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Evaluation of Plant Extract as Sustainable Corrosion Inhibitor for Mild Steel in an Acidic Environment for the Oil And Gas Industry

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Abstract: The feasibility of using *Acacia senegalensis* leaf extract as a green corrosion inhibitor for mild steel in 0.5 M hydrochloric acid was investigated using gravimetric and surface characterization techniques. The effects of inhibitor concentration, temperature, and exposure time were studied over the ranges 0–18 g/L (in 3 g/L increments), 30–70 °C (in 20 °C increments), and 3–15 days (in 3-day increments), respectively. Characterization of the extract was carried out using qualitative and quantitative phytochemical analyses, Fourier transform infrared (FTIR) spectroscopy, and gas chromatography–mass spectrometry (GC–MS). Surface morphology of the steel samples before and after corrosion tests was examined using scanning electron microscopy (SEM). The results indicated that the corrosion rate decreased with increasing inhibitor concentration and exposure time. A maximum inhibition efficiency of 97.8% was achieved at an optimum concentration of 12 g/L at 30 °C. However, at the same concentration and an elevated temperature of 70 °C, the inhibition efficiency decreased to 83.5%. FTIR and GC–MS analyses revealed the presence of functional groups and compounds such as C≡N, –N=C=S, C=C, and C=CH_2, as well as organic constituents including $C_{12}H_{22}O_2$, $C_{19}H_{36}O_2$, and $C_7H_{14}O_6$, which are responsible for adsorption and corrosion inhibition on the mild steel surface. SEM micrographs showed a severely corroded surface in the absence of the inhibitor, characterized by pits and cracks, whereas a smoother and more protected surface was observed in the presence of the extract. The high inhibition efficiency values (>70%) confirm that *Acacia senegalensis* leaf extract is an effective, eco-friendly, and cost-efficient alternative to conventional synthetic inhibitors. The extract, therefore, shows strong potential for application in protective coatings and corrosion control systems in the oil and gas industry.

1. Introduction

Corrosion of metallic materials is a major challenge in the oil and gas industry, particularly in environments containing strong acids such as hydrochloric acid (HCl). Hydrochloric acid is commonly used in industrial operations such as acidizing, pickling, descaling, and well stimulation, where it significantly accelerates the corrosion of steel pipelines, storage tanks, and production equipment (Aourabi *et al.*, 2021; Suleiman *et al.*, 2024; Salim *et al.*, 2024). This degradation leads to material failure, increased maintenance costs, environmental risks, and operational downtime. Consequently, corrosion control strategies, particularly the use of corrosion inhibitors, are essential for protecting metallic infrastructure and improving operational efficiency in the oil and gas sector (Guendouz *et al.*, 2025; Sirajo *et al.*, 2025).

Traditionally, synthetic corrosion inhibitors such as chromates, phosphates, and amines have been widely employed to mitigate corrosion in acidic media. However, many of these chemicals are toxic,

expensive, and environmentally hazardous (Bouklah *et al.*, 2006; Zarrouk *et al.*, 2012; Mu'azu *et al.*, 2022). In recent years, increasing environmental regulations and sustainability concerns have encouraged the development of eco-friendly "green inhibitors," particularly those derived from plant extracts (Verma *et al.*, 2018). Plant-based inhibitors are attractive because they are biodegradable, readily available, renewable, and often contain organic compounds with heteroatoms (such as oxygen, nitrogen, and sulfur) and π-electron systems that enhance adsorption on metal surfaces, thereby forming protective films that inhibit corrosion (Suleiman *et al.*, 2018).

However, the inhibition actions of the inhibitors are attributed to their interactions with the metal surface via physical or chemical adsorption processes, which take place through the replacement of water molecules by organic inhibitor molecules from the metal surface (Aliyu *et al.*, 2022; Suleiman *et al.*, 2020). Previous works have shown that the adsorption of an inhibitor on a metal surface depends on the nature, surface charge of the metal, adsorption mode, its chemical structure, and the type of electrolyte solution (Lgaz *et al.*, 2018; David and James, 1998). Another work carried out by (Finšgar and Jackson, 2014) also agreed that organic compounds containing hetero atoms such as phosphorus (P), nitrogen (N), sulfur (S), and oxygen (O) with high electron density, as well as those containing multiple bonds, are effective corrosion inhibitors. All plant products are organic in nature, and their constituents, such as tannins, organic and amino acids, saponins, alkaloids, flavonoids, glycosides, and pigments, are known to exhibit inhibiting action (Vorobyova *et al.*, 2023; Gusti *et al.*, 2019).

In continuation of our interests in the sustainability approach to corrosion mitigation, using an eco-friendly inhibitor for oil and gas applications in acidic environments, this work was designed to investigate the possibility of using *Acacia senegalensis* leaves extract in hydrochloric acid (0.5 M HCl) environments for developing sustainable and environmentally friendly corrosion control solutions for the oil and gas industry using potentiodynamic polarization, and weight loss techniques. Characterizations of the leaf extract by X-ray fluorescent (XRF), Fourier Transform Infrared Spectroscopy (FT-IR), Gas Chromatography Mass Spectrometry (GC–MS) and Scanning Electron Microscope/Energy Dispersive Spectroscopy (SEM/EDS) were also carried out.

