: $R_{ct(u)}$ is double layer capacitance for uninhibited acid and $R_{ct(i)}$ is double layer capacitance for inhibited acid.

Results and Discussion

Effect of acid concentration: The data presented in Table-1 indicates that as the acid concentration increases CR also increases. The CR was 486.41, 629.47, 767.76 and 891.75 mg/dm^{2}d corresponding to 0.5, 1.0, 1.5 and 2.0 M acetic acid concentrations respectively.At given inhibitor concentration, the % IE decreases with the increase in acid concentration. At 1.0 g/ L inhibitor concentration, the % IE of AZI leaves extract was 81.37, 81.06, 80.24 and 78.08 % with respect to 0.5, 1.0, 1.5 and 2.0 M acetic acid concentrations respectively (Table-1).

Effect of inhibitor concentration: At constant acid concentration, as the inhibitor concentration increases corrosion rate decreases while % IE increases. At 0.5 M acetic acid concentration the % IE was found to be 69.60, 71.57, 77.45 and 81.37 % correspond to 0.10, 0.25, 0.50 and 1.0g/L inhibitor concentration respectively (Table-1).

Effect of Temperature: In order to study the effect of temperature on corrosion of MS in acetic acid and corrosion mechanism, the WL measurements were carried out at different temperature like 313, 323 and 333 K, in 1.0 M acetic acid as corrosive medium. From the data presented in Table-2, it is reviled that as the temperature increases the CR increases and %IE decreases for given concentration of inhibitor.

Energy of activation (E_a): With the help of Arrhenius equation[38] as shown below, the value of energy of activation (E_a) has been calculated.

$$\log\frac{\rho_2}{\rho_1} = \frac{E_a}{2.303\,R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right) \tag{6}$$

Where, ρ_1 and ρ_2 are the CR at temperature T_1 and T_2 respectively.

The Arrhenius plot for the inhibition of the corrosion of MS in acetic acid is shown in Figure-1. The value of E_a presented in Table-2. The obtained by Arrhenius plot is in good agreement with value of E_a obtained by calculation value of (E_a).

Table-1: Effect of acetic acid concentration on CR & IE of AZI leaves extract on MS for an immersion period of 24h at 303±1 K.

Inhibitor Concentration g/L	Acid concentration							
	0.5 M		1.0 M		1.5 M		2.0 M	
	CR (mg/dm^{2}d)	IE (%)	CR (mg/dm^{2}d)	IE (%)	CR (mg/dm^{2}d)	IE (%)	CR (mg/dm^{2}d)	IE (%)
Blank	486.41		629.47		767.76		891.75	
0.1	147.83	69.60	190.75	69.69	233.67	69.56	276.59	68.98
0.25	138.29	71.57	181.21	71.21	224.14	70.80	262.28	70.59
0.5	109.68	77.45	147.83	76.52	190.75	75.16	228.90	74.33
1.0	90.61	81.37	119.22	81.06	152.60	80.24	195.52	78.07

Table-2: Temperature effect on the CR and value of (E_a) for the corrosion of MS in 1.0 M acetic acid containing AZI leaves extract for an immersion period of 2 h.

Inhibitor	Inhibitor Concentration (g/L)	Temperature						Energy of activation (E_a) (kJ mol^{-1})	
		313 K		323 K		333 K			
		CR (mg/dm^2 d)	IE (%)	CR (mg/dm^2 d)	IE (%)	CR (mg/dm^2 d)	IE (%)	Mean	From Arrhenius plot
Blank		858.37		1430.62		2288.98		42.04	42.47
Azadirachta indica	0.1	400.57	53.33	915.59	36.00	1831.18	20.00	65.75	65.84
	0.25	343.35	60.00	686.69	52.00	1201.72	47.50	54.16	54.30
	0.5	228.90	73.33	515.02	64.00	915.59	60.00	59.82	60.12
	1.0	171.67	80.00	343.34	76.00	629.47	72.50	56.24	56.29

As shown from the data presented in Table-2, the value of E_a for inhibited system are ranging from 54.16 to 65.84 kJ mol^{-1}, which is higher than that of uninhibited system (42.04 kJ mol^{-1}). The increase in E_a in presence of inhibitor has been associated with physisorption of the adsorptive film onto the metal surface. Higher values of E_a in the inhibited system compared to uninhibited system associated with increasing the energy barrier for the corrosion process, by the inhibition action of the AZI leaves extract, emphasizing electrostatic character of the inhibition (physisorption)[39,40].

Adsorption isotherm: Basic information on the interaction between inhibitors and a metal surface can be provided using the adsorption isotherm[41]. The surface coverage 'θ' suggest that a chemical bond is formed between the metal atoms and the inhibitor molecules. The Langmuir adsorption isotherm can be represented by following equation-7.

$$\frac{C_{inh}}{\theta} = \frac{1}{K_{ads}} + C_{inh} \tag{7}$$

Where, C_{inh} is inhibitor concentration and K_{ads} is equilibrium constant of adsorption process. The value of surface coverage θ ($\theta = W_u - W_i / W_u$) were calculated directly from the % IE of the inhibitor obtained from WL measurements at room temperature. A plot of extract concentration C/θ versus C is represented in Figure-2., which gives straight line with slope values equal to unity indicates that the system follows Langmuir adsorption isotherm[42].

