



CHARACTERIZATION OF ECO-FRIENDLY INHIBITOR BY AAS, FT-IR AND GC-MS FOR PROTECTION OF AISI 304 IN ACIDIC ENVIRONMENT

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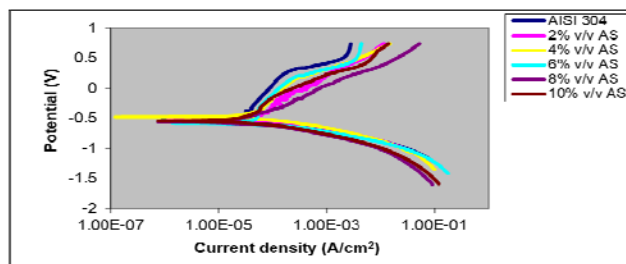
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Acacia senegalensis (AS) stems as green corrosion inhibitor for AISI 304 in 1 M hydrochloric (HCl) acid using both gravimetric and potentiodynamic polarization techniques was investigated. The stems were characterized by quantitative and qualitative analyses, Atomic absorption Spectroscopy (AAS), Fourier Transform Infrared Spectroscopy (FT-IR) and Gas Chromatography-Mass Spectrometry (GC-MS). Substrates before and after corrosion were characterized by scanning electron microscopy (SEM). The inhibitor concentration, time and temperature were varied accordingly. Corrosion rate increased with increase in temperature and decreased with increases in both inhibitor concentrations and time. Inhibition efficiency of 98.30% occurred at the value of 8% v/v and phytochemical results revealed tannins, alkaloids, saponins, flavonoids with their contents, AAS revealed 75% calcium, 16% magnesium, 3.35% manganese, FT-IR and GC-MS revealed some elements (N=C=S, C=N), chemical bonds/functional groups (NH₂) etc which were responsible for the protection of AISI 304. Inhibition efficiency obtained suggested the effectiveness of the inhibitor. The green inhibitor acted as mixed-type. The coupons without green inhibitor were rough with severe pits, while surface with green inhibitor was protected. The weight loss, polarization and the characterization were in good agreement with each other.



INTRODUCTION

The world demand for fossil fuels is still growing even though alternatives to such energy are currently being sought out globally. The consumptions of oil and natural gas account for over 60% of all global energy demands. It is obvious that the conventional method of extracting fossil fuels will not cease within the next few decades. For years, corrosion has been a major problem in various industries especially in oil and gas and has caused approximately 80-90% failures in this sector.^{1,2} The consequences of these forms

of corrosion are obvious, varying from huge material losses to unhealthy environment.³ Corrosion can be controlled and prevented by using suitable methods such as inhibitors (eco-friendly), cathodic protection, anodic protection, metallic coating, alloying, etc have been successfully developed to extend the service lifespans of these structures in such corrosive environments.⁴ Corrosion occurred in different forms in structures made of stainless steels during service in various environments. These forms of corrosion can be intergranular, pitting, sulphide stress cracking, and stress corrosion cracking.

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It has also been established that stainless steel is much more corrosion resistant compared to carbon steels in some circumstances, despite this corrosion still occur. Stainless steels corrode when in contact with some chemicals, notably acids, basics, and chloride ions. The passive layer may be attacked uniformly depending on the temperature and the concentration of corrosion agent. During the corrosion, the metal loss is distributed over the entire surface of the steel.⁴⁻⁶

However, the passive films are susceptible to breakdown in the presence of chloride ion, causing pitting corrosion. Pitting corrosion being classified as very dangerous threat and produces pit which looks small on surface but propagate deep inside the metals. This type of corrosion is considered more harmful than uniform attack.^{7,8}

Acid solutions are widely used in industries such as acid cleaning, acid descaling, acid pickling, and oil well acidizing which require the use of corrosion inhibitors in order to restrain their corrosion attack on metallic materials.⁹ Several attempts have been made to solve the corrosion problems associated with stainless steel and one of which was the use of corrosion inhibitors. However, most of these synthetic compounds show good anticorrosive action but highly toxic to both human beings and the environment.^{10,11} The toxicity has led to investigate the use of naturally occurring substances which are cost effective, readily available and renewable source of materials for a wide range of corrosion prevention formulations. Extracts of plant materials contain a wide variety of organic compounds and most of them contain hetero-atoms such as P, N, S, O. These atoms coordinate with the corroding metal atom (their ions), through their electrons. Hence protective films are formed on the metal surface and hence corrosion is prevented.¹²⁻¹⁵

In continuation of our interests on the corrosion inhibiting characteristics of plant extract, the present paper reports on the characterization of *Acacia senegalensis* (Gum Arabic stem) as eco-friendly inhibitor with variation of temperature of the medium between 35–80. Characterizations of the extract were done by phytochemical analyses, Atomic Absorption Spectrophotometer (AAS),

Fourier Transforms Infrared Spectroscopy (FT-IR) and Gas Chromatography-Mass Spectrometry (GC-MS). Scanning electron microscope (SEM) was used to analyse the surface morphology of the samples before and after the tests.