2. Experimental Design

2.1 Materials preparation

The mild steel coupon used for this study was obtained from a steel manufacturer in Port Harcourt, Rivers State. The chemical composition of mild steel samples in weight percent is shown in **Table 1.**

Table 1: Chemical composition of mild steel Element

Fe	C	Si	Mn	P	S	Co	Mo	Ni	Al
99.01	0.172	0.423	0.18	0.014	0.013	0,002	0.002	0.015	0.015

2.2 Solution Preparation for the Corrosion Tests

Solutions of 0.5 M HCl were prepared by diluting analytical grade with double-distilled water. Extracts were dissolved in the acid solution at the required concentrations (g/L). The solution in the absence of an inhibitor was taken as blank (0) for comparison purposes according to the work of (Suleiman *et al.* 2020). The test solutions were freshly prepared before each experiment by adding *Acacia senegalensis* extract directly to the corrosive solution. Concentrations of *Acacia senegalensis* extract used were: 0, 3, 6, 9, 12, 15, and 18 g/L, respectively. Experiments were performed in triplicate to ensure good results, and the

Table 1: Experimental design for the corrosion tests

Solutions	Compositions of the acid/extracts
A°	0.5 M HCl solution
B	*Acacia senegalensis* + 0.5 M HCl solution (*AS*: 3, 6, 9, 12, 15 & 18 g/L) and the concentration of acid remained constant.

° control

2.3 Preparation of inhibitor

Nine hundred grams of *Acacia senegalensis* leaf (**Figure 1**) after cleaning in water and drying at room temperature were extracted in 1.5 L of 70% ethanol and 30% distilled water as solvent, followed by the maceration method. The extract and the final stage of collecting the liquid at 100 °C before evaporation are presented in **Figure 1**. The concentration of the stock solution was expressed in terms of (g/L), and the concentrations of 3 – 18 g/L of the extract were prepared.

Figure 1: *Acacia senegalensis (AS) leaf*

2.4 Determination of Phytoconstituents of the Leaf Extract

The phytochemical constituents were determined by quantitative and qualitative methods. The analyses were carried out at the Multi-Users Laboratory, Ahmadu Bello University, Zaria, Nigeria.

2.5.1 Characterizations of Leaf Extract by Fourier Transform Infrared (FT-IR)

A small quantity of *AS* powder was then exposed to infrared radiation. The sample molecules selectively absorb radiation of a specific wavelength, which causes a change in the dipole moment of the sample molecules (Suleiman *et al*, 2018). The commonly used region for infrared absorption spectroscopy was from 4000 to 400 cm^{-1}. This is because of the absorption of radiation within this region. Fourier transform infrared (FT-IR) spectroscopy was carried out to identify the active ingredients (chemical bonding and functional groups) present in the extract. It was carried out using a Shimadzu 8400S spectrophotometer at the Multi-Users Laboratory, Ahmadu Bello University, Zaria. The spectra were recorded, and the interpretations were carried out using a standard library (Aliyu *et al*, 2022).

2.5.2 Characterizations of Leaf Extract by Gas chromatography-mass spectrometry (GC-MS)

About 1 mL of each of the concentration of the extract was analyzed by GC-MS using QP 2010 Plus Schmadzu Product equipped with two fused-silica capillary columns (60 m × 0.22 mm), film thickness at the National Research Institute for Chemical Technology, Zaria. Conditions under which was carried out are: column oven temperature 80 °C, injection temperature 250 °C, injection mode: split flow control mode: linear velocity, pressure: 108.0 kPa, total flow: 6.2 mL/min column flow: 1.58 mL/min, linear velocity: 46.3 cm/s, split ratio: 1.0. GC-MS was carried out and their chromatography mass spectrometry and compounds present in the extract were obtained accordingly (Suleiman *et al;* 2024). It was carried out at the Multi-Users Laboratory, Ahmadu Bello University, Zaria

2.6 Corrosion Measurement Methods

2.6.1 Gravimetric Measurements

The weight loss experiments were carried out in accordance with the methods reported elsewhere (Vorobyova *et al;* 2023). Coupon specimens with dimensions of 4 cm × 3 cm × 1 cm were abraded with various grades of wax-coated emery papers from 600 to 1600 grit. Specimens were degreased in absolute ethanol, dried in acetone, accurately weighed, and stored in moisture-free desiccators before use to avoid reaction with atmospheric air. In gravimetric experiments, pre-weighed coupons were immersed in 0.5

M HCl solution without and with inhibitor concentrations of 0-18 g/L *EH* leave extracts at an interval of 3 g/L for 12 days at an interval of 2 days for withdrawal. The experiments were carried out using a calibrated thermostat at temperatures of 30, 40, 50, 60, and 70°C, respectively. After the time elapsed, the specimens were removed, washed with distilled water, dried with acetone, and re-weighed accurately. To ensure the reproducibility of the weight loss results, each experiment was performed in triplicate, and mean values were used. From the weight loss obtained, corrosion rate, and inhibition efficiency (IE%) and the surface coverage (θ) were computed using the following relationships according to Equations (1-3) (Suleiman *et al;* 2019; Bammou *et al;* 2013).

