Inhibitory Action of *Spondias Mombin* Leaves Extracts on Corrosion of Mild Steel in 1M HCl

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ABSTRACT: Acid corrosion of steel and its associated financial and material costs are serious challenges to the chemical industry, and protecting these alloys through the use of effective corrosion inhibitors is imperative. In this study, the corrosion inhibition of mild steel in 1M HCl media using water and ethanol extracts of *Spondias mombin* leaves was investigated via weight loss technique, electrochemical impedance spectroscopy (EIS) and potentiodynamic polarization (PDP). The influence of temperature on inhibitor behaviour was also studied. Both extracts inhibited corrosion of mild steel via adsorption, following the Langmuir and Freundlich isotherms. The inhibition efficiency (IE) increased as extracts concentration was increased. After 24 and 72 hours exposure in the acid solution at 25 ℃, 500 ppm of extracts delivered maximum efficiency of (94.44 % and 76.52% for ethanol) and (51.52 % and 58,97 % for water). However, increasing temperature to 40 ℃ and 60 ℃ (after 24 hours) significantly boosted the efficiency of water extract (favoring inhibition via combined physical and chemical adsorption) but depreciated the performance of ethanol extract. The extracts provide good protection to mild steel in acidic environment and are therefore recommended as green alternatives to existing toxic ones.

KEYWORDS: Mild steel; Corrosion inhibition; Green product; Spondias mombin; Extracts

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I. INTRODUCTION

The financial and material cost of corrosion attack on industrial parts and machineries over the operating lifespan of any industry cannot be overemphasized. The effects on the environment is also humongous and worrisome. The estimated annual corrosion cost in industrial systems and on the environment in developed countries of the world is between 3 – 4% of their gross domestic product (GDP) and thus, the need for effective corrosion inhibition cannot be overemphasized (Alrefaee *et al*, 2020; Marzorati *et al*, 2019). This is however, massive in developing and poorer nations of the world. Carbon steel constitute the most abundantly used alloy for fabricating major equipment in the chemical process industry due to its natural abundance, cheapness and strength (Dohare *et al*, 2017; Palaniappan *et al*, 2020). Periodic descaling with dilute acid (also called acid-cleaning) is an inevitable industrial practice that aims to restore the material integrity of the steel-based equipment which would have developed enormous scales over prolong period of operation. Since steel cannot naturally form a protective passive layer during corrosion, the acid solution continues to attack the underlying alloy during the descaling process. Similarly, identifying a highly effective solvent for extracting the plants is also imperative as long as the solvent is environmentally safe.

Most chemical process industries inadvertently add toxic chemicals to acid-cleaning solutions in order to protect steel equipment during operations (Alrefaee *et al*, 2020; Ishak *et al*, 2019; Muthukumarasamy *et al*, 2020). When such solutions are discharged into the environment, they impact negatively on the biotic and abiotic population. Similarly, exposure of carbon steel and its alloys to the atmosphere or aqueous solution usually results in the development of compact, strongly adherent and continuous film (Alrefaee *et al*, 2021; Belakhdar *et al*, 2020; Berrissoul *et al*, 2020). This film formed is usually responsible for the corrosion resistance of carbon steel in most environments (Chen *et al*, 2020; Asfia *et al*, 2020) It has become imperative for the chemical industry to develop effective and efficient corrosion inhibitors that can substitute for these toxic ones. Plant extracts are remarkable in this regard (Ahanotu *et al*, 2020, Akinbulumo *et al*, 2020). They are naturally abundant, cheap and environmentally safe. The also contain phytochemicals which offer enormous active sites for interaction with the alloy surface (Dohare *et al*, 2017). These natural polymers, polysaccharides, amino acids, and their derivatives have been extensively studied as ecologically friendly alternatives to damaging corrosion inhibitors (Alrefaee *et al*, 2020; Chaudhary and Tak, 2022).

Several researches exist on the use of plant extracts as corrosion inhibitors for mild carbon steel in acidic solutions. The extracts are evaluated as inhibitors against metallic corrosion due to their environmentally friendly behavior and excellent inhibitory efficiency (Marzorati *et al*, 2019; Ishak *et al*, 2019; Chen *et al*, 2020; Asfia *et al*, 2020; Alrefaee *et al*,

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2020; Ahanotu *et al*, 2020). These authors worked on several plant extracts as effective inhibitors in different media. The extracts imparted excellent corrosion resistance in steel, established their inhibition via the adsorption of their molecules on the steel surface forming protective layer, acted as mixed-type corrosion inhibitors by blocking both anode and cathode reaction. Adsorption mechanism agreed with the Langmuir isotherm mostly, though few others show the Temkin adsorption model. The activation energy as well as other thermodynamic parameters showed strong interaction between the inhibitor and the mild steel surface.

Naturally, plant extracts have a variety of simple to complex phytochemicals that can efficiently adsorb across metal surfaces and form protective organic films. Aqueous extracts are chosen because they generally have more sustainable qualities (Asfia *et al*, 2020; Alrefaee *et al*, 2020; Ahanotu *et al*, 2020). Thus, this work reports a study conducted to find a green, cheap and environmentally safe corrosion inhibitor for C1020 mild steel in acidic solution from *Spondias mombin* leaves. Also known as yellow mombin or hug plum; a specie of tree and flowering plant in the family *Anacardiaceae*. Previously, *Spondias mombin* extracts have been reported for corrosion inhibition of aluminium (Al) in 0.5 M H_2SO_4 (Obi-Egbedi *et al,* 2012), stainless steel in 3.5 % NaCl (Oguike and Oni, 2019), mild steel in H_2SO_4 (Sidikat *et al*, 2018) and HCl (Magu *et al*, 2017). However, these works only focused on extracts of single solvents. Following the observations of Ahanotu *et al,* (2020), we reckoned that the performance of *Spondias mombin* extracts as corrosion inhibitor could be influenced by the choice of the extracting solvent, provided the solvent is environmentally friendly. Upon this premise, we employed different techniques to investigate the effect of extracting solvents (water and ethanol) on the corrosion inhibition performance of *Spondias mombin* extract using mild steel exposed to 1 M HCl at different times and temperatures. Adsorption isotherm was also applied to study the mode of adsorption (interaction) between the inhibitor and the alloy surface at different exposure periods and temperature.

II. MATERIALS AND METHODS

Two aqueous extracts of *Spondias mombin* leaves (water and ethanol as solvents) were investigated and tested. Weight loss technique, potentiodynamic polarization (PDP), and electrochemical impedance spectroscopy (EIS) were performed. Influence of temperature on the inhibitor behavior was studied. Also, adsorption isotherm analysis based on the variations in inhibitor concentration, corrosion time and temperature were studied. These techniques were used to determine the inhibition efficiencies (IE) and deduce mechanism of action of the *Spondias mombin* extracts.