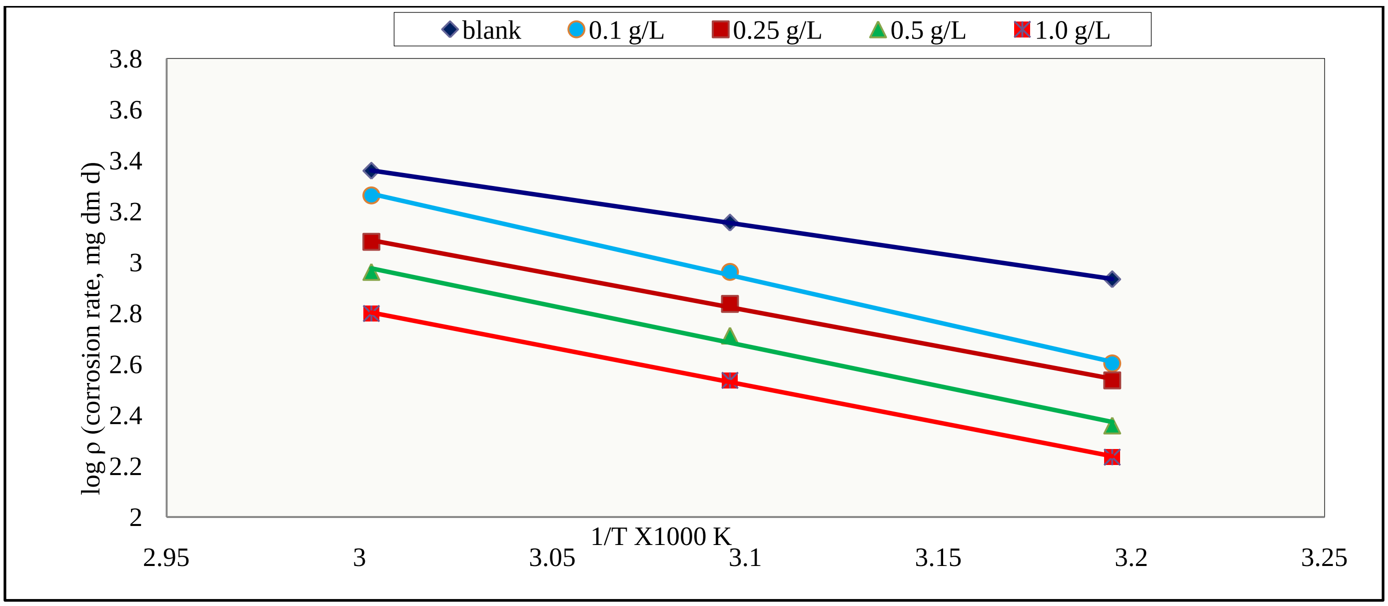


Figure-1: Arrhenius plot for corrosion of MS in 1.0 M acetic acid solutions in absence and presence of AZI leaves extract.

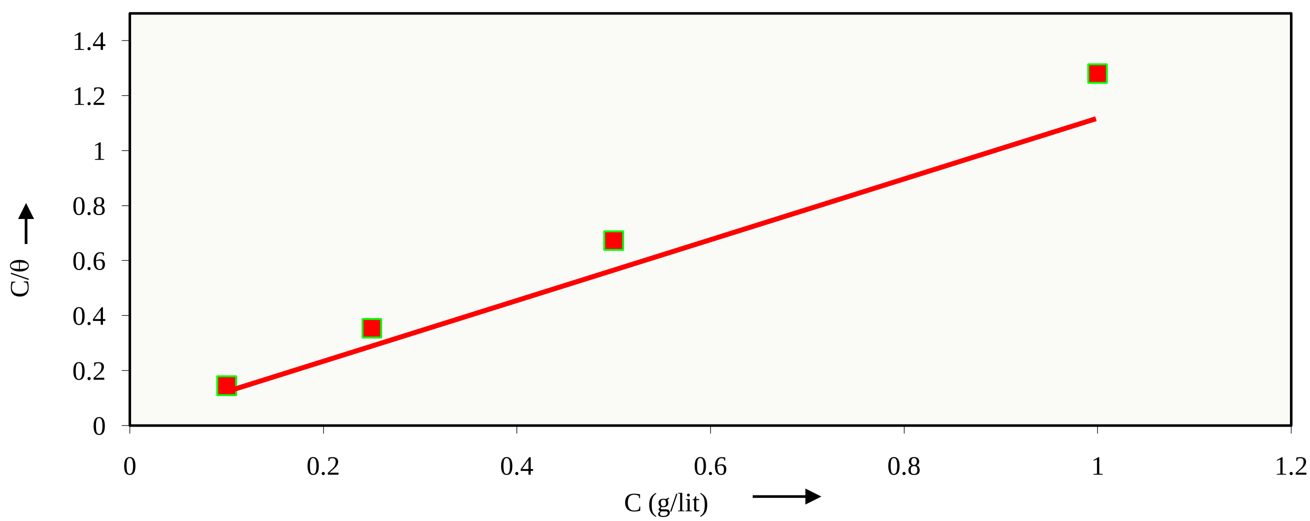


Figure-2: A plot of Langmuir adsorption isotherm for AZI Extract in 2.0 M acetic acid at 303 K.

Free energy of adsorption ($\Delta G°_{ads}$): In order to calculate thermodynamic parameters, The Langmuir adsorption isotherm was also established for different temperature of 313, 323 and 333 K and the intercept give the value of K_{ads}. The K_{ads} value is directly related to standard free energy of adsorption $\Delta G°_{ads}$ according to following equation[43].

$$K_{ads} = \frac{1}{C_{solvent}} \exp\left(\frac{-\Delta G°_{ads}}{RT}\right) \quad (9)$$

Where, K_{ads} intercept of the plot of inhibitor concentration 'C' versus C/θ for different temperature.