$$\text{Corrosion rate (mpy)} = \frac{534W}{DAT} \quad \text{..... Eq. 1}$$

where W, D, A and t will be in units of milligrams, grams per cubic centimetre, square inches, and hours, respectively. Inhibition efficiency (IE %) and surface coverage (θ) were calculated from the following equations:

$$\text{Inhibition efficiency (IE \%)} = \frac{CRa}{CRb} x \frac{100}{1} \quad \text{.....Eq. 2}$$

$$\text{Surface coverage } (\theta) = \frac{CRa - CRp}{CRa} \quad \text{.....Eq. 3}$$

2.7 Characterization of the coupons

A Scanning Electron Microscope (SEM) was used to provide basic information about the microstructure of the coupons. The samples were cut from the control. The cut samples were mechanically ground progressively on grades of SiC-impregnated emery paper (80-600 grits) (Ech-chihbi *et al;* 2024). The coupons were selected for SEM after the electrochemical analyses. The microstructure and the chemical compositions of the phases present in the test samples were studied. The SEM was operated at an accelerating voltage of 5 to 20 kV. **Figure 2** shows the SEM machine used for the characterization.

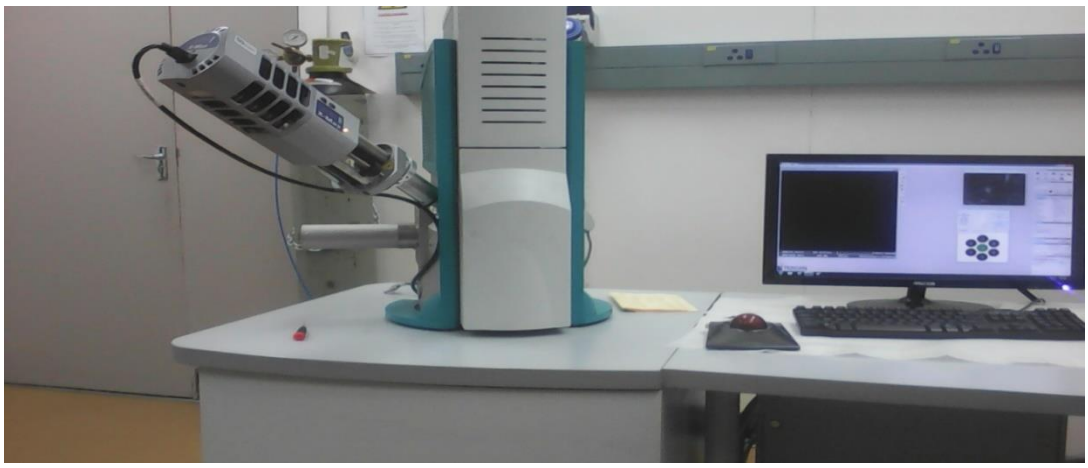


Figure 2: Photograph of the SEM machine used for characterization.

3. Results and discussion

3.1 Phytoconstituents of the Acacia senegalensis extract

The detailed results of phytochemical constituents present in the extract by quantitative and qualitative analyses showed that it contains Saponins, Tannins, Alkaloids, Flavonoids, Glycosides, and Volatile oil. **Tables 3 and 4** present the quantitative and qualitative analyses of *Acacia senegalensis Leaf (ASL)* extract, respectively.

From the results, the constituents can be adsorbed onto the metallic surface by blocking the active corrosion site or reducing the evolution of hydrogen gas at the cathode. This may be attributed to the fact that some of these phytoconstituents contain heteroatoms such as O, Br, and both aromatic and functional groups. This agrees with earlier research reported (Rocha and Gomes, 2017).

Table 3: The qualitative analysis of *Acacia senegalensis leaf* extract

Acacia senegalensis leaf extract	Tannins	Saponins	Flavonoids	Glycosides	Alkaloids	Volatile oil
	+	+	-	+	+	+

Table 4: The quantitative analysis of *Acacia senegalensis leaf extract*

Acacia senegalensis leaf extract	Tannins **(%)**	Saponins **(%)**	Flavonoids **(%)**	Glycosides **(%)**	Alkaloids **(%)**	Volatile oil **(%)**
	15.10±0.01	3.23±0.03	0.000	0.65±0.12	1.34±0.03	0.65±0.24

3.2. Fourier Transforms Infrared (FT-IR) Spectroscopy results

Figures 3 and 4 show the IR absorption spectra and their functional groups. The prominent peaks obtained from the FT-IR spectroscopy for the *Acacia senegalensis Leaf* extract were presented in **Table 4** and confirmed in the previous works (Ayuba *et al*, 2021; Bouyahia *et al*, 2022). The inhibitor showed an effective anticorrosion potential, and the results indicated that the inhibition mechanism involved blockage of the steel pipeline by inhibitor molecules via adsorption. In general, adsorption was influenced by the nature and surface charge of the metal, the type of aggressive electrolyte, and the chemical structure of inhibitors (Aliyu *et al*, 2022; Sirajo *et al*, 2025).