A. Materials

The materials used in the experiments were fresh samples of *Spondias mombin* leaves obtained from the campus of Edo State University Uzairue and validated by Dr. A.I. Anani of Department of Biological Science in the institution. Other materials are, dried and powdered Spondias mombin leaves, distilled water, analytical grade hydrochloric acid, and acetone.

The equipment used includes industrial blender, rotary evaporator, weighing balances, abrasive papers with 400 – 600 grit, mild steel coupons, Thermo Scientific ARL 9900 IntelliPower Series (0699) x-ray fluorescence (XRF) spectrometer with integrated x-ray diffractometer (XRD) capacity, Gamry Potentiostart/Galvanostat/ZRA Reference 600 work station and a Buchler Torramet specimen dryer.

B. Methods

1) Preparation of test solution

All chemicals and reagents used were of analytical grade and double distilled water was used for preparing solutions. The fresh *Spondias mombin* leave samples used in the experiment were thoroughly washed with distilled water. They were subsequently dried at room temperature for 14 days and then ground to power using an industrial blender. The dried extracts of the leaves obtained from both the water and ethanol extracts were used for the preparation of inhibitor test solutions. According to procedures reported by Ahanotu *et al,* 2020 and Magu *et al,* 2017, stock solutions of the *Spondias mombin* crude extract were prepared by refluxing (for 3 hours) the ground leaves using both water and ethanol (in the ratio of 1:10 (plant powder: solvent volume)). The amount of *Spondias mombin* extracted into each solvent was quantified by comparing the weight of the dried residue (after extraction) with the initial weight of powdered plant leaves employed for the extraction. Subsequently, calculated volumes of the filtrate were collected and dissolved in 1 M HCl to obtain different concentrations of 100, 200, 300, and 500 ppm.

2) Elemental composition analysis

The elemental composition of the metal electrode coupon was investigated using a Thermo Scientific (ThermoFisher Scientific Inc. Ecublens, SARL, Switzerland) ARL 9900 IntelliPower series 0699 x-ray fluorescence (XRF) spectrometer with integrated x-ray diffractometer (XRD) capacity. The instrument is equipped with a Quant AS software for total elemental analysis of up to 86 elements. It possessed a 12-point sample charger and a goniometer with the capacity to analyze specific element quantitatively and qualitatively. It has an elemental range: Boron (B) – Americium (Am), LLD (Concentration): 0.1 ppm – 100 %, resolution: $(M_n - K_a)$ – 135 eV, and sample throughput of up to 240 per 8 hours day.

3) Weight loss measurements

The mild steel was cut into weight loss coupons 0.23 cm thick (d), 3.08 cm wide (w) and 3.22 cm long (l) which gave a total surface area of 22.73 cm^2. The electrochemical measurement coupons had 1 cm^2 surface area exposed for testing after cold mounting in epoxy resins. Before the specimens were used for each experiment, they were abraded mechanically using abrasive papers with 400 – 600 grit, rinsed in distilled water and acetone and dried using a Buchler Torramet specimen dryer. Analytical reagent used was 36 wt % hydrochloric acid. This was dissolved in distilled water to prepare the corrodent (1 M HCl).

During weight loss experiments, duplicate coupons were immersed in the 1 M HCl solution without and with different doses of the different plant extracts. Samples were immersed for 24 hours and 72 hours period at 25 ℃ respectively. After each duration of immersion, the coupons were retrieved and cleaned according to ASTM G01-03 and ASTM G31-72 standard procedures. The weight loss after each immersion period was determined using Eqn. (1). Thereafter the effect of temperature was investigated, using the minimum and maximum inhibitor concentrations after 10 hours immersion at 40 ℃ and 60 ℃. The weight loss after immersion (Δw) was calculated thus:

$$\Delta W\ (\text{g}) = W_{(\text{before immersion})} - W_{(\text{after immersion})} \quad (1)$$

The corrosion inhibition efficiency (% IE) deduced from weight loss measurement was calculated using Eqn. (2) (Obot *et al*, 2019); where $\upsilon_{(\text{with inhibitor})}$ and $\upsilon_{(\text{without inhibitor})}$ represent corrosion of steel in the presence and absence of inhibitor respectively.

$$\%\,IE = 1 - \frac{\upsilon_{(\text{with inhibitor})}}{\upsilon_{(\text{without inhibitor})}} \times 100\% \quad (2)$$

4) Electrochemical studies

The electrochemical experiments involved in this work were conducted on a Gamry Potentiostart/Galvanostat/ZRA Reference 600 work station following the ASTM G3-89 (1994) and G5-94 (1994) standard procedures that utilize 150 ml as the volume of the test solutions. It uses a three-electrode system which consist of an epoxy-encapsulated mild steel (type C1020) as the working electrode, the auxiliary electrode was a graphite rod, and the reference electrode was a Ag/AgCl electrode. The electrochemical experiments were performed after monitoring the variation of open circuit potential (OCP) for an hour. The electrochemical impedance spectroscopy (EIS) measurements were performed at the frequency range of $10^5 Hz\ to\ 10^{-3} Hz$ with a $\pm 10\ mV$ amplitude signal and acquirement of 10 points/decade OCP. The signal amplitude perturbation was $\pm 10\ mV$. The potentiodynamic polarization (PDP) measurements were conducted at the potential of $\pm 0.25\ V$ versus open circuit potential (OCP) using a scan rate of $0.166\ mVS^{-1}$. The analysis of EIS data was done using Echem analyst while EC-lab software was used for PDP data analysis. The experiments were conducted in triplicate to achieve reproducibility. The use of equation given by (Fang *et al*, 2019) was employed to calculate the inhibition efficiency from EIS and PDP techniques. The inhibition efficiencies derived from the EIS and PDP measurements were calculated based on Eqns. (3) and (4); where R_{ct} is the resistance to charge transfer and i_{corr} is the corrosion current density.

$$\%\,IE_{EIS} = 1 - \frac{R_{\text{ct}(\text{without } inhibitor)}}{R_{\text{f}(\text{with } inhibitor)} + R_{\text{ct}(\text{with } inhibitor)}} \times 100\% \quad (3)$$

$$\%\,IE_{PDP} = 1 - \frac{i_{corr(with\ inhibitor)}}{i_{corr(without\ inhibitor)}} \times 100\% \quad (4)$$

Different adsorption isotherm models were adopted to investigate the thermodynamic interactions and properties of the inhibitor. From the investigated isotherm models, the activation energy, enthalpy change and Gibbs free energy parameters were evaluated.

