Corrosion Inhibition of Mild Steel in 1 M HCl solution using a mixture of *Azadirachta indica* and *Acalypha wilkesiana* Leaf Extracts

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ORIGINAL RESEARCH

Abstract— Protecting mild steel components from corrosion in acidic environments using inhibitors is a well-established industrial practice. Plant extracts can serve as alternative to conventional inhibitors especially when two or more plant extracts are combined. In this study, the potential of a mixture of *Azadirachta indica* (AI) and *Acalypha wilkesiana* (AW) leaf extract to inhibit corrosion of mild steel in 1M HCl solution was investigated. Weight loss measurements were conducted for single and combined plant extracts. Electrochemical impedance spectroscopy and Tafel polarization techniques were conducted to understand the mechanism and kinetics of the inhibition process for the plant extract mixture. GC–MS, FTIR, and phytochemical screening were used to characterize the chemical constituents of both plants-based inhibitors. The results indicated that performance of the extracts was in order: AI + AW mixture > AI > AW >, the higher corrosion protection of AI +AW mixture was attributed to synergistic interactions of bioactive compounds in the plant extract mixture.

Keywords— Acidic solution, green corrosion inhibitors, mild steel corrosion, sustainability.

1 INTRODUCTION

Mild steel components are widely used across diverse industries such as construction, manufacturing, and oil & gas. In these sectors, processes like acid pickling, descaling, and cleaning are essential to ensure operational safety and maintain equipment performance. However, mild steel is susceptible to corrosion in acidic solutions such as HCl and H_2SO_4, thereby necessitating the use of inhibitors. Conventional inhibitors used in these industries are synthetic chemicals which are not only expensive but hazardous to the environment. Consequently, inhibitors derived from organic sources have emerged as alternatives. (Shewata et al., 2024, Zakeri et al., 2022). Plant extracts obtained from different parts of the plant e.g leaves, stem, fruits, are cost effective and biodegradable in nature. They are rich in phytochemicals containing heteroatoms and π-electrons, which adsorb onto metallic surfaces and form a protective film layer, that reduces interaction between metal surface and electrolyte. (Holla et al., 2024, Zakeri et al., 2022).

Extracts from various plant leaves have been investigated and demonstrated to effectively inhibit corrosion of mild steel in hydrochloric acid (HCl) solution (Holla et. al, 2024, Shewata et al., 2024, Zakeri et al., 2022). Among the plants studied, *Azadirachta indica* leaves and *Acalypha wilkesiana* leaves have been reported to be effective in protecting mild steel from corrosion in HCl solution. A recent review on the inhibitive properties of *Azadirachta indica*, popularly known as Neem, has shown that it is effective in inhibiting corrosion of not only ferrous metals but also, nonferrous alloys like Al, Cu, brass in different acidic solutions recording up to 80-99% efficiency depending on concentration and temperature (Vashi, 2025). On the other hand, studies on the inhibitive properties of *Acalypha wilkesiana*, also known as copperleaf, on metals in acidic solutions, are limited. Pioneering work on leaf extract of *Acalypha wilkesiana* as inhibitor for mild steel in 1M HCl solution using weight loss method was reported by Adedayo et. al., 2022. Hussain and Acharya (2026) recently reported the inhibition efficiency of Acalypha wilkesiana in protecting aluminium against corrosion in 1N HCl solution. Recent advances in green corrosion inhibitors have shown that synergistic inhibition achieved by combining two or more inhibitors can reduce the rate at which mild steel corrodes in acidic solutions. To this end, studies on combination of plant extracts from leaves or biomass such as strawberry and zucchini (El Khatib et al., 2020), *Quercus robur* and *Anemone coronaria* (Kerouad et al., 2025 Mango and orange leaves (Aghogho et al., 2025), *Moringa Oleifera* and lignin-based polymer from coconut shell (Sadiq et al. 2024) has been reported to reduce corrosion rate of mild steel in acidic solutions. Hence, the aim of this study is to assess the potential of a mixture of *Azadirachta indica* (Neem) leaves and *Acalypha wilkesiana* (copperleaf) extract to minimize mild steel corrosion in 1M HCl solution.