Table-3: The standard thermodynamic parameters for the adsorption of AZI leaves extract on MS surface.

Temp. (K)	K_{ads} kJ mole^{-1}	$\Delta H°_{ads}$ kJmole^{-1}	$\Delta S°_{ads}$ Jmole^{-1}K^{-1}	$\Delta G°_{ads}$ kJmole^{-1}
313	18.18	-53.09	-116.92	-16.50
323	12.34	-	-116.95	-15.32
333	8.62	-	-116.93	-14.16

From the data presented in Table-3, the value of $\Delta G°_{ads}$ are negative and ranges from -14.16 to -16.50kJ mol^{-1}, concluded electrostatic interaction between MS surface and inhibitor molecule to be physically adsorbed on the MS surface[44] . The value of $\Delta G°_{ads}$ around -20kJ mol^{-1} is related with electrostatic interaction between charge molecule and metal surface (physisorption), while the higher value of $\Delta G°_{ads}$ than -40 kJ mol^{-1} consider coordinate type of bond by charge sharing or transfer between the inhibitor molecules and the metal surface (chemisorption)[45]. As the negative value of $\Delta G°_{ads}$ is related to spontaneous reaction, the adsorption of AZI leaves extract on MS surface is spontaneous.

Heat of adsorption ($\Delta H°_{ads}$): From the Vant Hoff equation as follows, the heat of adsorption $\Delta H°_{ads}$ were calculated using following equation[46].

$$\ln K_{ads} = \frac{-H°_{ads}}{RT} + \text{constant} \quad (10)$$

Where, 'R' is gas constant and 'T is absolute temperature.

As the concentration of inhibitor is not so large, the value of heat of adsorption obtained from the graph ln K versus 1/T is standard heat of adsorption shown in Figure-3.

As given in Table-3, the negative value of $\Delta H°_{ads}$, indicates the exothermic adsorption of inhibitor molecule on MS surface, leading to rise of rate of desorption process of the adsorbed inhibitor molecule from the mild steel surface with increase in temperature[47].

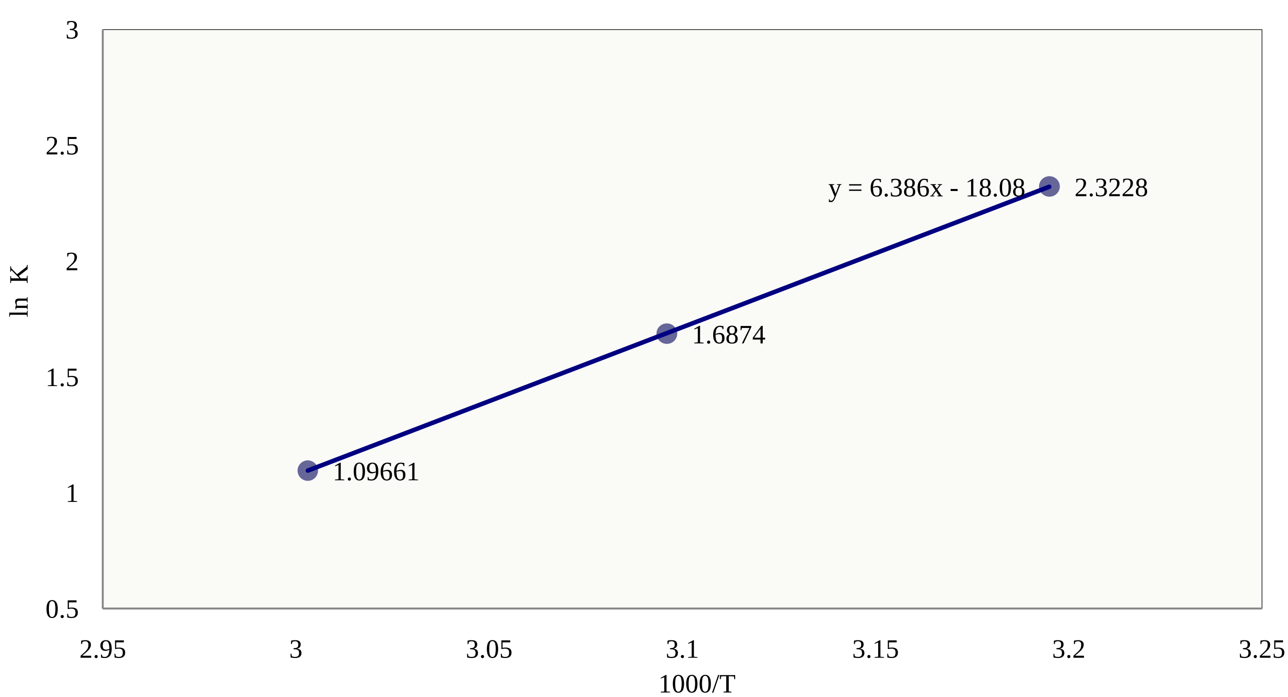


Figure-3: Vant Hoff plot.

Entropy of adsorption ($\Delta S°$ads): The entropy of adsorption ΔS_{ads} was calculated according to thermodynamic basic equation as follows[48].

$$\Delta S°_{ads} = \Delta H°_{ads} - \Delta G°_{ads} / T \quad (11)$$

The negative value of $\Delta S°_{ads}$ for AZI can be ascribed by possible formation of metal complex on the MS surface[49].

Potentiodynamic Polarization study: From the PDP study electrochemical parameters of corrosion of MS in acetic acid can be evaluated. From the Tafel plot the value of corrosion potential (E_{corr}), corrosion current density (I_{corr}), the value of Tafel slope (βa and βc) were measured and presented in Table-4.