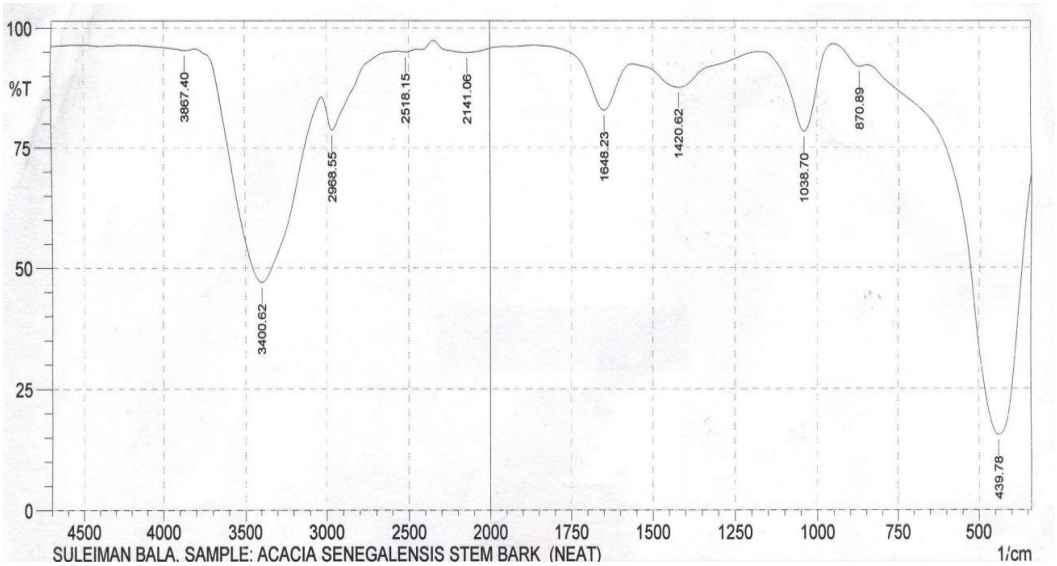
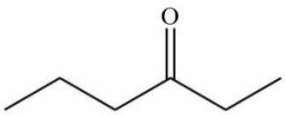
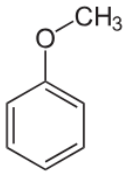


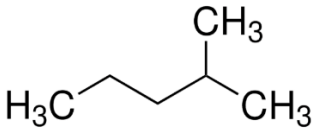
Figure 3: IR absorption spectrum of *Acacia senegalensis leaf* extract



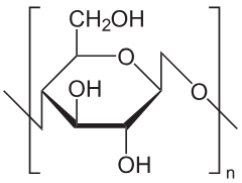
1. Hexanone



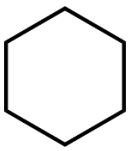
2. Aromatic



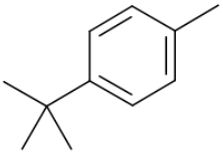
3. 2,4-dimethyl pentane



4. Polysaccharides



5. Cyclohexane



6. 4-tert-butyltoluene

Figure 4: Chemical bonds/Functional groups of IR Absorption Spectrum of *Acacia senegalensis leaf* extract

Table 4: Prominent peaks obtained from reflectance FTIR spectroscopy for *AS leaf* extract

Frequency (cm^{-1})	Band assignment
439.78	-
870.89	$(CH_2) > 3$
1038.7	R–CH=CH–R
1420.62	$C=CH_2$ mono, 1,1
1648.23	C=C stretch
2141.06	–N=C=S
2518.15	C≡N
2968.55	CH_2
3400.62	Aliphatic primary amines have a weak NH_2

3.3 Gas Chromatography-Mass Spectrometry (GC-MS) analysis

GC–Mass Spectrum of *Acacia senegalensis leaf (AS)* is also presented in **Figures 5 and 6**. The compounds identified in the ethanol distillate are presented in **Table 5,** and the structures of the

compounds identified in the *AS* leaf extract are also similar to the findings (Sirajo *et al*, 2025; Suleiman *et al*, 2024). The IR absorption bands are around 870, 1038. 1420.62, 1648.23, 2141.06, 2518.15, 2968.55 and 3400.62 cm^{-1} for *Acacia Senegalensis* indicate the presence of CH_2, R–CH=CH–R, C=CH_2 mono, 1,1, C=C stretch, –N=C=S, C≡N, CH_2, NH_2 functional groups, which fit well with these constituents as reported by Suleiman *et al*, 2020. The functional groups obtained from the GC-MS have an anticorrosion property capable of mitigating the corrosion in such an environment as reported by (Ansari *et al*, 2015; Chaubey *et al*, 2017). The extract contains oxygen atoms, hydroxyl, aromatic rings and hydrocarbon, which are the centres of adsorption. However, adsorption involving organic molecules at the metal solution interface may occur in any of the following ways: (*i*) the electrolytic attraction between charged molecule and the charged metal; (*ii*) interaction of unshared electron pairs in the molecules with the metal; (*iii*) interaction of s electrons with metal; (*iv*) combination of the above (Mu'azu *et al*, 2022).