2 MATERIALS AND METHODS

2.1 PREPARATION AND CHARACTERISATION OF PLANT EXTRACTS

Fresh neem and copperleaf leaves obtained from a farm in Ogun state, Nigeria was used in this study. The leaves were washed in water and dried in air for 14 days. The dried leaves were thereafter ground with an electric blender and sieved using a 600-micron sieve size. 30 g of each powder was extracted using Soxhlet extraction, ethanol (250 ml) was the solvent. The extract obtained was filtered and concentrated using a rotary evaporator to remove the ethanol solvent. Qualitative phytochemical screening of the plant extracts was conducted using standard reagents as described in Adebayo et. al., 2022 and Bolade et.

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al., 2018. Bioactive compounds and functional groups in the extract were characterized using an Agilent 5977B GC/MSD (Mass Selective Detector) coupled with an 8860 GC system and Agilent Cary 630 FTIR/ATR spectrometer respectively.

2.2 WEIGHT LOSS EXPERIMENT

Mild steel flat bar with composition (in wt.%) of 0.21C, 0.47 Mn, 0.23 Si, 0.03 S, 0.06 Ni, 0.02 P, 0.1 Cr, balance Fe was cut into coupons with dimension 15 mm x 15 mm. Thereafter, the coupons were ground with SiC emery different paper grades (60, 120, 240, 600, 800), first washed with distilled water then rinsed with acetone. The coupons were then immersed in 1M HCl solution (200 ml) with or without 0.5 ml of Neem, Copperleaf and their mixture respectively. After 7 days of immersion, the mild steel coupons (MS) were washed with water and weighed. Inhibition efficiency (I.E) was estimated using Equation 1.

$$I.E = \frac{w_1 - w_2}{w_1} \text{ x } 100\% \quad (1)$$

Where, w_1 is the weight of MS in 1M HCl solution with no plant extract, w_2 is the weight of MS in 1M HCl with 0.5 ml of the plant extract. The essence of the weight loss test was to ascertain if the mixture of the leaf extract of Neem and Copperleaf could inhibit corrosion better than individual extract.

2.3 ELECTROCHEMICAL TEST

Electrochemical test was conducted on only the combined plant extracts. Mild steel coupons were ground with SiC emery paper of different grades (60, 120, 240, 600, 800), rinsed with distilled water and acetone and then stored in a desiccator. A conventional three electrode system was employed for the electrochemical test. The working electrode was the metal samples, encapsulated in epoxy. The reference electrode was saturated calomel electrode (SCE) and the counter electrode was graphite rod. 250 ml 1M HCl solution with or without the combined plant extracts (0.5 ml, 1 ml, 2 ml) was the electrolyte. Open circuit measurement (OCP) was conducted for 60 minutes after which EIS measurement was conducted at an amplitude perturbation of 10 mV from a frequency range of 10^6 Hz to 10^{-2} Hz in the potentiostatic mode. Tafel polarisation was conducted at a scan rate of 1 mV/s from -250 mV vs OCP to +250 mV vs SCE. The experiments were conducted using a Gamry 1000E potentiostat/galvnostat.

Inhibition efficiency (*I.E*) was calculated from the EIS data using Equation (2).

$$I.E = \frac{R_{ct\,(acid+extract)} - R_{ct\,(acid)}}{R_{ct\,(acid+extract)}} \; x\,100 \quad (2)$$

Where, $R_{ct\ (acid\ +\ extract)}$ and $R_{ct\ (acid)}$ are the charge transfer resistance of mild steel in 1M HCl solution with or without the plant extract mixture respectively. For Tafel polarisation, Inhibition efficiency (I.E) was calculated using Equation (3).

$$I.E = \frac{i_{corr(acid)} - i_{corr(acid+extract)}}{i_{corr(acid)}} \quad (3)$$

Where, $i_{corr\ (acid\ +\ extract)}$ and $i_{corr\ (acid)}$ represent the corrosion current density of MS in 1M HCl solution with or without the plant extracts respectively.

3 RESULTS AND DISCUSSION

3.1 CHARACTERIZATION OF PLANT EXTRACTS

Table 1 shows the qualitative assay of Azadirachta indica and *Acalypha Wilkesiana*. Phytochemicals such as Tannin, flavonoid, phenol, saponins, and terpenoid and glycoside compounds were detected in varying amounts in the extracts with +++ meaning the bioactive compounds was present in large amount; ++ for moderately present and + for present. These compounds, which contain oxygen and pi-electrons, protect metal surfaces by forming a protective film that inhibits corrosion. Adsorption of these phytochemicals on metal surface is known to occur by electrostatic forces (physisorption) or electron sharing (chemisorption) or a combination of both processes (Holla et al, 2024, Zakeri et al., 2022).