From the data presented in Table-4, it was observed that the I_{corr} and CR is decrease on addition of AZI leaves extract in acid solution compare to blank. It may be due to adsorption of the components of the AZI leaves extract on MS surface. From the data it was found that the value of E_{corr} for uninhibited system was -0.610 V, while in presence of the inhibitor the value of E_{corr} is -0.656 V. Generally, an inhibitor is said to be anodic or a cathodic if the variation of E_{corr} to the blank is higher of about 85 mV[50,51]. In the present study, the difference of the value of E_{corr} was 46 mV (Table-4) which suggest that the AZI leaves extract is functioning as a mixed type of inhibitor. %IE of the inhibitor was directly calculated from corrosion current density I_{corr} obtained for inhibited and uninhibited system and were presented in Table-4. %IE calculated from Tafel plots well agreed (within ± 7%) with the values obtained from WL data. Figure-4 represents the PDP curves MS specimen in 0.5M acetic acid for blank and in presence of 1.0g/L concentration of AZI leaves extract as inhibitor.

From the PDP curve it was observed that in presence of the inhibitor the curve moved tovard lower current density compare to blank, without much change in the value of E_{corr}. This suggests that AZI leaves extract inhibits the corrosion of MS in acetic acid by forming a adsorbed surface film without changing the mechanism corrosion. Both the anodic and cathodic Tafel slope (β_a and β_c) of inhibited system have changed with respect to blank system, shows polarization of both the anodes as well as the cathodes as from Figure-4.

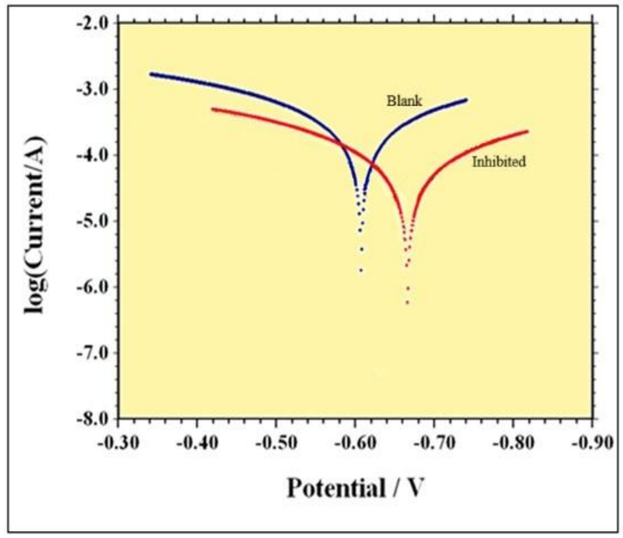


Figure-4: Polarization curves of MS in 0.5 M acetic acid in absence and in presence of 1.0 g/L AZI inhibitor.

EIS measurement: From the ESI measurement, the typical Nyquist plot was obtained by plotting real impedance (Z') versus imaginary impedance (Z") for corrosion of MS in 0.5 M acetic acid without and with AZI leaves extract at room temperature of 298 K as shown in Figure-5(a) and in Figure-5(b). The value of 'R_{ct}' and 'C_{dl}' were calculate and presented in Table-5.

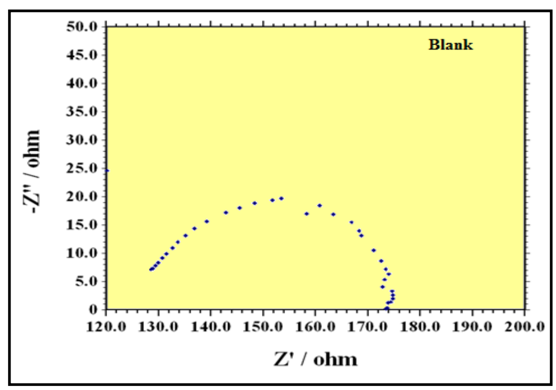


Figure-5(a): The Nyquist plot for corrosion of MS in 0.5 M acetic acid without AZI leaves extract.

Table-4.: The electrochemical parameters of corrosion of MS in 0.5 M acetic acid in presence and absence of 1.0 g/L AZI leaves extract as inhibitor, from Polarization measurements at 298 K.

System	E_{corr} (V)	I_{corr} (μA/ cm^2)	Tafel slopes(V/ decade)			I.E. (%) calculated from	
			Anodic (+βa)	Cathodic (-βc)	Tafel constant (β) (V)	WL method	PDP method
Blank	-0.610	244	5.195	4.659	1.0679	-	-
AZI	-0.656	63.12	5.534	4.981	1.1398	81.37	74.13

β = Tafel constant, β= (βa X βc) / [2.3 (βa + βc)]

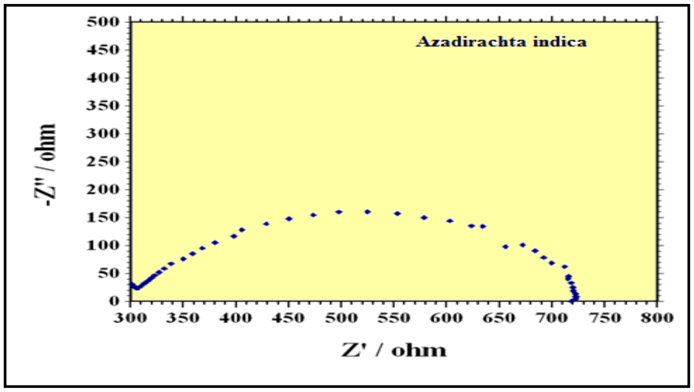


Figure-5(b): The Nyquist plot for corrosion of MS in 0.5 M acetic acid containing 1.0 g/L of AZI.