MATERIALS AND METHODS

Materials preparation

The AISI 304 coupon used for this study was obtained from a steel manufacturer company in Port Harcourt, Rivers State. The chemical composition of metal samples in weight percent is shown in Table 1.

Preparation of *Acacia senegalensis* extract

The plant stems of *Acacia senegalensis* (AS) were washed with tap water two times to remove dust particles and cut into small pieces. These were then kept in an open place to dry at room temperature (30°C). The dried plants were then grounded into fine powder using mortar and pestle. 600 g of ground sample was extracted in 1.5 L of 70 % ethanol and 30 % distilled water were used as solvent using maceration method by separating funnel. The concentrations of the extract were obtained.¹⁶

Characterizations of *Acacia Senegalensis* extract

The phytochemical constituents were determined by quantitative and qualitative methods. The analyses were carried out at the Energy Centre, University of Nigeria Nsukka.

Atomic Absorption Spectrophotometer (AAS) was carried out to determine the following metals: Mg, Zn, Fe, Mn, Cu, Pb and P. All of these were carried out using the method of analyses described by others.¹⁷ The experiment was carried out at the Industrial Chemical Laboratory, National Research Institute for Chemical Technology Zaria, Nigeria.

Table 1

Chemical composition of AISI 304

| Grade | Cr | Mn | Mo | S | Ni | N | Si | V | P | C | Fe |
|----------|-------|------|------|-------|------|------|------|------|-------|------|---------|
| AISI 304 | 18.20 | 1.54 | 0.14 | 0.008 | 10.8 | 0.05 | 0.50 | 0.09 | 0.033 | 0.07 | Balance |

Fourier transforms 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. The spectra were recorded, and the interpretations were carried out using a standard library.¹⁸

The analysis of *Acacia Senegalensis* by GC-MS was carried out and their chromatography mass spectrometry and compounds present in the extract were obtained accordingly.

Weight loss technique

The coupons used for gravimetric weight loss were prepared and modified according to the standard recommended by ASTM, (2011) G 1. A hole of about 1 mm was drilled at one end of the sample and a thread was attached for hanging in the environment in order to obtain complete immersion.²⁰⁻²³ All specimens were mechanically polished to a mirror like finish using emery papers with increasing grit sizes (100–1200), and degreased using acetone, before start the experiments. Already-weighed specimens were separately immersed in 500 millilitres (ml) of 1 M solution for 2, 4, 6, 8 and 10 days respectively. After the elapsed time, the specimens were taken out, washed, dried and reweighed. All the experiments were performed in triplicates, and average values obtained were recorded. The experiment was carried out at four different temperatures of 35, 50, 65 and 80°C. Inhibition efficiency (IE%) and the degree of surface coverage (θ) of investigated inhibitor on the corrosion of AISI 304 were calculated from equation 1.²⁴

$$IE \% = \frac{CR_a - CR_p}{CR_a} \times 100 \quad (1)$$

where, CR_a and CR_p are the corrosion rates in the absence and presence of the inhibitor.

Electrochemical measurements

The electrochemical measurements were performed in a conventional three-electrode assembly containing a cylindrical carbon steel specimen with an exposed area of 1 cm² as working electrode (WE), a platinum foil of surface area 2 cm² as counter electrode and a saturated calomel electrode (SCE) provided with a Luggin capillary as a reference electrode. They were

immersed in 1 M HCl solution until a steady-state open circuit potential (OCP) was obtained. Potentiodynamic polarization measurements were done using an Autolab potentiostat (PGSTAT30 computer controlled) with the General-Purpose Electrochemical Software (GPES) package version 4.9. The HCl solution was degassed with ultrapure nitrogen bubbling to avoid any reactions with dissolved oxygen. Tafel polarization measurements were made for a potential range of -200 mV to +200 mV with respect to OCP at a scan rate of 1 mV/s. From the electrochemical studies, corrosion potential and corrosion current were calculated. The inhibitor efficiency was calculated from equation 2.²⁵

$$IE \% = \frac{i_{corr} - i'_{corr}}{i_{corr}} \times 100\% \quad (2)$$

where i_{corr} and i'_{corr} are the corrosion current densities of AISI 304 in the absence and presence of the inhibitor, respectively.