III. RESULTS AND DISCUSSION

A. Elemental composition of metal electrode coupons

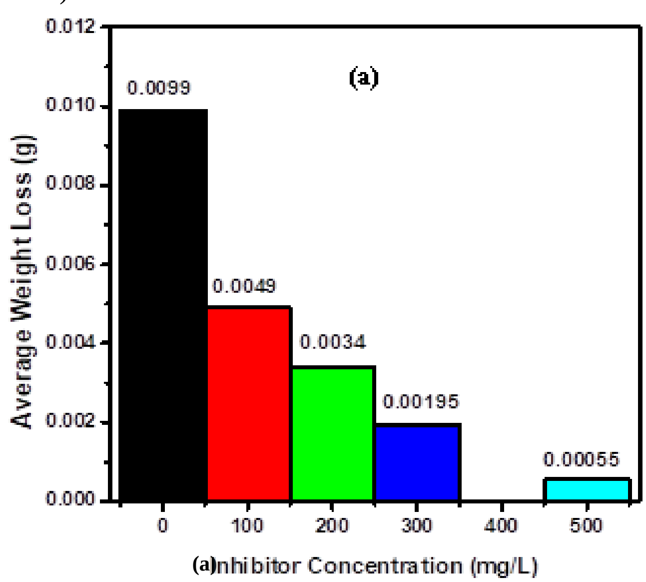
The elemental composition of the metal electrode coupons obtained using a Thermo Scientific (ThermoFisher Scientific) ARL 9900 IntelliPower series 0699 XRF spectrometer integrated with XRD capacity is presented in Table 1. The result confirmed the presence of major and trace elements which were in agreement with those obtained by (Al-Otaibi *et al*, 2014).

Table 1 Chemical composition of the mild steel

Element	C	Mn	Si	Al	P	Fe
% Comp.	0.21	0.05	0.38	0.01	0.09	99.26

B. Weight loss analysis

The results of the average weight loss investigations conducted on the mild steel coupons (C1020) after immersion for 24 hours and 72 hours in 1 M HCl solution without and with 100, 200, 300 and 500 ppm of the ethanol extract of *Spondias mombin* leaves are presented in Figure 1. Figure 1 shows a decrease in weight loss due to the presence of the ethanol extract for all concentrations and at the two different immersion times. This decrease in weight increases with increasing concentration to the optimum (500 ppm). Consequently, there is increase in the calculated inhibition efficiencies with increasing concentration of the extract with about 94 % maximum inhibition efficiency achieved at 500 ppm extract concentration at 24-hour immersion and 77 % at 72 hours immersion. The implication of this scenario is that the addition of the ethanol extract results in the release of the phytochemicals present in the plant which in turn interacts with the anodic and cathodic sites of the mild carbon steel. This further results in the site blockage and mitigation of the associated corrosion reactions. Generally, steel corrosion in acid solutions usually involves anodic oxidation of Fe to Fe^{2+} and cathodic reduction of H^+ to $H_{2(g)}$. Thus, the blocking mechanism hinders the transfer of electrons between the two sites which in turn lowers the corrosion rate (Onyeachu *et al*, 2020).



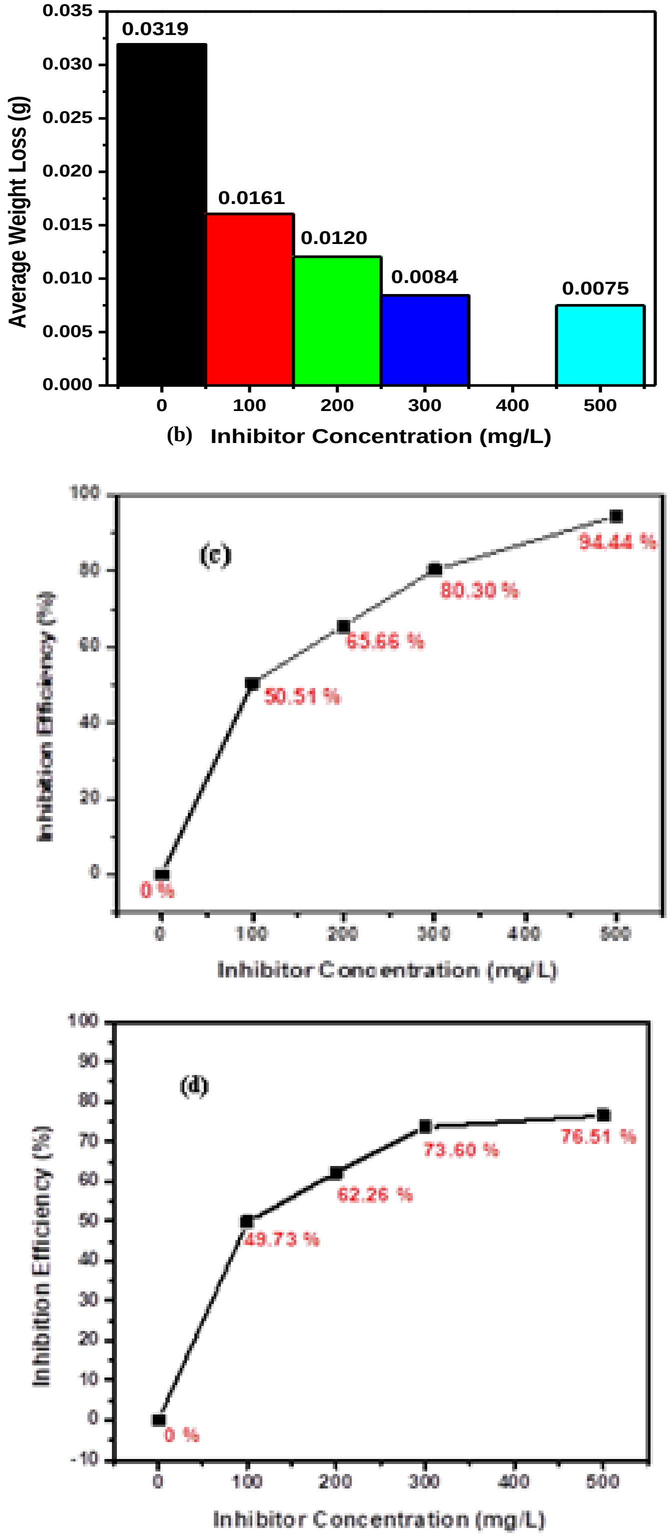
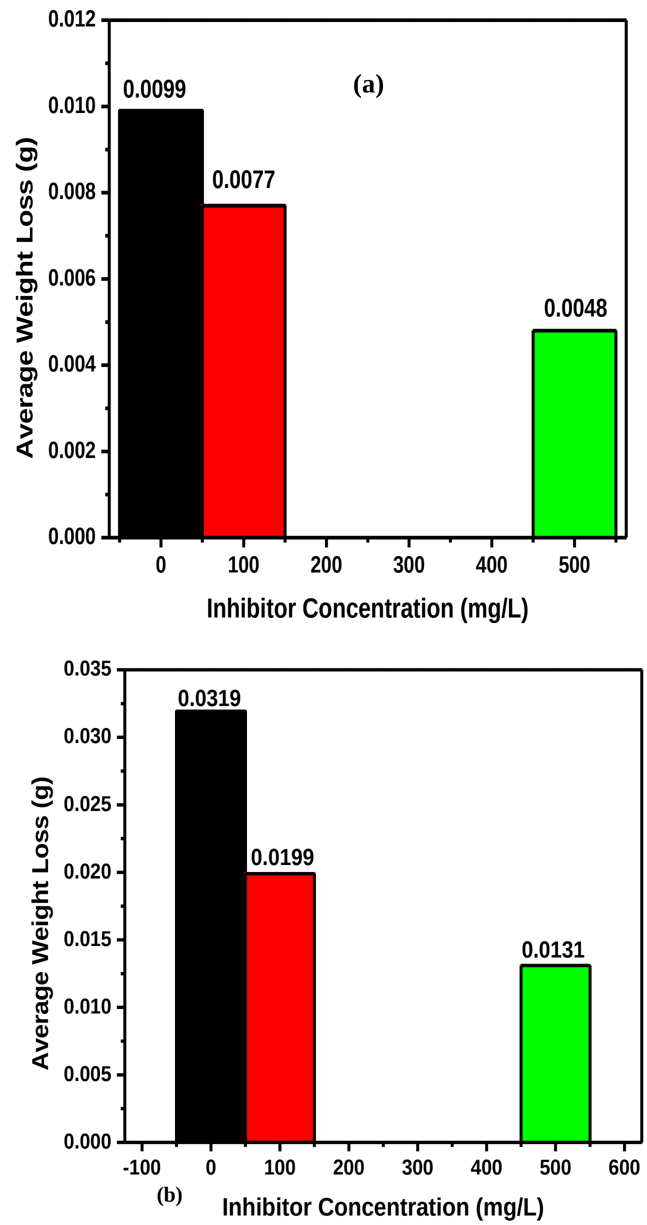
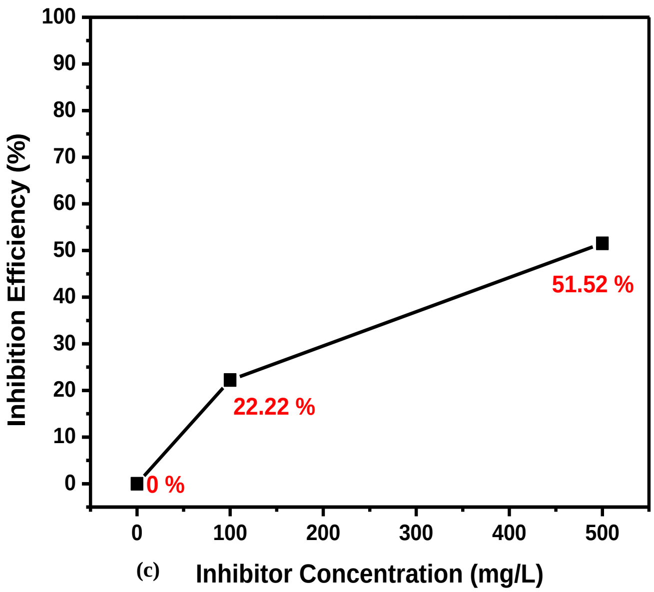