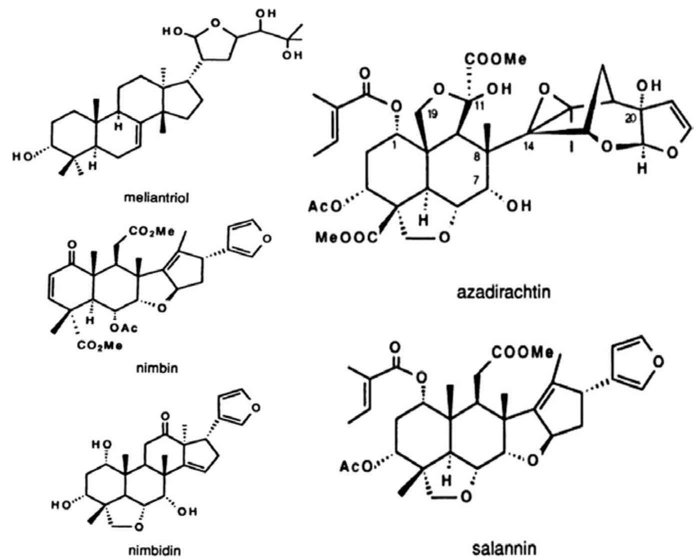
The almost semicircle, not perfect semicircle appearance of Nyquist plot was observed as shown in Figure-5(a) and Figure-5(b). The variation from perfect semicircle has been attributed to frequency dispersion[52]. The almost semicircle nature of the impedance plots indicates that the corrosion of MS is mainly controlled by charge transfer process[53]. The diameter of capacitive loop is bigger in presence of AZI leaves extract as inhibitor than that in the absence of it. The higher value of R_{ct} is related to high frequency capacitive loop. The electrochemical parameters obtained from ESI measurement for corrosion of MS in 0.5 M acetic acid with and without of 1.0g/L AZI leaves extract as inhibitor are represented in Table-5.

Table-5: The electrochemical perameters obtained from EIS.

System	R_{ct} (Ω cm^2)	C_{dl} (μF / cm^2)	I.E. (%) Calculated from	
			EIS method	WL method
Blank	56.22	145	-	-
AZI	250.73	5.707	77.80	81.37

The addition of inhibitor increases R_{ct} value from 56.22 to 250.73 Ω cm^2, while the C_{dl} value tend to decrease from 145 to 5.707 μF/cm^2 in presence of inhibitor, which may be due to the adsorption of AZI leaves extract component on MS surface. The increase in the value of R_{ct} was caused by adsorption of the inhibitor molecules by gradual replacement of water molecules on the MS surface to form a protective film which reduces dissolution of metal[52]. The decrease in C_{dl} values, caused by a decrease in local dielectric constant and/or an increase in the thickness of the electrical double layer, suggests that the water molecules are replaced by inhibitor molecules[54]. This decrease in double layer capacitance C_{dl}, indicates the formation of a protective inhibitor layer on the MS surface.

Mechanism of AZI leaves extract: As natural product AZI leaves extract is composed of numerous naturally occurring organic compounds. The structures of the main active chemical compounds present in AZI leaves extract are shown:



Structures of main constitutes of AZI leaves exract.

According to earler studies aqueous AZI leaves extract is organic in nature and contains phytochemicals like protein, azadirachtin, tetranortriterpenoid, triterpenes, liminoids, steroids, tannin, saponin, anthraquinone, steroids, alkaloid, terpens, phenols, and glycosides[12,26,27,]. The most important active constituent of AZI leaves extract are azadirachtin, nimbolinin, nimbin, nimbanene, nimbidin, nimbandiol, sodium nimbinate, gedunin, salannin, and quercetin[54-58] .

The presence of compounds like these in AZI leaves extract may have contributed to the inhibitory action exhibited against corrosion of MS in acetic acid. Neem leaves are exceedingly bitter due to the high tannin content as well as the presence of a series of complex triterpene glycosides in their composition[59]. The inhibitive properties of tannins result from reaction of the polyphenolic fraction of the tannin molecule with metal ions, thereby forming a highly cross-linked network of metal tannate moieties, which ensures effective protection of the metal surface[60]. Tannins are made up of polyphenols and their acidic and heterocyclic derivatives. These constituents were composed mostly of oxygen-containing organic compounds. Furthermore, these compounds also may form complexes with the metallic cations. These complexes can cause blockage of micro anodes and or micro cathodes that are generated on the surface under corrosive conditions, and hence can retard the dissolution of the metal[61]. Lone pairs of elecrons are peresent on oxygen (O), sulphur (S) and nitrogen (N) atoms, by which they can be absorbed on the metal surfase. The creation of adsorption layer of component of AZI leaves extract on metal surface make a barrier for charge and mass transfer leading to a dissolution of MS in corrosive environment. As a result, the corrosion rate of the metal is decreased in presence of the extract. Eddy and Mamza[24] alsosupport that there is interaction between the component of AZI leaves extract and the surface of MS.

According to Nahl´e et al.[62] tannins have ability to form tanninate salts with ferric ions. Ferric tanninate salt can form highlt cross -linked network on metal surface that protect the metal from corrosion. Similarly, triterpenes also have functional groups such as (OH, C = O, C = C) that can be interact with the metal surface and protect it from the attack of acid.