The inhibition is possibly because Cl^{-1} is hydrated in HCl and would be poorly adsorbed onto the metal surface, leaving more active sites for the adsorption of the inhibitor—neutral species, and thus, inhibition efficiency is increased with the increasing concentrations of inhibitor in HCl medium. Hence, it can be concluded that while adding the inhibitor to HCl solution, the anions like COOH, OH present in the inhibitor solution, and the unshared pair of electrons present on the various hetero atoms present in the functional groups like C=O, O–H, N–H, NH_2 get adsorbed on the steel pipeline. This is similar to the findings of (Sirajo *et al*, 2025).

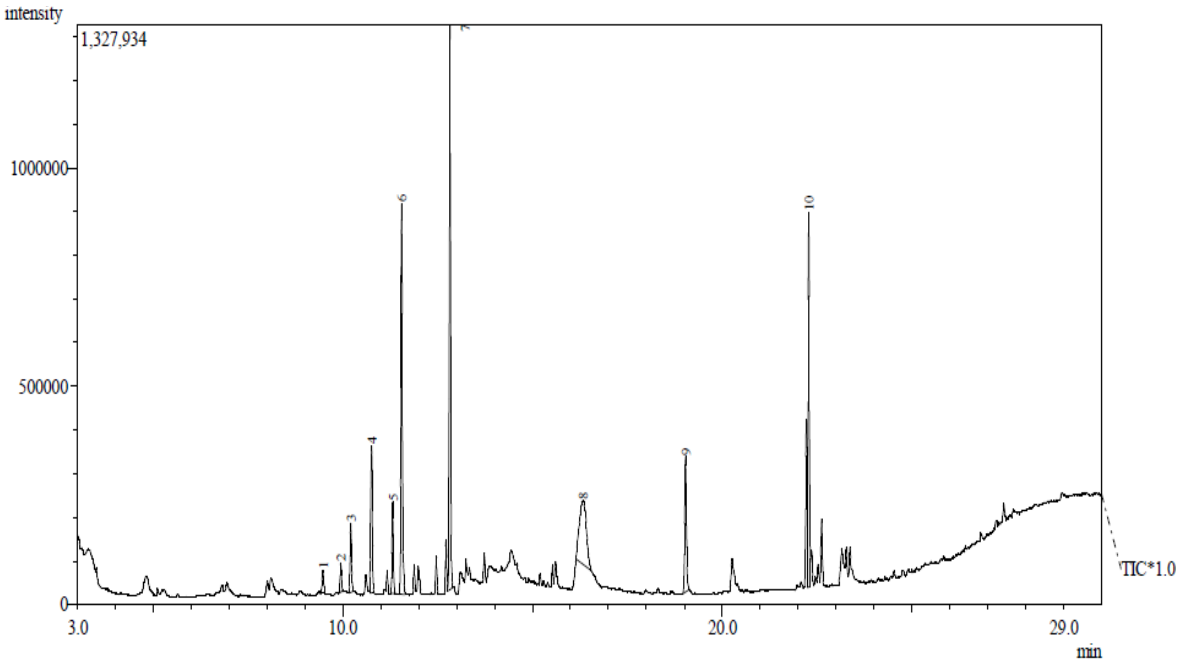


Figure 5: Chromatogram and corresponding mass spectra of *AS* extract showing the peaks of the compounds

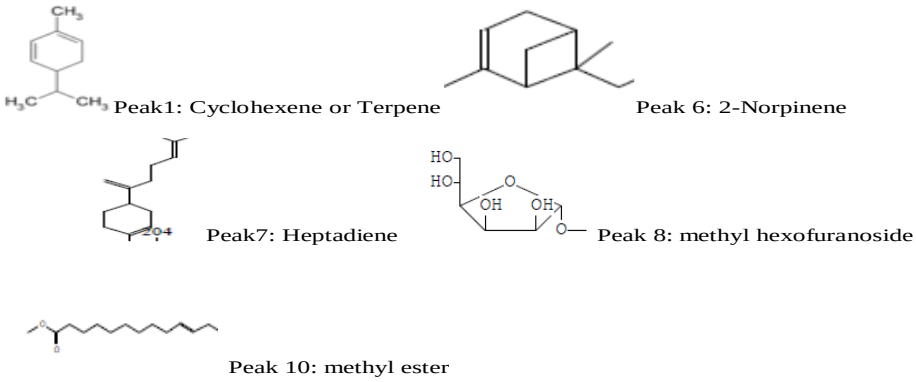


Figure 6: The structures of the compounds (peaks 1,6-8,10) present in *AS*

Table 5: The chemical compounds identified in the ethanol distillate of *Acacia Senegalensis (AS)* leaf extract by GC-MS analysis

Peaks	Extract	Compounds Name	Molecular Formula	Molecular Weight g/mol
1		Cyclohexene or 3-methyl-6-(1-methylethylidene)-	$C_{10}H_{16}$	136
2		6-Octen-1-ol, 3,7-dimethyl-, acetate	$C_{12}H_{22}O_2$	198
3	*Acacia Senegalensis (AS)*	2,6-Octadien-1-ol, 3,7-dimethyl-, acetate,	$C_{12}H_{20}O_2$	196
4		Cyclohexane, 1-ethenyl-1-methyl-2	$C_{15}H_{24}$	204
5		Bicyclo 4,11,11-trimethyl-8-methylene-, [	$C_{15}H_{24}$	204
6		Bicyclo[3.1.1]hept-2-ene, 2, 2-Norpinene	$C_{15}H_{24}$	204
7		Cyclohexene, 1,5-Heptadiene,	$C_{15}H_{24}$	204
8		alpha-d-annofuranoside, methyl	$C_7H_{14}O_6$	194
9		Hexadecanoic acid, methyl ester	$C_{17}H_{34}O_2$	270
10		11-Octadecenoic acid, methyl ester	$C_{19}H_{36}O_2$	296