Figure1: Weight loss analysis and inhibition efficiency after (a, c) 24 hours and (b, d) 72 hours of C1020 steel in 1 M HCl containing different concentrations of ethanol extract of *Spondias mombin* leaves at 25 °C.

Figure 2 shows the weight loss results and inhibition efficiencies achieved using water extract of the *Spondias mombin* leaves at 24 hours and 72 hours with different concentrations at 25 °C. The results showed weight losses by the steel coupons in the acid solutions at the different periods. The inhibition efficiencies are observed to be lower in comparison to that achieved using the ethanol extract which implies that the ethanol, being a more volatile and organic solvent, has more capacity to extract the active phytochemicals from the plant than the distilled water (Obi-Egbedi *et al*, 2012). The more phytochemical extracted by the ethanol solvent implied that more organic molecules are available to adsorb onto the steel surface and hence, protect it from corrosion and corrosive agents. However, it was observed that the phytochemicals extracted by the distilled water appeared to be more persistent on the steel surface over time and are not easily lost due to attack by the acid species. This could be seen by the increase in efficiency to 59 % occasioned by weight loss with 500 ppm water extract concentration after 72 hours. Sidikat *et al*, (2018) also observed similar improvement in efficiency of *Spondias mombin* water extracts for steel in H_2SO_4 solution.





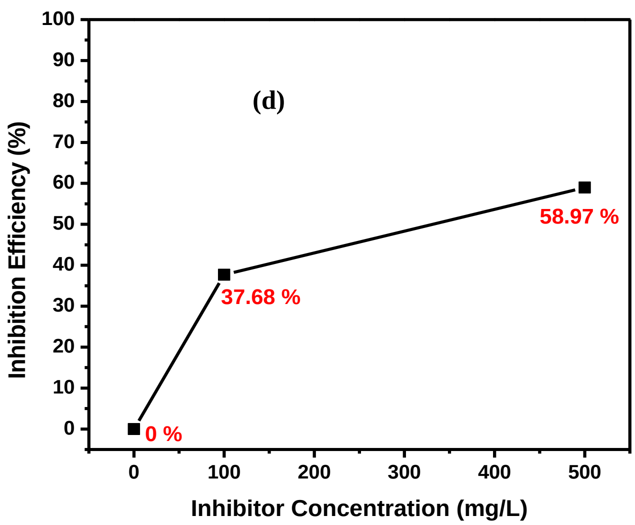
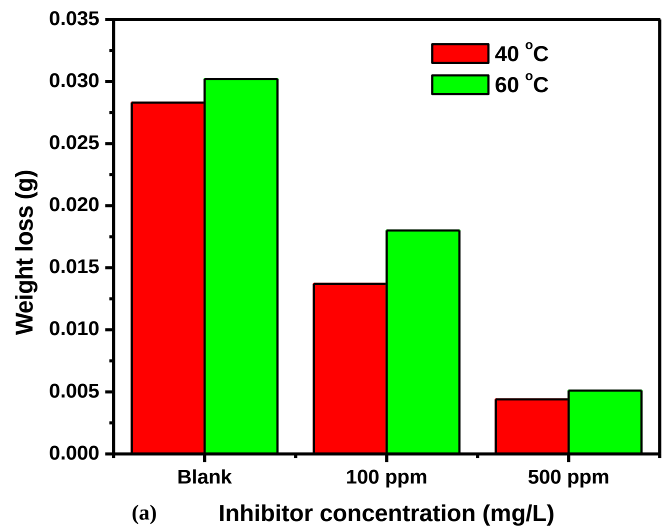
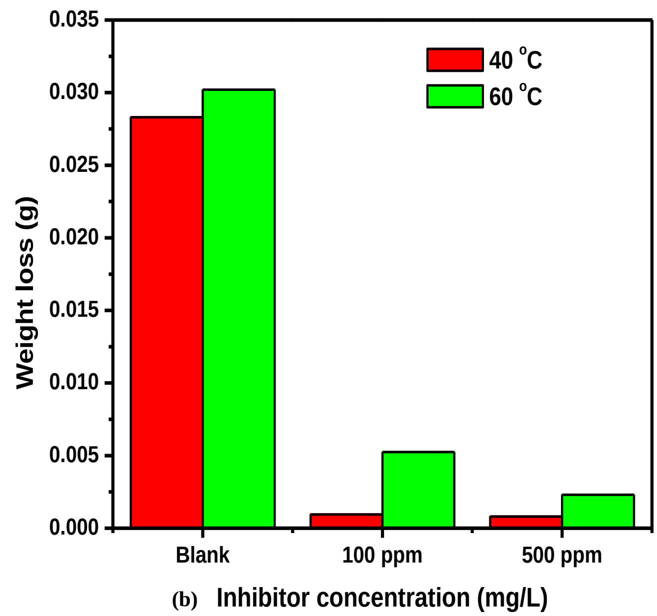