Characterization of the coupons

The AISI 304 surface was prepared for SEM studies by taking the specimens from the optimum concentrations of the inhibitor. The AISI 304 at the optimum were washed with distilled water, dried and analysed using SEM. A Philips model XL30SFEG scanning electron microscope was used for the surface analysis.²⁶

RESULTS AND DISCUSSION

Phytoconstituents of the AS 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 2 and 3 presented the quantitative and qualitative analyses of *Acacia senegalensis* (AS) extract respectively. From the results, the constituents can be adsorbed onto the metallic surface by blocking the active corrosion site or reduce the evolution of hydrogen gas at the cathode. This may be attributed to the facts that some of these phytoconstituents contain heteroatom such as O, N, S, P, and both aromatic and functional groups. This agrees with earlier research reported.³

Table 2

Quantitative analysis of *Acacia senegalensis* (AS) extract

| S/No | Stem | Alkaloids (%) | Tannins (mg/100g) | Saponins (%) | Flavonoids (%) | Glycosides (mg/100g) | Volatile oil (%) |
|------|------|---------------|-------------------|--------------|----------------|----------------------|------------------|
| 1 | AS | 12.34 | 1423 | 7.23 | 8.11 | 912 | 3.63 |

Table 3

Qualitative analysis of *Acacia senegalensis* (AS) extract

| S/No | Stem | Alkaloids | Tannins | Saponins | Flavonoids | Glycosides | Volatile oil |
|------|------|-----------|---------|----------|------------|------------|--------------|
| 1 | AS | ++ | ++ | ++ | ++ | ++ | ++ |

Table 4

Chemical compositions of (AS) extract (Metallic cations) from AAS Analysis

| Name of extract | Ca | Mg | Cr | Co | Mn | Pb | Cu | Zn |
|---------------------------------|----|----|------|------|------|------|------|------|
| <i>Acacia senegalensis</i> (AS) | 75 | 16 | 0.98 | 0.43 | 3.55 | 1.54 | 0.12 | 2.33 |

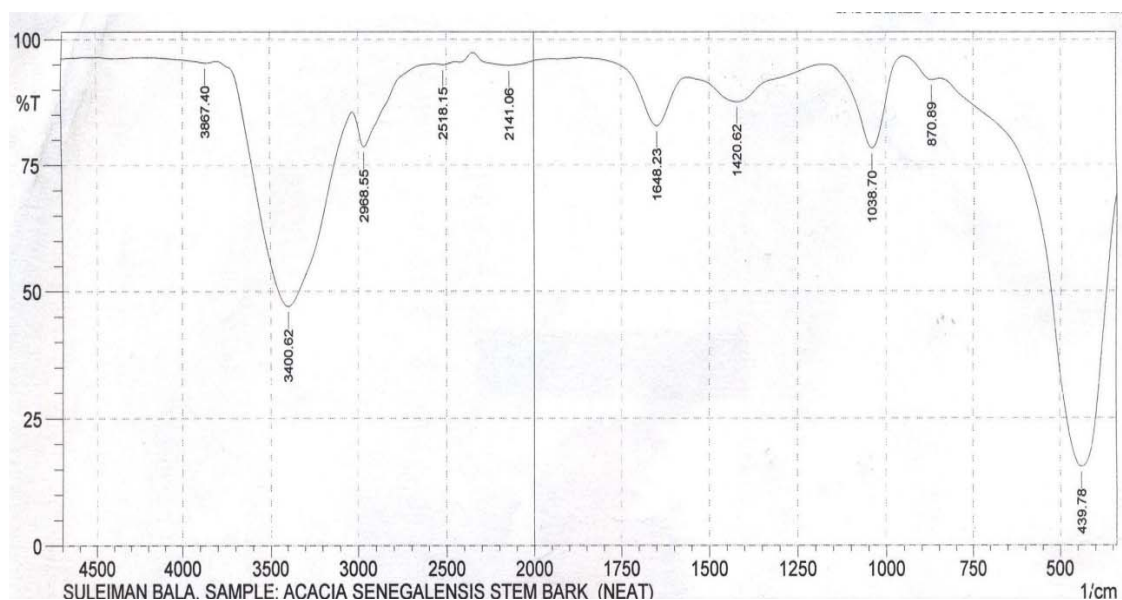


Fig. 1 – IR absorption spectrum of AS bark extract.

Metallic elements in the extract-using AAS

Table 4 presented metallic elements present in the *Acacia senegalensis* (AS) extract subjected to Atomic Absorption Spectrophotometer (AAS). From the results, AS extract contain calcium 75% followed by magnesium 16%, manganese and chromium while others appear to be minors. These metallic elements were adsorbed during the corrosion process onto surface which also acts as physical barrier to restrict the diffusion of ions to and from the system. The metallic elements prevent the samples from participating in further anodic and cathodic reactions hence, resulting in lowering corrosion rates.²⁷

Fourier Transforms Infrared (FT-IR) Spectroscopy results

Figures 1 and 2 shows the IR absorption spectra and their functional groups. The prominent peaks obtained from the FT-IR spectroscopy for the *Acacia senegalensis* extract were presented in tables 5 and 6, these also confirm the previous works.^{18,28} The inhibitor showed an effective anticorrosion potential and the results clearly indicated that the inhibition mechanism involved blockage of the AISI 304 by inhibitor molecules via adsorption. In general, the phenomenon of adsorption was influenced by the nature and surface charge of the metal, by the type of aggressive electrolyte and by the chemical structure of inhibitors.²⁸