Table 1. Qualitative phytochemical screening for *Azadirachta Indica* and *Acalypha wilkesiana* extract

Phytochemicals	*Azadirachta indica* extract	*Acalypha wilkesiana* extract
Tannin	++	+++
Saponin	-	+
Flavonoid	++	-
Alkaloid	-	+
Terpenoid	-	+
Steroid	-	++
Phenol	+++	-
Glycoside	++	-

Figure 1 shows the FTIR spectrum for leaves extract of *Azadirachta indica* and *Acalypha Wilkesiana*. Similar functional groups were observed in both extracts. These functional groups were: -OH stretch at 3387.60 – 3346.69 cm^{-1} representing -OH bonds in alcohol or phenols, C=C stretching vibrations at 1615.8 cm^{-1}, C-H bonds at 1436.9 cm^{-1}, C=O bonds at 1353 cm^{-1} and C-O bonds at 1216.1 cm^{-1}, The identified functional groups are consistent with previous studies (Adebayo et. al, 2022, Bolade et al.,2018) Figure 2 presents the GC-MS spectra of leaf extract of *Azadirachta indica* and *Acalypha wilkesiana* respectively. Bioactive compounds and their relative abundance and retention time (RT) in minutes detected in *Azadirachta*

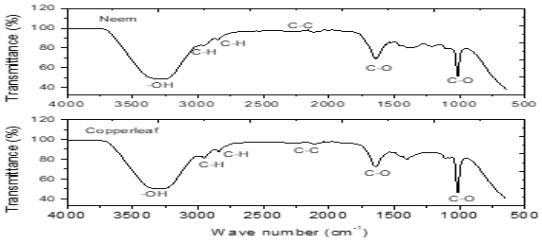

Fig. 1. FTIR spectra of Azadirachta indica and Acalypha Wilkesiana leaf Extract

indica as shown in figure (2a) was: Phytol (25.88%, RT=17.00 min), 9,12-Octadecadienoic acid, methyl ester (13.47%, RT=18.71 min), Hexadecenoic acid, ethyl ester (10.53%, RT=11.97 min), n-Hexadecanoic acid (9.24%, RT =17.3 min), 12-Octadecadienoic acid, methyl ester (8.13%, RT =13.85 min), Oleic acid (7.18%, RT=13.54 min) and excluding compounds with less than 2% peak area in order of relative abundance. On the other hand, the bioactive compounds in *Acalypha wilkesiana* as presented in Fig. 2(b) were: Palmitoleic acid (29.04%, RT=18.01 min). Tetradecanoic acid-, ethyl ester (26.62%, RT=11.97 min) n-Hexadecenoic acid (18.35%, R.T = 13.85 min), E-2-Octadecadecen-1-ol (13.31%, RT = 13.83 min), 9-Octadecenoic acid (Z)-, methyl ester (12.67%, RT=13.54 min). These compounds indicate the presence of fatty acids, fatty acid esters, and fatty alcohols in agreement with the functional groups identified in Figure 1.

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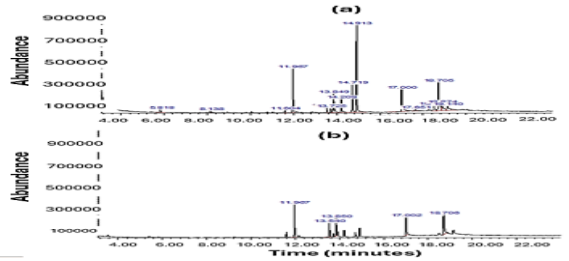

Fig. 2. GC-MS spectra of (a) *Azadirachta Indica* and (b) *Acalypha Wilkesiana* leaf extract.

3.2 Weight Loss Method

Figure 3 presents the inhibition efficiency (I.E) of leaf extracts of *Azadirachta indica*, *Acalypha Wilkesiana* and their combination on mild steel after one-week in 1M HCl solution. *Acalypha wilkesiana* exhibited moderate protection with I.E of 45.16%, while Azadirachta indica achieved a higher I.E. of 70.96 %. The mixture of both extracts, however, exhibited I.E. of 90.32% after one week of immersion. This trend implies that combining the two extracts provided higher protection for mild steel in the acidic solution. This improvement is attributed to synergistic interactions between the phytochemical components of the mixture which enhances surface coverage and protective film formation.