Figure 2: Weight loss and inhibition efficiency after (a, c) 24 hours and (b, d) 72 hours of C1020 steel in 1 M HCl containing different concentrations of water extract of *Spondias mombin* leaves at 25 ℃.

Figure 3 presents the temperature effect on weight loss experienced by the C1020 mild carbon steel immersed in 1 M HCl solution without and with 100 and 500 ppm ethanol and water extracts of *Spondias mombin* leaves for 24 hours. With the ethanol extract, it can be seen that increasing the temperature up to 40 ℃ and 60 ℃ respectively, significantly increases the rate of weight loss and depreciates the inhibition efficiency, compared with the values at 25 ℃ (See Figures 1 and 2). On the other hand, with water extract, the reverse occurs such that the efficiency increases significantly, as temperature increases. When temperature favors enhanced inhibition efficiency, the adsorption definitely occurs by a chemical process, while it occurs as a physical adsorption if the efficiency depreciates with temperature increase. Temperature can increase the rate of corrosion by increasing the energy and activity of the corrosion species (Alrefaee *et al*, 2020). This enables them to attack the metal surface more vigorously. Increasing temperature can also denature the organic inhibitor and make it less efficient. On the other hand, temperature could also favor enhanced efficiency if the inhibitor adsorbs by a chemical mechanism. Thus, the phytochemicals extracted by water are more stable to temperature and adsorb chemically on the steel surface. This also explains why the efficiency of water extract improved over time (up to 72 hours immersion). Contrarily, the phytochemicals extracted by ethanol are not stable at higher temperature and are, therefore, readily lost from the steel surface. This explains why the efficiency of the ethanol extract decreases as temperature increases (Alrefaee *et al*, 2020).





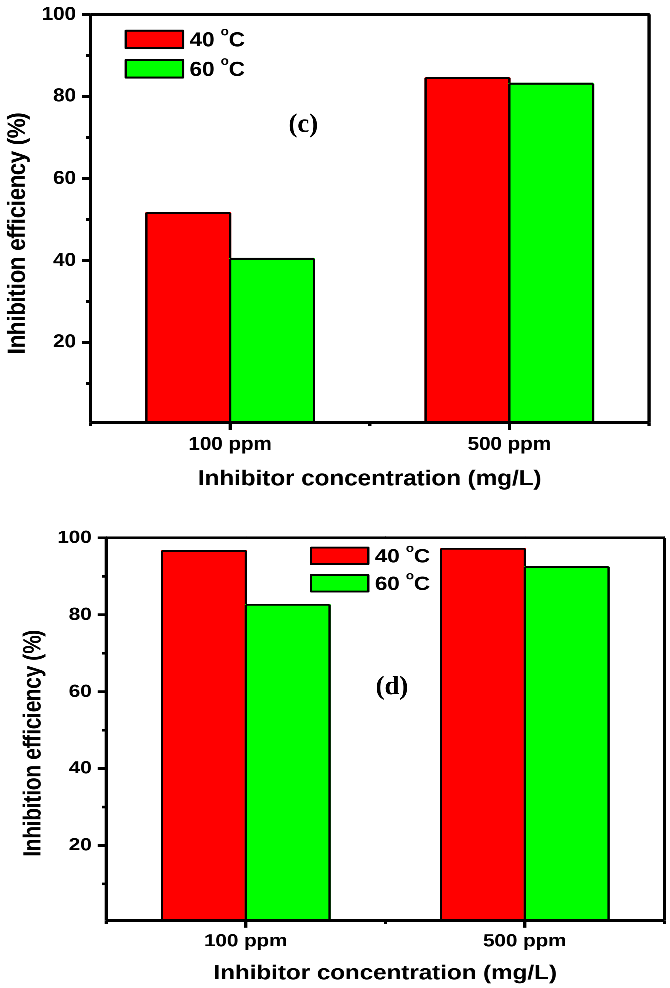


Figure 3: Temperature effects on weight loss and inhibition efficiency at 40 ℃ and 60 ℃ after 24 hours immersion of C1020 steel in 1 M HCl containing different concentrations of (a, c) ethanol extract and (b, d) water extract of *Spondias mombin* leaves

C. *Adsorption isotherm analysis*

Using three different adsorption isotherm models, the mode of interaction between the Spondias mombin leave extracts and the acid solution and mild steel coupons was analyzed. The adsorption isotherm models investigated were: Langmuir, Freundlich and Temkin isotherms. The analysis is presented in Figure 4.

The most appropriate model is usually identified by the isotherm with the highest coefficient of determination (R2). Figure 4 shows that the Freundlich isotherm model has the highest value of the coefficient of determination (R2) with a value of 0.9975. A positive Langmuir isotherm predicts that the phytochemicals adsorb only to form a monolayer of inhibitor film on the steel surface. A positive Temkin isotherm predicts the formation of a multilayer by the corrosion inhibitor (Magu *et al*, 2017; Marzorati *et al*, 2019). On the other hand, the Freundlich isotherm depicts that the inhibitor is adsorbing on a rough and uneven surface (Akinbulumo *et al*, 2020; Chaudhary and Tak, 2022). From Figure 4, it can be seen that the adsorption of the Spondias mombin extract followed the Langmuir and Freundlich isotherms. This indicates that the extract components adsorbed as single layer on very roughened steel surface during the corrosion (Sidikat *et al*, 2018; Obi-Egbedi *et al*, 2012). This mode of adsorption could easily detach.