Conclusion

The study concludes that, The CR of MS increases with the increase in acetic acid concentration. The AZI leaves extract found to be effective corrosion inhibitor for MS in acetic acid, and the %IE increases with increase inhibitor concentration. AZI leaves extract shows 81.37% as maximum %IE at inhibitor concentration of 1.0 g/L. The inhibition mechanism follows the Langmuir adsorption isotherm. The negative values of ΔG^{o}_{ads} suggest the spontaneous adsorption of inhibitor molecule onto the MS surface.The PDP measurement indicates that the AZI leaves extract behaved as a mixed type of inhibitor.The conclusion obtained from PDP and EIS measurements are in good agreement with WL data with marginal variation due to limitations of the technique itself.

Acknowledgments

The authors are thankful to the Department of Chemistry, Navyug Science College, Surat, Gujarat, India for providing laboratory facilities.

References

1. Rafiquee, M. Z. A., Khan, S., Saxena, N. & Quraishi, M. A. (2007). Influence of some Thiadiazole derivatives on corrosion inhibition of Mild Steel in formic and acetic acid media. *Port. Electrochim. Acta*., 25(4), 419-434.

2. Chaudhari, H. G. & Vashi, R. T. (2016). The study of henna leaves extract as green corrosion inhibitor for mild steel in acetic acid. *J. Fundam. Appl. Sci*., 8(2), 280-296.

3. Vashi, R. T. & Chaudhari, H. G. (2017). The Study of Aloe-vera gel extract as green corrosion inhibitor for Mild steel in acetic acid. *Int. J. Innov. Res. Sci. Engg. Tech.,* 6(11), 22081-22091.

4. Vashi, R. T. & Chaudhari, H. G. (2020). The Study of Corrosion Inhibition Ability of Hexamine on Mild Steel in Acetic Acid Solution. *Int. J. Eng. Res & Tech.*, 9(09), 1071-1077.

5. *Bouchtart, A., Rguiti, M., El Mouaden, K.,* Albourine, A., Chaouiki, A., Ralghi, R., Bazzi, L. & Chetouani, A. *(2020).* Mild steel corrosion inhibition by some heteroatom organic compounds in acetic acid medium. *Moroccan J. of Chem.*, 8(4), 982-993.

6. Gerengi, H. (2012). Anticorrosive properties of Date Palm (Phoenix dactylifera L.) fruit juice on 7075 type Aluminum alloy in 3.5% NaCl solution. *Ind. Eng. Chem. Res*., 51, 12835−12843.

7. Abdel–Gaber, A. M., Abd-El-Nabey, B. A., Sidahmed, I. M., El-Zayady, A. M., Saadawy, M. M. (2006). Inhibitive action of some plant extracts on the corrosion of steel in acidic media. *Corros. Sci*., 48(9), 2765-2779.

8. Yanpallewar, S. U., Sen, S., Tapas, S., Kumar, M., Raju, S. S. & Acharya, S. B. (2003). Effect of Azadirachta indica on paracetamol-induced hepatic damage in albino rats. *Phytomed*., 10(5), 391- 396.

9. Ghosh, V., Sugumar, S., Mukherjee, A. & Chandrasekaran, N. (2016) Neem (Azadirachta indica) oils; In book Essential Oils in Food Preservation. *Flavor and Safety*. 67, 593-599.

10. Prashanth, G. K. and Krishnaiah, G. M. (2014). Chemical composition of the leaves of Azadirachta Indica Linn (Neem). *Int. J. Adv. Eng. Tech., Manag. & Appl. Sci*., 1(5), 21-31.

11. Tiwari, S., Verna, A. K., Chakraborty, S., Dharma, K. and Singh, V. C. (2014). Neem (Azadirachta indica) and its potential for safe guarding health of animals and human- A Review. *J. Bio. Sci*., 14(2) 110-123.

12. Dasgupta, T., Banerjee, S., Yadava, P. K. & Rao, A. R. (2004). Chemopreventive Potential of Azadirachta indica (Neem) Leaf Extract in Murine Carcinogenesis Model System. *J. Ethnopharmacol.*, 92, 23-36.

13. Deepa Rani, P. & Selvaraj, S. (2011). Azadirachta Indica Leaves as Green Inhibitor for Brass in Natural Sea Water Environment. *Asian J. Research Chem*., 4(9), 1469-1473.

14. Saleem, S., Muhammad, G., Hussain, M. A., & Bukhari, S. N. A. (2018). A comprehensive review of phytochemical profile, bioactives for pharmaceuticals, and pharmacological attributes of Azadirachta indica. *Phytotherapy research*, 32(7), 1241-1272.

15. Prieto, P., Pineda, M. & Aguilar, M. (1999). Activity of a standardized neem (Azadirachta Indica) seed extract on the rodent malaria parasite plasmodium berghei. *Anal. Biochem.*, 269, 337–341.

16. Ali Hussain, H.E.M. (2002). Reversal of diabetic retinopathy in streptozotocin induced diabetic rats using traditional Indian anti-diabetic plant, Azadirachta Indica (L.). *Indian J Clin Biochem*. 17, 115–123.

17. Loto, C. A., Loto, R. T., & Popoola, A. P. I. (2011). Effect of neem leaf (Azadirachita indica) extract on the corrosion inhibition of mild steel in dilute acids. *Int. J. Phys. Sci*., 6(9), 2249–2257.

18. Ameh, E. M., Ekwoba, L., Ocheme, G. W., Oteno, F., Umar, A. Y., & Esseoghene, E. L. (2025). Corrosion Inhibition Study Ethanolic Extract of Neem Leaves (Azadirachta indica) on Zinc metal in 0.1 M HCl and 0.1 M NaOH. *J. Mater. Environ. Sci.*, 16(2), 341- 353.