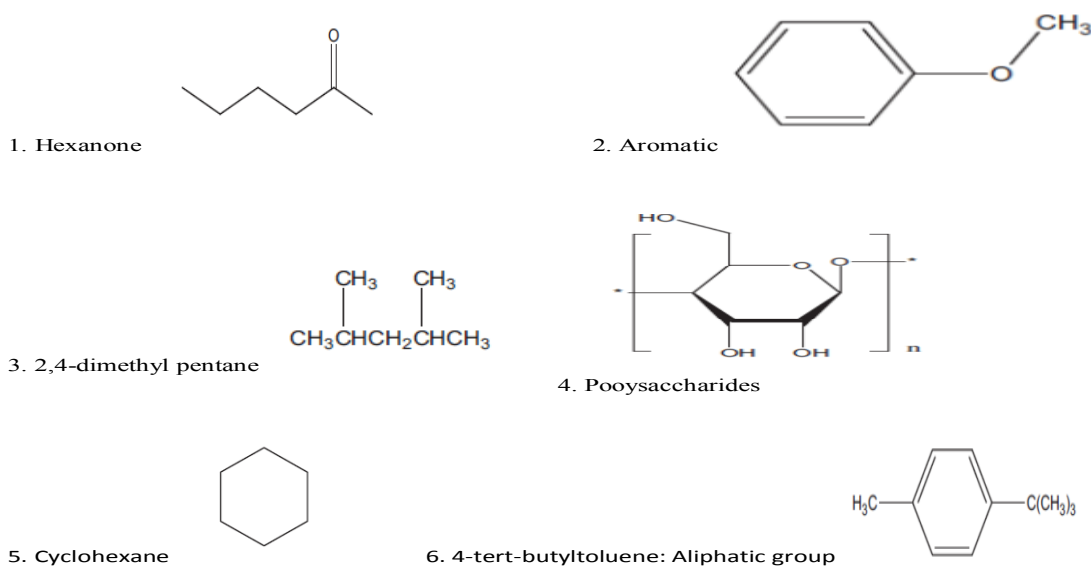
Fig. 2 – Chemical bonds/Functional groups of IR Absorption Spectrum of *AS* extract.

Table 5

Peaks and intensity for *AS* extract from reflectance FT-IR spectroscopy

| S/No | Peak | Intensity | Corr. Intensity | Base (H) | Base (L) | Area | Corr. Area |
|------|---------|-----------|-----------------|----------|----------|---------|------------|
| 1 | 439.78 | 15.454 | 58.329 | 846.78 | 339.48 | 133.023 | 83.628 |
| 2 | 870.89 | 91.994 | 1.287 | 949.01 | 846.78 | 2.776 | 0.236 |
| 3 | 1038.7 | 78.329 | 17.732 | 1178.55 | 949.01 | 11.683 | 7.484 |
| 4 | 1420.62 | 87.551 | 5.843 | 1560.46 | 1178.55 | 15.024 | 4.29 |
| 5 | 1648.23 | 82.784 | 10.783 | 1866.19 | 1560.46 | 11.901 | 4.226 |
| 6 | 2141.06 | 94.861 | 1.869 | 2347.45 | 1952.99 | 7.944 | 2.297 |
| 7 | 2518.15 | 94.97 | 0.344 | 2568.3 | 244.82 | 2.63 | 0.097 |
| 8 | 2968.55 | 78.611 | 8.252 | 3034.13 | 2568.3 | 24.457 | 3.592 |
| 9 | 3400.62 | 47.027 | 43.336 | 3797.96 | 3035.09 | 131.815 | 88.477 |

Table 6

Prominent peaks obtained from reflectance FTIR spectroscopy for *AS* 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 |

Gas Chromatography-Mass Spectrometry (GC-MS) analysis

GC-MS analysis data obtained from the *Acacia senegalensis* extract compounds identified in the

ethanol distillate were presented in Tables 7 and 8. Figures 3 and 4 also presented the GC-MS spectra and the structures of the compounds identified in the *AS* extract which is also similar to the findings.^{18,29}

Both the Figures revealed the presence of Cyclohexene, 3, 7 dimethyl, 1-ethenyl-1-methyl-2, methyl ester and other phenolic compounds. 2, 2-Norpinene has R. time at 11.553-11.650, Heptadiene at 12.822-12.908, methyl hexofuranoside at 16.33-16.550 and methyl ester at 22.279-22.333. Analyzed extract of *AS* mainly consists of 2, 2-Norpinene (18.52%), Heptadiene (23.74%) followed by methyl ester (17.69%) as major constituents.³⁰ The tables revealed the functional groups which are good corrosion inhibitors as reported.³³ These extracts

contain oxygen atoms, hydroxyl, aromatic rings and hydrocarbon which are the centres of adsorption. However, adsorption involving organic molecule 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.^{3,30}