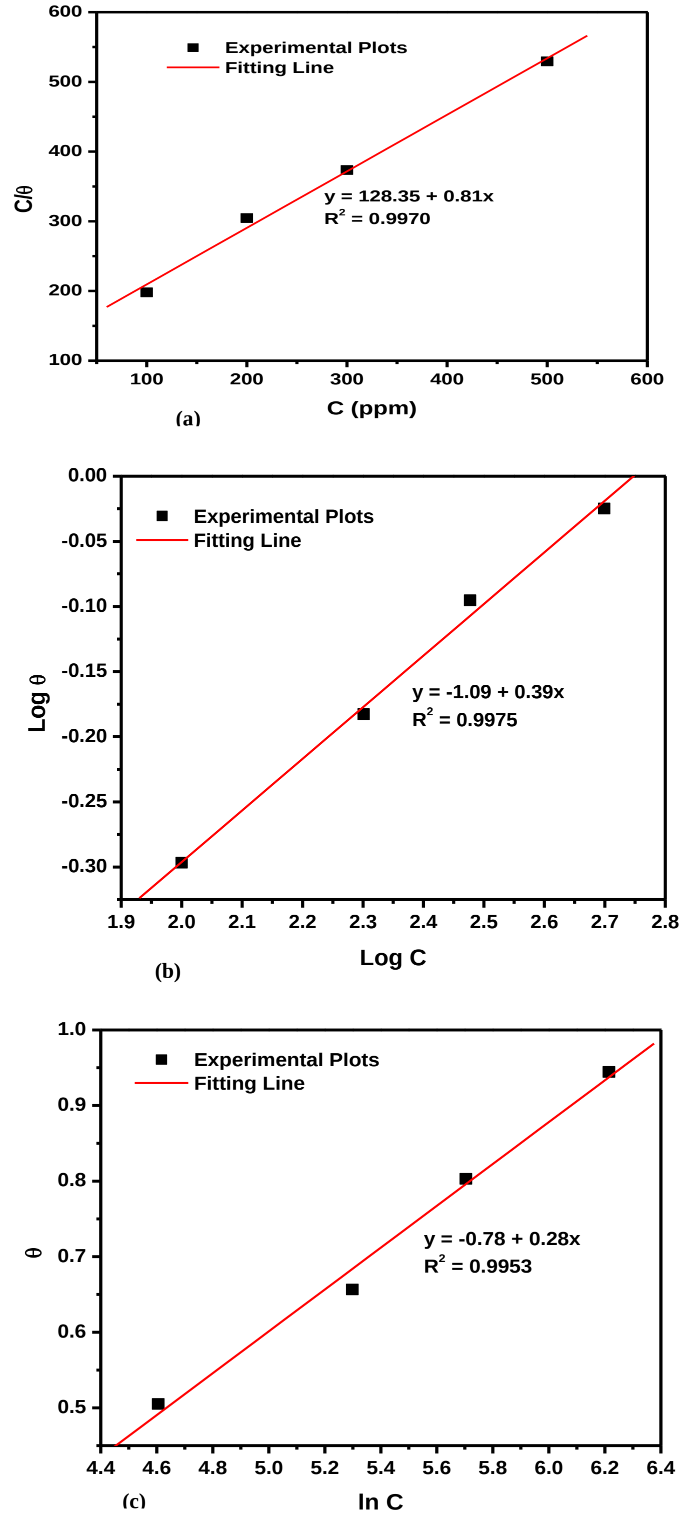


Figure 4: (a) Langmuir (b) Freundlich and (c) Temkin and isotherm plots for C1020 steel in 1 M HCl containing different concentrations of water extract of *Spondias mombin* leaves at 25 ℃.

D. Electrochemical studies

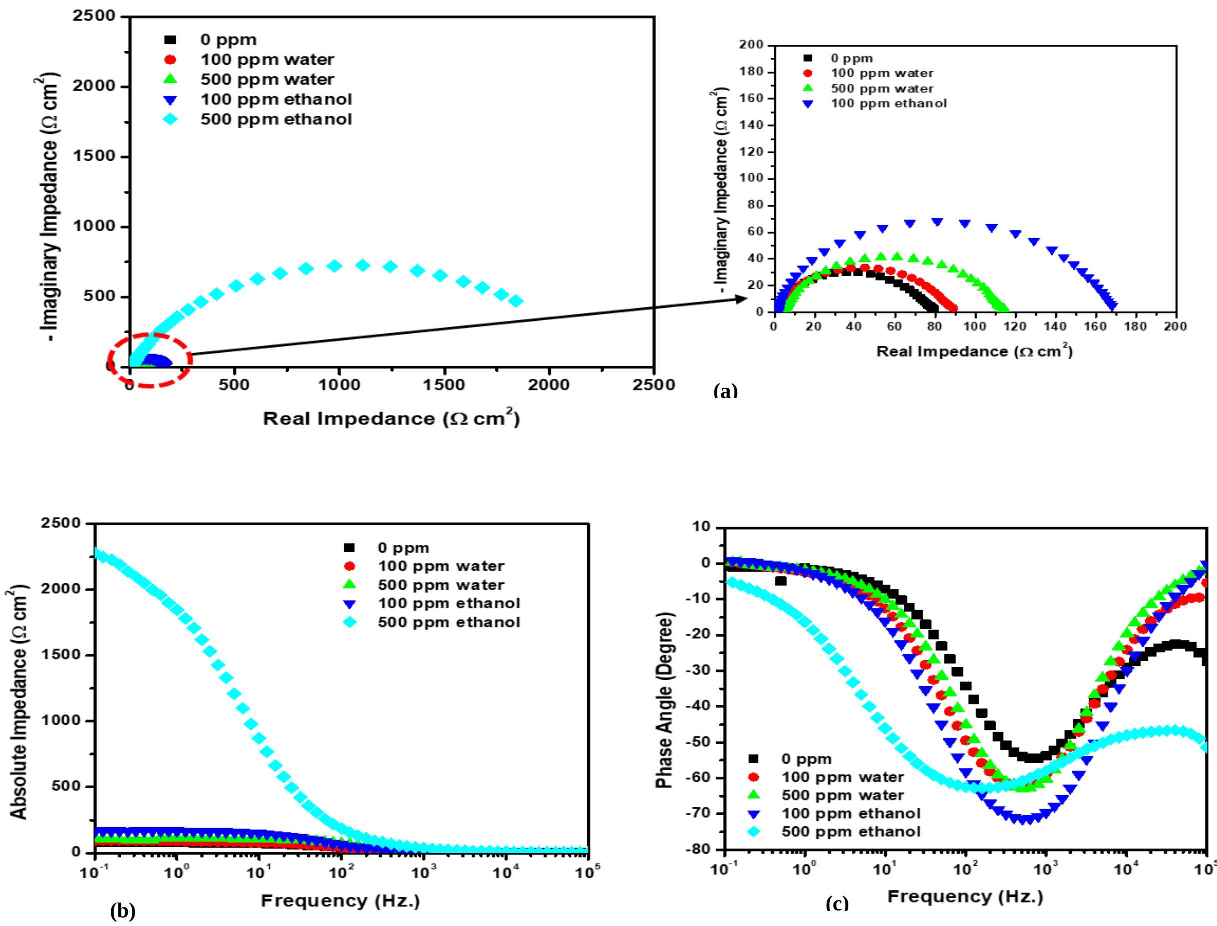
1) Electrochemical impedance spectroscopy (EIS)