19. Okpala, A. N., Ogbonnaya, E. A., & Waidi, Y. B. (2022). Effect of Azadirachta Indica (Neem) Leaf Extract on the Corrosion of Medium Carbon Steel in Sulphuric Acid. *Research & Development*, 3(2), 99-105.

20. Vashi, R. T. & Prajapati, N. I. (2019). Corrosion Inhibition of Aluminium in Hydrochloric Acid Solutions by Azadirachta indica (Neem) Leaves Extract as Green Inhibitor. *Int. J. Green Herb. Chem. Sec. A*, 8(2), 444-452.

21. Patel, B. B., & Vashi, R. T. (2017). Azardiracha indica (Neem) extract as green inhibitor for corrosion of brass in nitric acid media. *J. Applicable. Chem.*, 6(3), 340-349.

22. Valek, L., & Martinez, S. (2007). Copper corrosion inhibition by Azadirachta indica leaves extract in 0.5 M sulphuric acid. *Materials Letters*, 61(1), 148-151.

23. Elachi, E. E., Yusuf, K. D., Justine, A., Paul, M. & Madugu, A. B. (2021) Comparison of the Inhibitive Effects of Neem (Azadirachta indica) Leaves Extract and Benzamide in Tetraoxosulphate (VI) Acid Solution. *J. New-views in Eng. and Tech*., 3(3), 32-42.

24. Eddy, N. O., & Mamza, P. A. P. (2009). Inhibitive and adsorption properties of ethanol extract of seeds and leaves of Azadirachta indica on the corrosion of mild steel in H_2SO_4. *Portugaliae Electrochimica Acta*, 27(4), 443-456.

25. Patel, K. K., & Vashi R. T. (2015). Azardiracha indica extract as corrosion inhibitor for copper in nitric acid medium. *Res. J. Chem. Sci*., 5(11), 59-66.

26. Sharma, S. K., Mudhoo, A., Jain, G. & Khamis E. (2009). Corrosion inhibition of Neem (Azadirachta indica) leaves extract as a green corrosion inhibitor for Zinc in H_2SO_4. *Green Chem. Lett. Rev*., 2(1), 47-51,

27. Sharma, K. S., Mudhoo, A., Jain, G., & Sharma, J. (2010). Corrosion inhibition and adsorption properties of Azadirachta indica mature leaves extract as green inhibitor for mild steel in HNO_3. *Green Chem. Lett. Rev.*, 3(1), 7-15.

28. Loto, A. C., Loto, R. T. & Popoola, A. P. I. (2011). Effect of neem leaf (Azadirachta indica) extract on the corrosion inhibition of mild steel in dilute acids. *Int. J. Phys. Sci.*, 6(9), 2249–2257.

29. Tokala, V. N. B. & Gupta, P. (2017). Corrosion inhibition and adsorption properties of Azadirachta indica (Neem) leaves extract as a green inhibitor for Zinc in H_2SO_4. *Int. J. Current Res.*, 9(12), 63131-63135.

30. Waidi, Y. B. & Philip, O. Y. (2022). Investigating the Efficacy of Azadirachta Indica (Neem) Leaf on Mild Steel Corrosion in 1M Sulphuric Acid (H_2SO_4). *AJSET*, 7(3), 121-129.

31. Okafor, P. C., Ebenso, E. E., & Ekpe, U. J. (2010). Azadirachta Indica Extracts as Corrosion Inhibitor for Mild Steel in Acid Medium. *Int. J. Electrochem. Sci.*, 5(7), 978 - 993.

32. ASTM standards (1978). Method for chemical cleaning after testing. 681, 41-72.

33. El-Etre, A. Y., Abdallah, M., & El-Tantawy, Z. E. (2005). Corrosion inhibition of some metal using Lawsonia extract. *Corrosion Science*., 47(2), 385-395.

34. Yadav, M., Kumar, S. Yadav, M., Kumar, S., Sinha, R. R., Bahadur, I., & Ebenso, E. E. (2015). New pyrimidine derivatives as efficient organic inhibitors on mild steel corrosion in acidic medium: electrochemical, SEM, EDX, AFM and DFT studies. *Journal of Molecular Liquids*, 211, 135-145.

35. Shah, A. M., Rahim, A. A., Hamid S. A., & Yahya, S. (2013). Green inhibitors for copper corrosion by Mangrove tannin. *Int. J. Electrochem. Sci.,* 8(2), 2140-2153.

36. Khamis, E., Ameer, M. A., AlAndis, N. M., & Al-Senani, G. (2000). Effect of thiosemicarbazones on corrosion of steel in phosphoric acid produced by wet process. *Corrosion.*, 56(2), 127-138.

37. Arab, S. T., & Emran, K. M. (2005). Effect of temperature on the corrosion inhibition of iron base metallic glass alloy in neutral solutions. *Bulletin of electrochemistry*, 21(11), 513.

38. Patel, K.K. & Vashi, R.T. (2015). Azadirachta Indica Extract as corrosion Inhibitor for Copper in Nitric Acid Medium. *Res. J. Chem. Sci.*, 5(11), 59-66.

39. Umoren, S. A., Obot, I. B., Ebenso, E. E., Okafor, P. C., Ogbobe, O., & Oguzie, E. E. (2006). Gum arabic as a potential corrosion inhibitor for aluminium in alkaline medium and its adsorption characteristics. *Anti-Corros. Methods Mater.*, 53(5), 277-282.

40. Oguzie, E. E. (2008). Evaluation of the inhibitive effect of some plant extracts on the acid corrosion of mild steel. *Corros. Sci.*, 50(11), 2993-2998.