Table 7
GC-MS data of *Acacia Senegalensis* extract

| Peaks | R Time | I Time | F. Time | Area | Peak Report HC | | Height % | A/H |
|-------|--------|--------|---------|----------|----------------|---------|----------|-------|
| | | | | | Area % | Height | | |
| 1 | 9.471 | 9.425 | 9.525 | 149655 | 1.16 | 50286 | 1.16 | 2.98 |
| 2 | 9.942 | 9.900 | 10.000 | 187609 | 1.45 | 67655 | 1.56 | 2.77 |
| 3 | 10.210 | 10.158 | 10.283 | 423848 | 3.29 | 158441 | 3.66 | 2.68 |
| 4 | 10.755 | 10.708 | 10.825 | 924529 | 7.17 | 337204 | 7.79 | 2.74 |
| 5 | 11.313 | 11.258 | 11.375 | 550400 | 4.27 | 209953 | 4.85 | 2.62 |
| 6 | 11.553 | 11.375 | 11.650 | 2388362 | 18.52 | 893753 | 20.65 | 2.67 |
| 7 | 12.822 | 12.775 | 12.908 | 3062007 | 23.74 | 1293754 | 29.90 | 2.37 |
| 8 | 16.337 | 16.150 | 16.550 | 1902646 | 14.74 | 146573 | 3.39 | 12.98 |
| 9 | 19.034 | 18.967 | 19.125 | 1027047 | 7.96 | 310804 | 7.18 | 3.30 |
| 10 | 22.279 | 22.242 | 22.333 | 2280833 | 17.69 | 858842 | 19.85 | 2.66 |
| | | | | 12896927 | 100.00 | 4327265 | 100.00 | |

Table 8

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

| Peaks | Extract | Compounds Name | Molecular Formula | Molecular Weight g/mol |
|-------|--|---|--|------------------------|
| 1 | <i>Acacia Senegalensis</i> (<i>AS</i>) | 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 | | 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 4,1,1,1-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 ₇ H 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 |

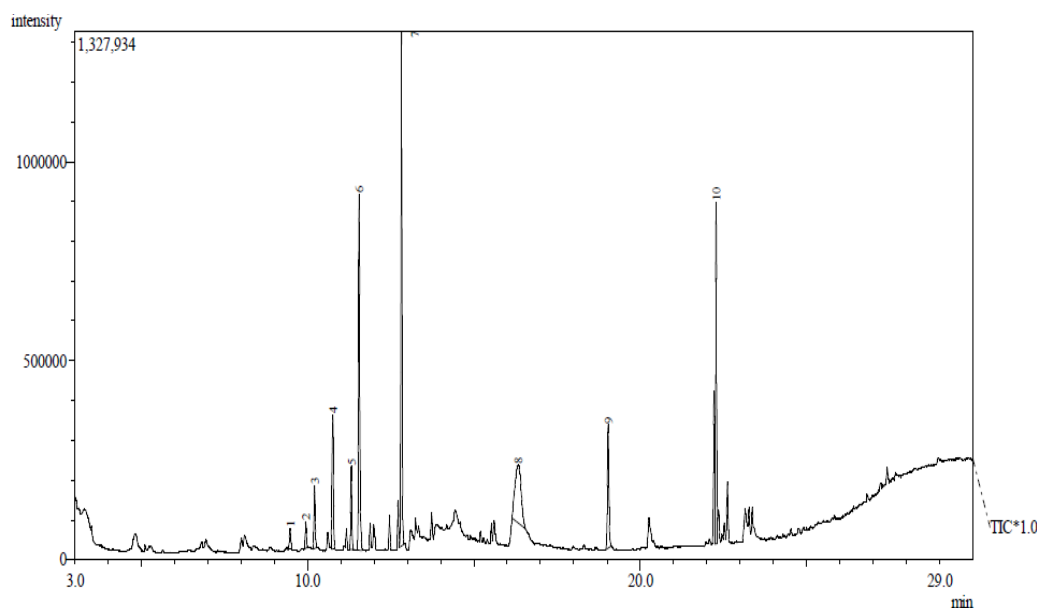


Fig. 3 – Chromatogram and corresponding mass spectra of *AS* extract showing the peaks of the compounds.