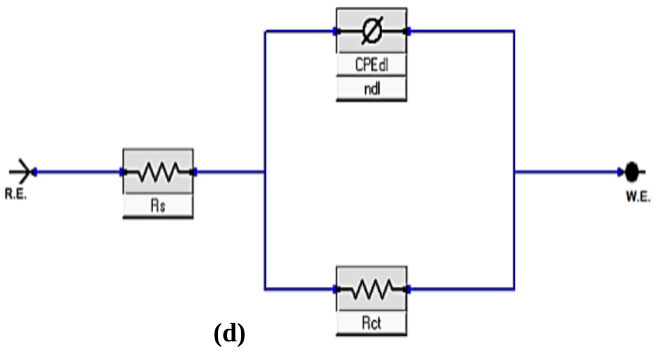
The analysis of the EIS is presented in the form of a Nyquist, absolute impedance and phase angle plots as shown in Figure 5. The addition of different concentrations of the *Spondias mombin* leave extracts caused the size of the Nyquist arcs to expand significantly in comparison to the size displayed by the uninhibited solution (blank solution). This is shown in Figure 5(a). This enlargement of the Nyquist arc size depict lower rate of corrosion and increase in corrosion resistance (Fang *et al*, 2019; Asfia *et al*, 2020; Chaudhary and Tak 2022). It can be seen that the ethanol extract shows larger sizes than the water extract, which confirm that the ethanol extract exhibits greater protection of the steel surface than the water extracts. This can be attributed to the fact the ethanol solvent extracts more of the active components of the plant extract, providing more molecules to adsorb and cover the steel for protection against the acid corrosion (Ahanotu *et al*, 2020; Akinbulumo *et al*, 2020).

The Nyquist trend is also supported by the absolute impedance plots in Figure 5(b) whereby the addition of inhibitor extracts continuously increases the value of impedance at low frequency, compared with the blank solution. Again the phase angle plots reveal higher peaks in the presence of inhibitor extract. Higher peaks depict greater corrosion resistance (Chaudhary and Tak 2022; Fang *et al*, 2019).

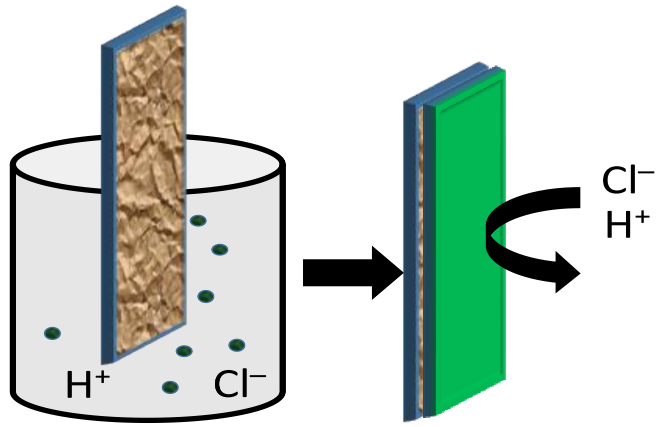
However, only single peaks are observed in the phase angle plots. This is the reason the impedance behavior of the inhibited and uninhibited steel is modelled using the one-time electrical equivalent circuit in Figure 5(d). The electrical elements in the model are defined as solution resistance(R_s), double layer admittance (Y_{dl}) roughness parameter (n) and the charge transfer resistance(R_{ct}). The value of R_{ct} is a measure of corrosion resistance. Higher R_{ct} values depict greater corrosion resistance. The single peak shows that the corrosion resistance impacted on the steel is via the inhibitor molecules modifying the electric double layer at the steel-solution interface (Chaudhary and Tak 2022; Fang *et al*, 2019; Ahanotu *et al*, 2020). This double layer modification causes the repulsion of water and chloride ions from the acid away from the steel surface, as depicted in Figure 5(e).

The extrapolated electrical elements, as depicted by Figure 5(d) are presented in Table 2. The results show that the inhibitor addition greatly lowers the amount of charges admitted into the electric double layer at the steel-solution interface. This is why lower Y_{dl} values are obtained in the presence of plant extracts than in the blank solution.





(d)



(e)

Figure 5: EIS analysis shown as (a) Nyquist (b) absolute impedance and (c) phase angle plots, along with (d) electrical equivalent circuit model and (e) schematic illustration of C1020 steel in 1M HCl containing water and ethanol extracts of *Spondias mombin* leaves at 25 ℃.

Table 2 EIS parameters obtained for corrosion of C1020 steel in 1 M HCl solution containing different concentrations of ethanol and water extract of *Spondias mombin* leaves at 25 ℃.

		CPE_{dl}				
Conc. (ppm).	R_s *(Ω cm²)*	Y_{dl} *(μFcm⁻² sⁿ⁻¹)*	α_{dl}	R_{ct} *(Ω cm²)*	*Goodness of Fit (×10⁻³)*	*% IE*
		Water extract				
0	2.21	89.52	0.89	77.12	0.47	–
100	1.83	66.54	0.85	87.31	0.73	14.60
500	3.79	62.67	0.77	121.00	1.33	36.26
		Ethanol extract				
0	2.21	89.52	0.89	77.12	0.47	–
100	1.59	56.90	0.91	167.69	4.82	54.01
500	2.09	42.87	0.70	2004.10	3.20	96.15

Also the R_{ct} values are greater with extracts, especially the ethanol extract. This confirms that the extracts definitely protected the steel surface when added to the acid solution. The extent of protection is understood by calculating the inhibition efficiency (% IE). From the analysis in Table 2, the water extract gave an efficiency approximately 36 % at optimum concentration tested, while the ethanol extract gave efficiency approximately 96 % with the 500 ppm concentration.

However, the extracts shifted both anodic and cathodic current to lower values. The implication is that the extracts exhibited mixed-type inhibitions since they were able to lower both anodic and cathodic reactions (Ahanotu *et al*, 2020; Ishak *et al*, 2019; Obi-Egbedi *et al*, 2014). The corrosion current density was obtained by extrapolating the PDP curves around 10 mV of the cathodic and anodic transition point. The corrosion current density (i_corr) is a measure of corrosion rate. Lower i_corr depict lower rate of corrosion and higher corrosion resistance (Belakhdar *et al*, 2020; Fang *et al*, 2019).