41. Muthamma, K., Kumari, P., Lavanya, M., & Rao, S. A. (2021). Corrosion Inhibition of Mild Steel in Acidic Media by N-[(3,4-Dimethoxyphenyl) Methyleneamino] -4-Hydroxy-Benzamide. *Journal of Bio- and Tribo-Corrosion*, 7(10), 1-19.

42. Arellanes-Lozada, P., Cuautli, C., Likhanova, N. V., Desión-Palacios, M., Lijanova, I. V., Arriola-Morales, J., & Olivares-Xometl, O. (2025). Corrosion Inhibition of API 5L X60 Steel in Acid Medium: Theoretical and Experimental Approaches. *ACS Omega.*, 10(18), 18864-18880.

43. Umoren, S. A., Obot, I. B., Ebsenso, E. E. & Obi-Egbedi, N. O. (2009). The inhibition of aluminium corrosion in hydrochloric acid solution by exudate gum from Raphia hookeri. *Desalination*, 247(1-3), 561-572.

44. Ekuma, F. K., Odoemelam, S. A., Ekanem, U. I. & Okoyeagu, A. (2018). Synthesized Schiff bases from linoleic and benheric acids as inhibitor of mild steel corrosion in HCl. *Res. J. Chem. Sci.*, 8(9), 12-25.

45. Li, L., Zhang, X., Lei, J., He, J., Zhang, S. & Pan, F. (2012). Adsorption and corrosion inhibition of Osmanthus fragran leaves extract on carbon steel. *Corrosion Science.*, 63, 82–90.

46. Zhao, T. P. & Mu, G. N. (1999). The adsorption and corrosion inhibition of anion surfactants on aluminium surface in hydrochloric acid. *Corrosion Science.*, 41(10), 1937-1944.

47. Sobhi, M., El-Noamany, H. H., & El-Etre, A. Y. (2014). Corrosion Inhibition Study of Some Novel Compounds for Carbon Steel in 1 M HCl Solution. *J. Bas. & Environ. Sci.*, 1, 164-173.

48. Hegazy, M. A., El-Tabei, A. S., Bedair, A. H. & Sadeq, M. A. (2012). An investigation of three novel nonionic surfactants as corrosion inhibitor for carbon steel in 0.5 M H_2SO_4. *Corrosion Science.*, 54, 219-230.

49. Ebenso, E. E., Alema, H., Umoren, S. A. & Obot, I. B. (2008). Inhibition of mild steel corrosion in sulphuric acid using alizarin yellow GG dye and synergistic iodide additive. *Int. J. Electrochem. Sci*., 3(12), 1325-1339.

50. Li, W., Zhao, X., Liu, F., & Hou, B. (2008). Investigation on inhibition behavior of S-triazole–triazole derivatives in acidic solution. *Corrosion science*, 50(11), 3261-3266.

51. Farahati, R., Ghaffarinejad, A., Mousavi-Khoshdel, S. M., Rezania, J., Behzadi, H., & Shockravi, A. (2019). Synthesis and potential applications of some thiazoles as corrosion inhibitor of copper in 1 M HCl: Experimental and theoretical studies. *Prog. Org. Coat*., 132, 417–428.

52. Wang, D., Xiang, B., Liang, Y., Song, S., & Liu, C. (2014). Corrosion control of copper in 3.5 wt.% NaCl solution by domperidone: experimental and theoretical study. *Corrosion Science*, 85, 77-86.

53. Rosliza, R., Nik, W. W., & Senin, H. B. (2008). The effect of inhibitor on the corrosion of aluminum alloys in acidic solutions. *Mater. Chem. Phys*., 107(2-3), 281-288.

54. Amrita Kumari, Navneet Kaur, Manvinder Kaur, Husain, F. M., Bhowmik, P. K., Sohal, H. S. (2025). Sustainable corrosion prevention of mild steel in acidic media with Rumex Nepalensis herb extract. *RSC Adv.*, 15(2), 924-937.

55. Singh, A., Ebenso, E. E., & Quraishi, M. A. (2012). Corrosion inhibition of carbon steel in HCl solution by some plant extracts. *Int. J. Corros*., 2012(1), 897430.

56. Ganguli, S. (2002). Neem: A therapeutic for all seasons. *Current Science*, 82(11), 1304.

57. Siddiqui, B. S., Afshan, F. & Faizi, S. (2001). Three novel tetracyclic triterpenoids of biogenetic interest from the leaves of Azadirachta indica. *Tetrahedron.*, 57(52), 10281-10286.

58. Ugwu, E. U., Okore, O. E., Olagbemiro, T. O. & Chindo, I. Y. (1997). Comparative studies of the azadirachtin content of the seeds of Azadirachta indica (neem). *J. Chem. Soc.*, Nigeria, 22(1), 112-118.

59. Martinez, S. & Stern, I. (2001). Inhibitory mechanism of low-carbon steel corrosion by mimosa tannin in sulphuric acid solutions. *J. Appl. Electrochem*., 31(9), 973-978.

60. Arab, S. T., Al-Turkustani, A. M. & Al- Dhahiri, R. H. (2008). effect of Azadirachta indica extract and iodide ions on the corrosion inhibition of aluminium in acid media. *J. Korean Chem. Soc*., 52(3), 281-294.

61. Nahl´e, A., Abu-Abdoun, I., Abdel-Rahman, I. & Al-Khayat, M. (2010). UAE-Neem extract as a corrosion inhibitor for carbon steel in HCl solution. *Int. J. Corros*,. Article ID 460154, 1-9.