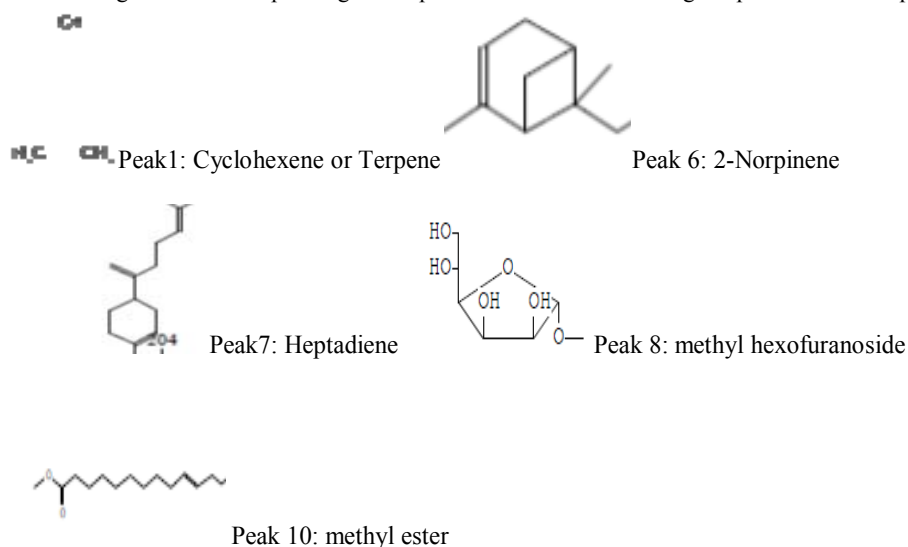


Fig. 4 – The structures of the compounds (peaks 1,6-8,10) present in *AS*.

Effect of *AS* Concentrations on AISI 304

Weight loss measurements performed on AISI 304 immersed in 1 M HCl solution with and without (*AS*) extract for 10 days. The results obtained in the absence and the presence of the inhibitor at various concentrations were presented in Figure 5. The inhibition efficiency increases with the increasing inhibitor concentration, which could be due to the increases in the mass and charge transfer to the AISI 304 surface leading to the adsorption of inhibitor molecules and reduction in the metal dissolution as shown in the plant characterizations. Further increase in

the inhibitor concentration causes little or negligible change and the higher inhibition efficiency occurred at the optimum concentration of the inhibitor (8% v/v). Owing to the acidity of the corrosive medium, the extract which contains the phytochemical constituents, metals, 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 figures 1-4 and tables 2-8 respectively. This assertion also agrees with the findings of the previous studies³⁴. The high inhibition efficiency recorded was possibly due to the fact that 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 increase concentrations of the inhibitor in HCl medium. Hence, it can be concluded that while adding the inhibitor to HCl solution the anions like $-N=C=S$, $C\equiv N$, $COOH$, 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 got adsorbed on the AISI 304. These observations also confirm the works.^{3,17}

Effect of Temperature on Inhibition Efficiency

The temperatures effect on the inhibition efficiency investigated on AISI 304 at range of 35-80°C were shown in Figure 6. The inhibition

efficiency decreases with increase in temperature. At higher temperature, 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.⁶⁻⁸

Potentiodynamic polarization

The potentiodynamic polarization carried out was to determine the effect of extract of *acacia senegalensis* (AS) inhibition of AISI 304 in 1 M hydrochloric acid (HCl). Figure 7 presented the plot Tafel curves of 304 SS in HCl solution with various concentrations of inhibitor. The inhibition efficiency percent (IE%) was calculated using the equation 2. The electrochemical parameters obtained from the polarization measurements were presented in Table 9.

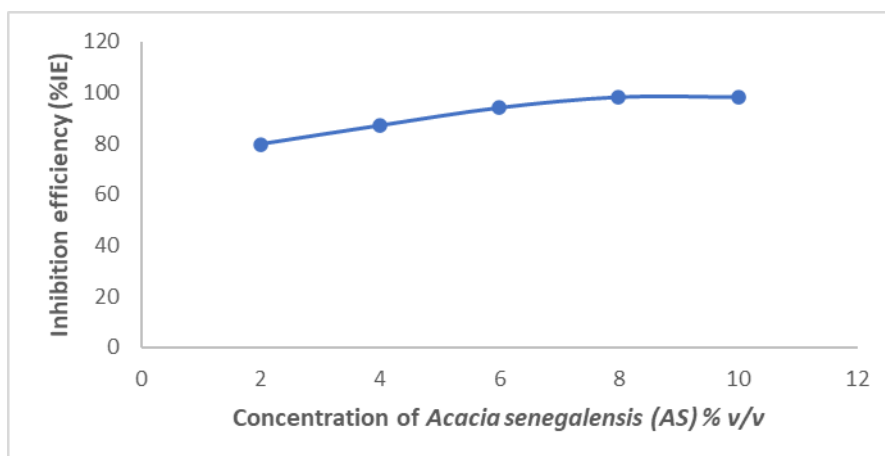


Fig. 5 – Variation of inhibition efficiency (% IE) with inhibitor concentration at 303 K.