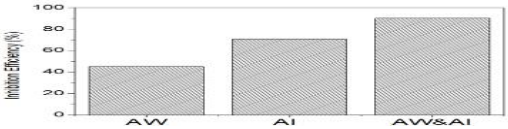

Fig. 3. Inhibition efficiency extract of *Azadirachta Indica* (AI), *Acalypha wilkesiana* (AW) on mild steel in 1M HCl solution after one week.

3.3 Electrochemical Impedance Spectroscopy

EIS data for mild steel in 1M HCl solution with or without the plant extracts mixture at room temperature is presented in Figure 4 in form of Nyquist plot. Single depressed capacitive loops at all concentration of the extract indicate that corrosion of mild steel in HCl solution is limited by charge transfer from mild steel into the electrolyte whether the plant extract was present or not. The depressed semicircle also indicate that the metal-electrolyte interface does not behave like an ideal capacitor due to the presence of surface inhomogeneity and roughness of the metal surface amongst other factors. Compared to the metal in the blank HCl solution, the diameter of the capacitive loop of the metals in 1M HCl solution containing the combined extract increased as concentration increased implying reduced charge transfer from the metal into the electrolyte due to formation of a protective film layer that slows down interaction between the metal and the electrolyte. The Nyquist plot in Fig. 4 was further analysed using the electrical equivalent circuit (EEC) shown in the inset of Figure 4 to elucidate the corrosion process. In the EEC models, electrolyte resistance is represented by Rs, charge transfer resistance, by Rct and CPE is the constant phase element that accounts for the non-ideal capacitance behaviour at the metal-solution. The impedance of a CPE is given is given by $Z_{CPE} = 1/Y_o\,(jw)^n$ where ω the angular frequency, j is the imaginary unit ($j^2 = -1$), Y_o is the admittance of the CPE, n is the CPE exponent, and its values ranges from -1 to 1. The admittance of the CPE [Y_o] can be converted into pure capacitance (C) by $C = 1/R\left(Y_o.R\right)^{\frac{1}{n}}$ (Lasia, 2014).

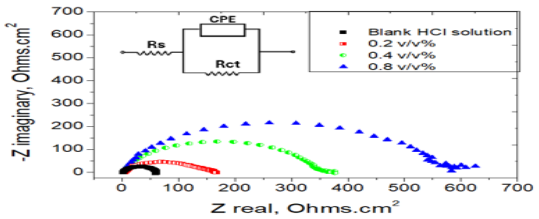

Fig. 4. Nyquist plot for mild steel in 1M HCl solution with plant extract mixture.

Table 2. EIS parameters and I.E. of mild steel in 1M HCl solution with or without plant extract mixture

Inhibitor Conc. (v/v%)	R_p ($\Omega.m^2$)	C_{dl} µF.cm^{-2}	n	%P
0	59.26	392.65	0.92	-
0.2	176.50	216.71	0.78	66.42
0.4	349.00	79.49	0.86	83.02
0.8	566.70	51.11	0.87	89.54

Table 2 shows the result of EEC modelling the EIS data. An increase in the charge transfer resistance (R_{ct}) and a corresponding decrease in the double layer capacitance (C_{dl}) was observed as concentration of the inhibitor increased for 0 to 0.8 v/v%. This observed trend indicate that the protective film formed on the metal surface by the extract mixture was effective in protecting mild steel from corrosion in the HCl solution. A decrease in capacitance as concentration increased indicate that more phytochemical molecules adsorb onto the steel surface, displacing water molecules and ions. This reduces the dielectric constant of the interface and increases the effective thickness of the electrical double layer (El Khatib, (2020), Kerouad et al. (2025), Quraishi et al. (2010). The maximum inhibitive efficiency of 89.54 % was achieved at concentration of 0.8 v/v%.

3.4 Polarization Studies

Tafel polarization curves for mild steel in 1M HCl solution with or without the plant extracts mixture is presented in Fig. 5. Electrochemical parameters obtained from these curves are presented in Table 3. Addition of the plant extract mixture to 1M HCl solution resulted in a decrease in i_{corr} as concentration increased. On the other hand, a slight but positive shift was observed for corrosion potential (Ecorr) of the blank metal when the inhibitors were added. The change in E_{corr} was less than 85 mV indicating that the plant extract mixture acted a mixed-type inhibitor resisting both anodic and cathodic reactions (Holla et al., 2024). Table 3 further shows that I.E of the plant extracts increased as concentration of the inhibitors increased. The higher value of I.E in the Tafel test compared to that of EIS is attributed to the nature of the tests. Tafel polarisation test is known to be a destructive, non-steady-state technique while EIS probes the system gently under near-equilibrium conditions.