3.4 Effect of *Acacia Senegalensis (AS)* leaf *extract* on mild steel

Weight loss measurements were performed on mild steel immersed in 0.5 M HCl solution with and without (*AS*) extract for 18 days. The results obtained in the absence and the presence of the inhibitor at various concentrations are presented in **Figure 7**. The inhibition efficiency increases with the increase in inhibitor concentration, which could be due to the increase in the mass and charge transfer to the mild steel surface, leading to the adsorption of inhibitor molecules and reduction in the metal dissolution, as shown in the plant characterizations by both FT-IR and GC-MS spectroscopies. Further increase in the inhibitor concentration causes little or negligible change, and the highest inhibition efficiency occurred at the optimum concentration of the inhibitor (15 g/L). Owing to the acidity of the

corrosive medium, the extract, which contains the phytochemical constituents, functional groups from both the FT-IR and GC-MS, respectively, could not remain in the solution in its free base state and may exist as neutral species or in its cationic form, which were presented in **Tables 4 and 5**, respectively. This assertion also agrees with the findings of the previous studies (Salghi *et al*, 2017; Sirajo *et al*, 2025)

The high inhibition efficiency recorded was possibly because Cl^{-1} was hydrated in HCl, and this can be poorly adsorbed onto the metal surface, leaving more active sites for the adsorption of the inhibitor – neutral species, and thus inhibition efficiency increased with an increase in concentrations of the inhibitor in HCl medium. Hence, it can be concluded that while adding the inhibitor to HCl solution the anions like COOH, OH present in the inhibitor solution, and the unshared pair of electrons present on the various hetero atoms present in the functional groups like Br=O, O–H, O–H, got adsorbed on the mild steel. These observations also confirm the works of (Suleiman *et al*, 2020; Aliyu *et al*, 2022; Lrhoul *et al*, 2023).

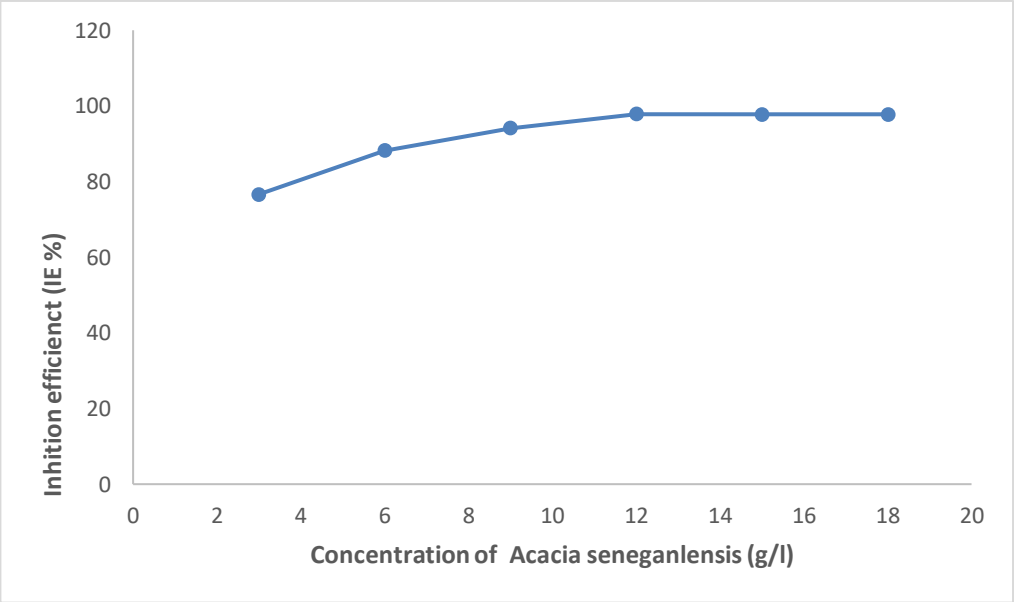


Figure 7: Variation of inhibition efficiency (% IE) with inhibitor concentration at 303 K

3.5 Effect of Temperature on Inhibition Efficiency

The temperature effect on the inhibition efficiency investigated on mild steel at a range of 30-70°C is shown in **Figure 8**. The inhibition efficiency decreases with an increase in temperature. At higher temperatures, the hydrogen evolution increases on the metal surface and leads to desorption of the adsorbed inhibitor film from the metal surface, as noted. It could also be attributed to an increase in the rates of ionization and diffusion of active species in the corrosion process. These phenomena also confirm to the previous findings of (Ansari *et al*, 2015; Chaubey *et al*, 2017).