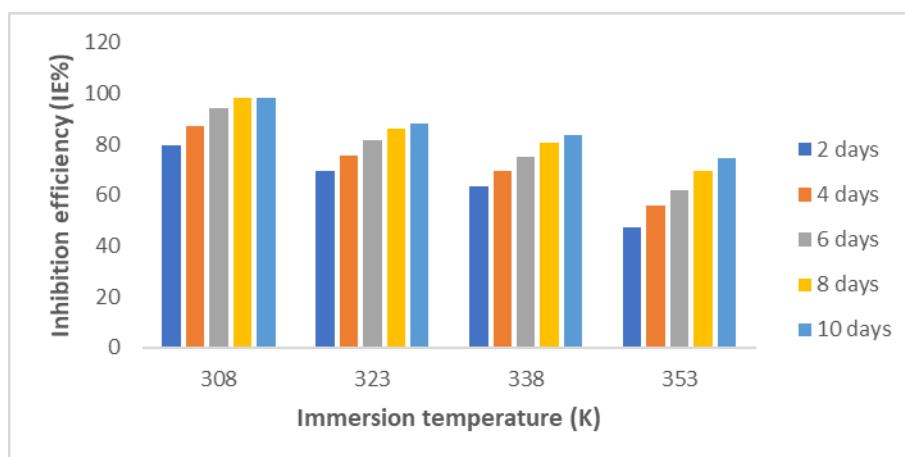
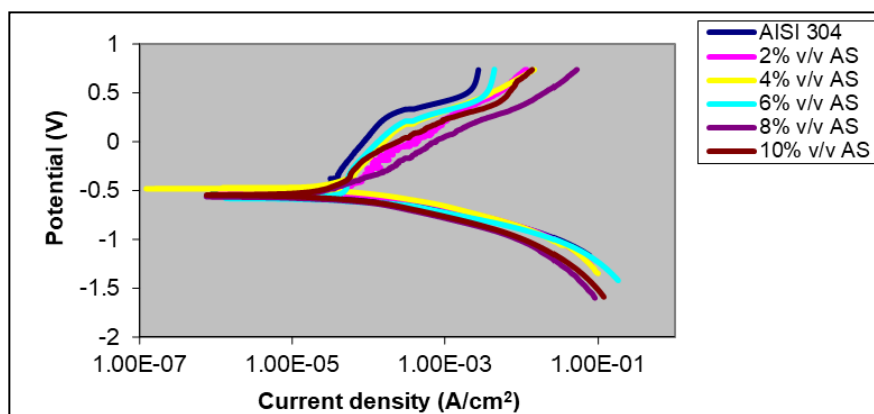


Fig. 6 – Variation of inhibition efficiency (% IE) with concentration of inhibitor at different temperatures (35-80 °C).

Table 9

Potentiodynamic polarization parameters of AISI 304 steel in 1 M HCl in the absence and presence of *AS* extract at 30°C

| Concentrations (% v/v) | a V/Dec | c V/Dec | E_{corr} V/SCE | I_{corr} , cm^2 | % IE |
|---------------------------|-----------|-----------|---------------------|---------------------|-------|
| Blank | 100 | 97 | -560 | 10.31 | - |
| 2 | 92 | 86 | -550 | 2.36 | 77.11 |
| 4 | 92 | 79 | -546 | 3.20E-01 | 86.45 |
| 6 | 83 | 73 | -530 | 6.43E-03 | 98.40 |
| 8 | 82 | 70 | -520 | 1.20E-04 | 98.13 |
| 10 | 80 | 70 | -510 | 3.48E-06 | 97.10 |

Fig. 7 – The Tafel curves for AISI 304 in 1 M HCl in absence and presence of *AS* extract concentrations at 303 K.

The polarization measurement results shown in Table 9 indicates that the effect of addition of *AS* extract on corrosion inhibition of AISI 304 in hydrochloric acid decreased current density with increase in inhibitor concentration. The inhibition of both anodic and cathodic reactions was increased with increase in *AS* extract concentration. Inhibitors indicated anodic or cathodic type when corrosion potential shifted more than 85 mV of the corrosion potential absence inhibitor¹⁵. From Table 9, E_{corr} shifted was less than 85 mV and can be classified as mixed type corrosion inhibitor. The Tafel plots show that the presence of the extract caused a decrease in both the anodic and cathodic current densities. The addition of *AS* extract to the HCl solution reduces the anodic dissolution of iron and retards the cathodic hydrogen evolution reactions. Both corrosion current density and corrosion rate were considerably reduced in the presence of the extract. The inhibitor used was found to inhibit AISI 304 in the presence of HCl by means of adsorption of ions and molecules on the metal surface. In this way a protective covering was formed around the metal surface, which denies the access of corrosive environment.¹⁸ The cathodic (β_c) and anodic Tafel slopes (β_a) did not change significantly with the addition of the *AS* extract. The irregularity of β_a and β_c proved that the *AS* extract was a mixed inhibitor modified the mechanism of anodic dissolution and cathodic

hydrogen evolution.^{22,23} The optimum concentration and percentage inhibition efficiency were obtained at 8% v/v and 98.13% respectively.