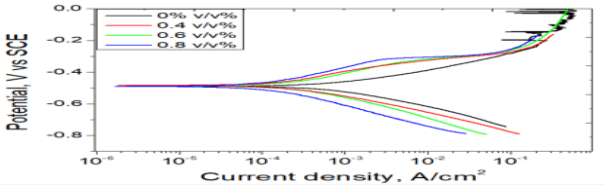

Fig. 5. Tafel polarization curves for mild steel in 1M HCl solution with mixture of Neem and copperleaf extracts.

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Table 2. Tafel polarization and I.E. of mild steel in 1M HCl solution with or without plant extract mixture

Material	Ecorr (V vs SCE)	i_{corr} (A/cm²)	%I. E
Blank	-0.49	5.82 x 10^{-4}	-
0.2	- 0.48	1.42 x 10^{-4}	68.79
0.4	- 0.49	8.75 x 10^{-5}	84.96
0.8	- 0.47	5.06 x 10^{-5}	91.30

3. 5 Adsorption Isotherm

The adsorption behaviour of the mixture of Neem and Copperleaf extracts on metal surface was evaluated by fixing the EIS experimental data into Langmuir adsorption isotherm model expressed as

$$\frac{C_{inh}}{\theta} = {}^{1}/_{K_{ads}} + C_{inh} \quad (4)$$

where C_{inh} is the concentration of the inhibitor, θ is the surface coverage and K_{ads} is the adsorption equilibrium constant. The standard free energy of adsorption, ΔG^{o}_{ads} can be estimated using

$$K_{ads} = \frac{1}{55.5}\, exp^{{}^{-\Delta G^{o}_{ads}}/_{RT}} \quad (5)$$

Figure 6 shows the plot for the isotherm model. A linear relationship with *Adj* R^2 of 0.998 was obtained, this signifies that the adsorption process obeys Langmuir model. Thus, implying that molecules of the phytochemicals in the extract adsorb onto the metal surface forming a uniform and stable monolayer, with no significant lateral interaction between the adsorbed molecules [Holla et al., 2024, Zakeri et al., 2022]. K_{ads} was estimated from the intercept of the plot (Fig. 6) to be 8.23 v/v%$^{-1}$ and the standard free energy of adsorption ΔG^{o}_{ads} was -22.35 kJ mol^{-1}. This value indicates that the electrostatic interaction between the charged phytochemical molecules and the charged mild steel surface was by physisorption (Holla et al., 2024, Zakeri et al., 2022).

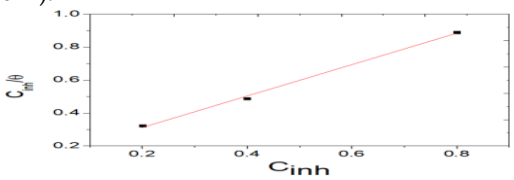

Fig. 6. Langmuir adsorption plot for mild steel in 1M HCl with Neem and copper leaf plant extracts

4 Conclusion

The potential of a mixture of *Azadirachta indica* and *Acalypha wilkesiana* leaves extracts to inhibit corrosion of mild steel in 1M HCl solution was investigated. Gravimetric studies demonstrated that inhibition efficiency of the mixture was the highest (90.32%) while that Acalypha Wilkesiana was the lowest (45.16%). Tafel polarisation for the plant extract mixture indicated that the combined *Azadirachta indica* and *Acalypha Wilkesiana* leaves extract acted as a mixed-type inhibitor with its inhibitive performance increasing as concentration increased from 0 to 0.8v/v%. EIS revealed that increasing the concentration of the extract mixture resulted in higher resistance to charge transfer at the mild steel–electrolyte interface. This increase in charge transfer resistance with increasing concentration of plant extracts was attributed to enhanced coverage of the plant extract molecules on the steel surface resulting in formation of a more compact protective film. Langmuir isotherm analysis indicated that the protective film was formed through physisorption. GC–MS, FTIR characterization, and phytochemical screening revealed the presence of esters, alcohols, organic acids and functional groups responsible for inhibition in both plant extracts. The improved performance of the mixture was attributed to synergistic interactions between the phytochemical components of the mixture which enhanced surface coverage and protective film formation.

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