3.5 Surface morphological analyses

The morphology of mild steel samples as received, without and with optimum concentrations of *Acacia Senegalensis (AS)* leaf in hydrochloric acid solutions were presented in **Figures 9a – 9c** respectively. **Figures 9a** presented the SEM/EDS of mild steel as-received sample in a polished state, **Figures 9b** is the polished sample in the presence of 0.5 M HCl solution without extract.

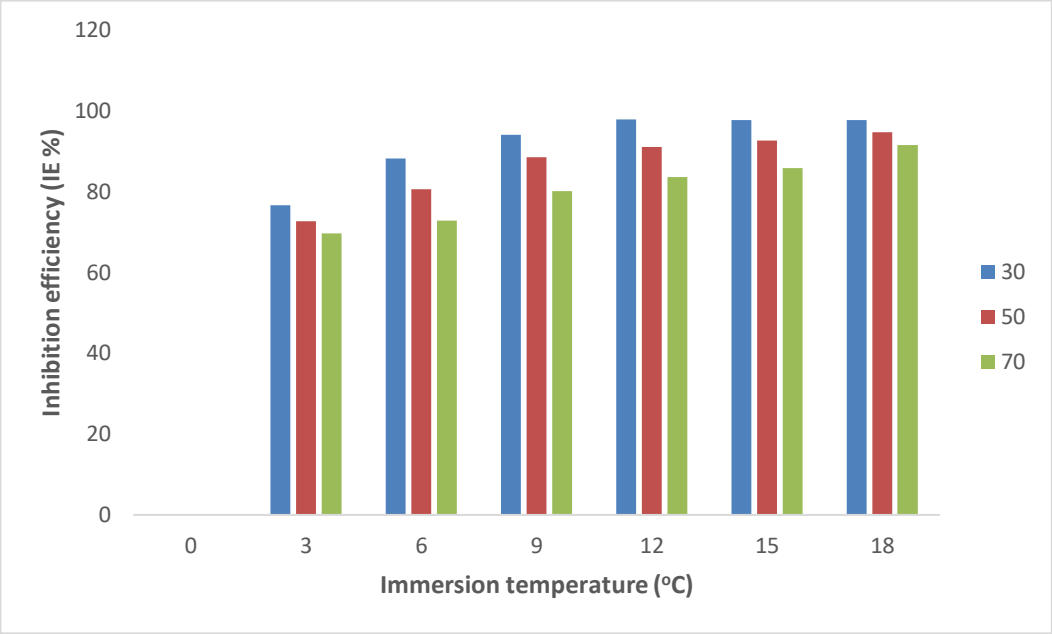
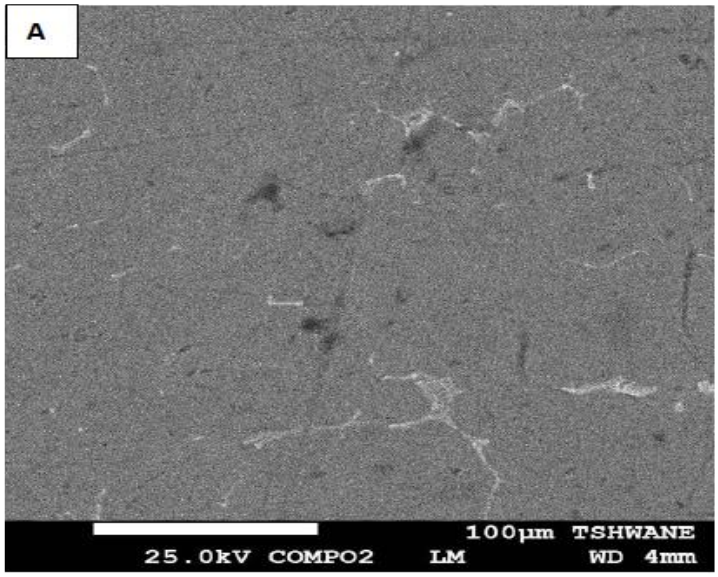
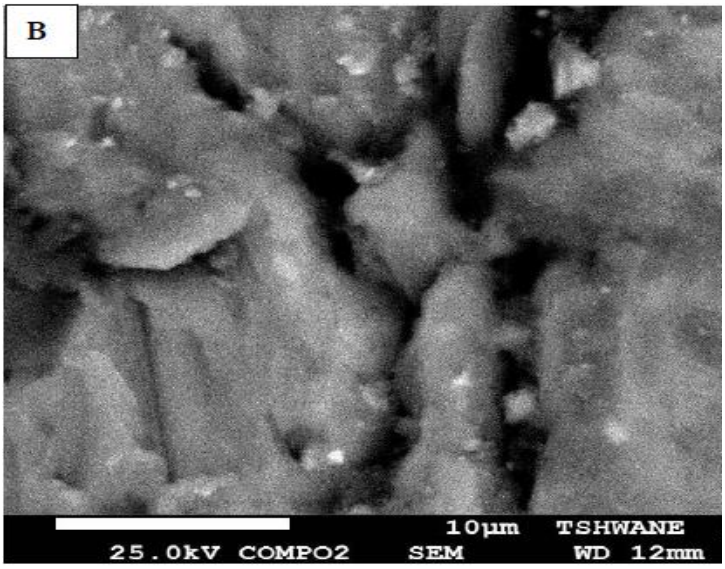