Surface morphological analyses

The morphology of AISI 304 samples as-received, without and with optimum concentrations in *Acacia senegalensis* (*AS*) hydrochloric acid solutions were presented in figure 8(a-c). Figure 8 (a-c) presented the SEM morphologies of AISI 304 where (a) is the as-received sample in a polished state, (b) is the polished sample in the presence of 1 M HCl solution without extract. Finally (c) represented the polished sample in 1 M HCl solution with the extract of *AS* at the optimum concentration. The surface of the coupon in (a) was completely smooth, without any indentations except the polished surface that was revealed. In (b), 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.³⁵ As the time progresses,

growth of pits increases from the SEM evaluation, it is clear that the corrosion resistance decreases which confirmed that both weight loss and Tafel results obtained are in agreement with each other and similar to the findings.²²⁻²⁵

In (c), the coupon exposed to corrodent in the presence of optimum concentration 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 AISI 304 surface. Comparing the morphology of the (b-c), the AISI 304 lost some of its component elements to corrosion in 1 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 active components compete for direct adsorption on AISI 304 surface. The adsorption of components of *AS* stems extract could be attributed to their functional groups obtained from phytoconstituents, AAS, FT-IR, and GC-MS results. The *AS* can be considered to be good and effective corrosion inhibitor of material in acid and similar to the previous findings.²⁷⁻³⁰

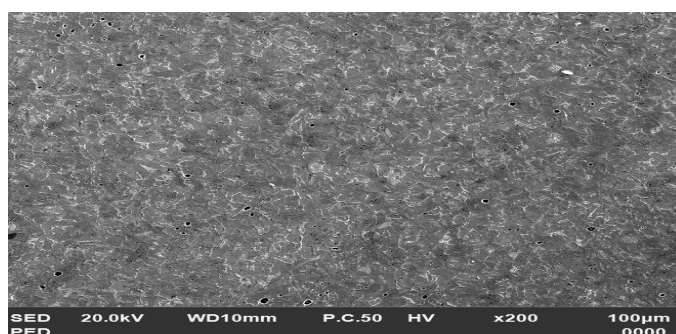


Fig. 8(a) – SEM microstructure of as-received polished AISI 304.

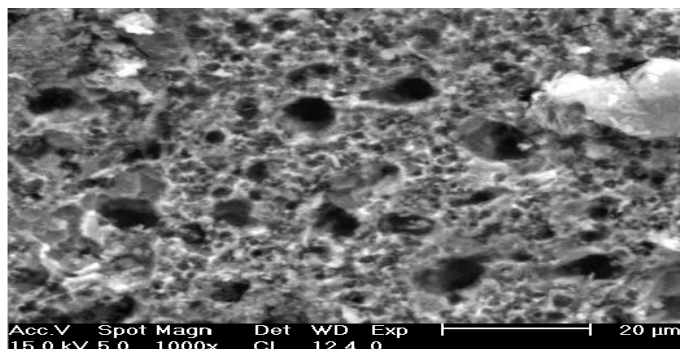


Fig. 8(b) – SEM microstructure of AISI 304 in 1 M HCl.

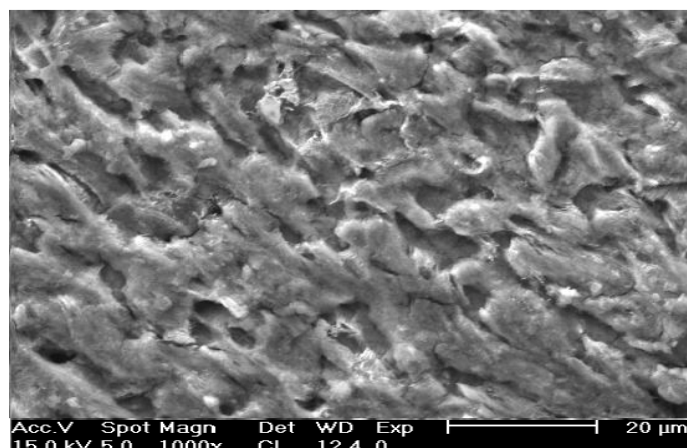


Fig. 8(c) – SEM microstructure of AISI 304 with the optimum *AS* extract in 1 M HCl.

CONCLUSIONS

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

Acacia senegalensis (AS) extract acted as an efficient anti-corrosive agent for stainless steel in 1 M HCl solution. At the optimal point of concentration, it can increase the lifespan of the material by 98.30%, and this can be utilized in industries.

The gravimetric weight loss technique showed the inhibiting effect of AS with percentage inhibition efficiency of 98.30% at 8% v/v but decrease with increase in temperature. The Potentiodynamic polarization results showed that *Acacia senegalensis* (AS) extract acted as mixed type inhibitor.

The AAS, FT-IR and GC-MS revealed some major constituents such as Cr, Mn, Ni, Cyclohexane, Azodicarbonnamide (NH₂ group), Trphenyl phosphine oxide, Ethyl methyl sulphide, Cyclohexane, 1-ethenyl-1-methyl-2, methyl hexofuranoside, 2, 2-Norpinene, which formed a protective thin film layer preventing the discharge of hydrogen ion (H⁺) ions in the presence of acidic solution.

The SEM morphology of the adsorbed protective films on the stainless-steel surface confirmed the high performance of inhibitive effect of the active components in *Acacia senegalensis* (AS) extract.

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