Figure 8: Variation of inhibition efficiency (% IE) with concentration of inhibitor at different temperatures (30-70°C)

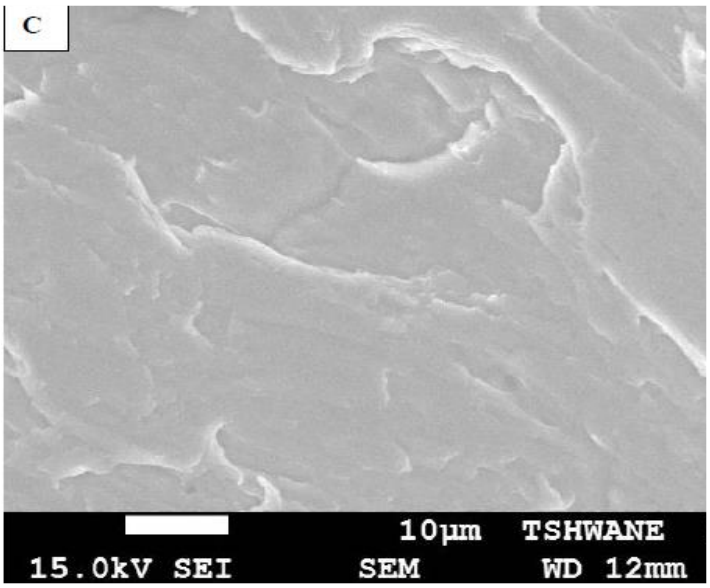
Finally, **Figures 9c** represented the polished sample in 0.5 M HCl solution with the optimum concentration of *AS* extract. The surfaceof the coupon in **Figures 9a** was completely smooth, without any indentations except the polished surface that was revealed. In **Figures 9b**, the pits initiation commenced which is often linked to the presence of local defects at the metal surface such as flaws in the oxide or segregation of alloying elements, presence of aggressive anions such as chlorides in the environment. Pit initiation occurs on the alloy surface passivated by an oxide film due to the damage caused by passivation of the electrolyte resulting in anodic reaction on the metal surface while the unexposed protective surrounding becomes the cathode leading to localized corrosion (Al-Otaibi *et al*, 2014). As the time progresses, growth of pits increases from the SEM evaluation, it is clear that the corrosion resistance decreases which confirmed that weight loss results obtained is in agreement with each other and similar to the findings (Okafor *et al*, 2007); Rocha, *et al*, 2017). In **Figures 9c**, the coupon exposed to corrodent in the presence of an optimum concentration of 15 g/L was less rough, and most of the elements present were enhanced in the presence of the extract. Hence, the propagation of pits in the material was impeded by the adsorption of the inhibitor on the mild steel surface. Comparing the morphologies of **9b and 9c**, the mild steel lost some of its component elements to corrosion in a 0.5 M HCl solution without extract. The difference could be an indication of oxygen-bearing active components in the extract adsorbing onto the metal surface, and seems to be a confirmation to the earlier assertion that the extract's active components compete for direct adsorption on mild steel surface (Suleiman *et al*, 2019; Tremocoldi *et al*, 2018). The adsorption of components of the *AS* leaves extract could be attributed to their functional groups obtained from phytoconstituents, FT-IR, and GC-MS results. Some researchers suggested that the inhibitory process acted via the synergistic intermolecular effect of the various components of the natural extract (Suleiman *et al*, 2019; Lrhoul *et al*, 2023; Zriouel *et al*, 2026). The *EH* can be considered to be a good and effective corrosion inhibitor of material in acid, similar to the previous findings (Abd Elkader *et al*, 2022; Salazar-López *et al*, 2020).



Figures 9a: SEM/EDS of as-received mild steel coupon



Figures 9b: SEM/EDS of mild steel in 0. 5 M HCl in the absence of *AS* extract



Figures 9c: SEM/EDS of mild steel at the optimum of 15 g/L of *AS* extract

Conclusions

From the research carried out, the following conclusion can be drawn:

1. *Acacia Senegalensis (AS)* leaf extract acted as an efficient anti-corrosive agent for mild steel in 0.5 M HCl solution. At the optimal concentration of 12 g/L, it can increase the lifespan of mild steel by 97.80%, and this can be utilized in both the oil and gas industries.
2. The gravimetric weight loss technique showed the inhibiting effect of *AS* with a percentage inhibition efficiency of 97.80% at 12 g/L at 30°C, but decreased to 83.50% at 12 g/L at a temperature of 70°C.
3. The phytoconstituents, FT-IR and GC-MS revealed some major constituents which formed a protective thin film layer, preventing the discharge of hydrogen ions (H^+) in the presence of acidic solution.
4. The SEM morphologies of the adsorbed protective films on the mild steel surface confirmed the high performance of the inhibitive effect of the active components in *Acacia Senegalensis (AS)* extract, such as C≡N, –N=C=S, C=C stretch, $C=CH_2$ mono, 1,1, $C_{12}H_{22}O_2$, $C_{19}H_{36}O_2$, and $C_7H_{14}O_6$

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