2) Potentiodynamic polarization (PDP)

Figure 6 shows the result of the polarization of the steel samples in the acid solution without and with concentrations of 100 and 500 ppm of the different extracts. The influence of the extracts on the anodic and cathodic reactions on the steel surface during the corrosion in the acid solution is investigated using the PDP technique. In the present study, the predominant anodic reaction is the oxidation of Fe to Fe^{2+} while that of the cathodic reaction is the reduction of H^+ to H_2(g). The influence of both extracts on the corrosion potentials of the steel was observed to be minimal as seen the Figure 6. This implies that the extracts had minimal influence on the thermodynamic propensity of the steel to corrode in the acid solution (Muthukumarasany *et al*, 2020; Magu *et al*, 2017; Chen *et al*, 2020).

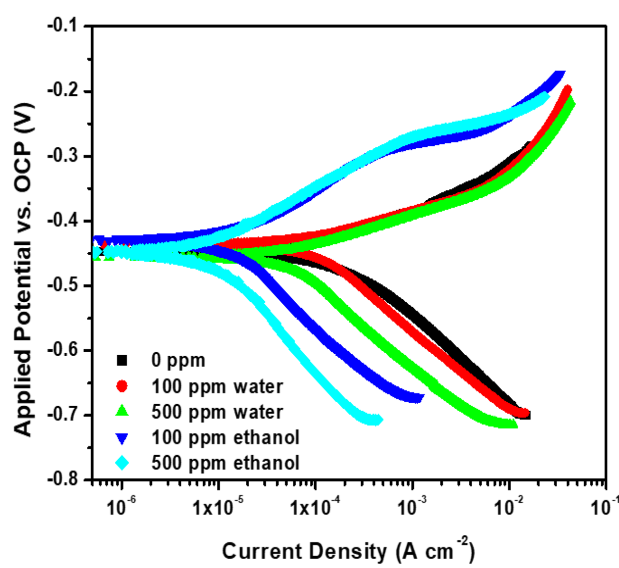


Figure 6: PDP analysis of C1020 steel in 1 M HCl containing water and ethanol extracts of *Spondias mombin* leaves at 25 ℃.

Table 3 Polarization parameters obtained for corrosion of mild steel type - C1020 in 1 M HCl containing different concentrations of ethanol and water extract of *Spondias mombin* leaves at 25 ℃.

Sample	E_{corr} (mV)	i_{corr}(μA/cm^2)	β_a (mV/decade)	$-\beta_c$ (mV/decade)	% IE
		Water extract			
0	– 436.00	102.00	53.60	139.40	–
100	– 447.00	84.70	50.50	161.40	16.96
500	– 452.00	63.06	52.10	142.80	38.18
		Ethanol extract			
0	– 436.00	102.00	53.60	139.40	–
100	– 456.00	55.50	47.20	133.20	53.75
500	– 448.00	8.69	45.90	146.80	94.42

Table 3 shows that both extracts addition lowers the i_corr values, which implies that the extracts lowers the corrosion rate of the steel. However, it was observed that the ethanol extract causes the greater reduction in i_corr which confirms that the ethanol extract performs better than the water extract (Obi-Egbedi *et al*, 2014; Sidikat *et al*, 2018; Al-Otaibi *et al*, 2014). Again the efficiency of the inhibitors (% IE) shows that the ethanol extract is approximately 94 % at 500 ppm.

IV. CONCLUSION

The ethanol and water extracts of *Spondias mombin* leaves have shown promising corrosion inhibition properties for mild steel in 1 M HCl media. The values obtained in percentages for inhibitor efficiencies showed that the extracts could serve as effective green inhibitor for mild steel in acidic media. The inhibition efficiency of both extracts on corrosion inhibition increases with increase in concentration of each extracts. Both extracts in the acid solution exhibited mixed-type inhibitions due to their ability to lower both anodic and cathodic reactions. The PDP analysis reveals that the extracts act as mixed type inhibitor and its mechanism of inhibition is adsorption.

The adsorption model of inhibition on the mild steel surface is via Langmuir and Freundlich adsorption isotherms. The EIS investigation reveals that the inhibition of corrosion on the mild steel is due to the formation of a single protective film on the metal surface and the inhibition increases as the extract concentrations increase. This result collaborates with that obtained via weight loss and potentiodynamic studies. The results of the investigations confirmed that the extracts of *Spondias mombin* leaves has potential to prevent the corrosion of mild steel in acidic environment and therefore serves as a potential green inhibitor for the prevention of corrosion of mild steel.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing interests.

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AUTHOR CONTRIBUTIONS

K.K. Adama: Conceptualization, Weight loss experiments, Validation, Writing–original draft. **I.B. Onyeachu:** Conceptualization, Methodology, Electrochemical experiments, Writing–review & editing.

REFERENCES

Ahanotu, C. C.; I.B. Onyeachu; M.M. Solomon; I.S. Chikwe; O.B. Chikwe and C.A. Eziukwu. (2020). *Pterocarpus santalinoides* Leaves Extract as Sustainable and Potent Inhibitor for Low Carbon Steel in a Simulated Pickling Medium. Sustainable Chemistry and Pharmacy, 15: 100196.

Akinbulumo, O.A.; O. J. Odejobi and E. L. Odekanle. (2020). Thermodynamics and Adsorption Study of the Corrosion Inhibition of Mild Steel by *Euphorbia heterophylla L.* Extract in 1.5M HCl, Results in Materials, 5: 100074.

Alrefaee, S.H.; K.Y. Rhee; C. Verma; M.A. Quraishi and E.E. Ebenso. (2020). Challenges and Advantages of using Plant Extract as Inhibitors in Modern Corrosion Inhibition Systems: Recent Advancements. Journal of Molecular Liquids, 321: 114666.

Al-Otaibi, M.S.; A.M. Al-Mayouf; M. Khan; A.A. Mousa; S.A. Al-Mazroa and H. Z. Alkhatwan. (2014). Corrosion Inhibitory Action of Some Plant Extracts on the Corrosion of Mild Steel in Acid Media, Arabian Journal of Chemistry, 7: 340-346.

Asfia, M.P.; M. Rezaei and G. Bahlakeh. (2020). Corrosion Prevention of AISI 304 Stainless Steel in Hydrochloric Acid Medium using Garlic Extract as Green Corrosion Inhibitor: Electrochemical and Theoretical Studies. Journal of Molecular Liquids, 315: 113679

ASTM G01-03 (2003). Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens, ASTM International.

ASTM G31-72 (2004). Standard Practice for Laboratory Immersion Corrosion Testing of Metals, ASTM International.

ASTM G3-89 (1994). Conventions Applicable to Electrochemical Measurements in Corrosion Testing, 30. Annual Book of ASTM Standard.

ASTM G3-94 (1994). Making Potentiostatic and Potentiodynamic Anodic Polarization Measurements, 48. Annual Book of ASTM Standard.

Belakhdar, A.; H. Ferkous; S. Djellahi; R. Sahraoui; H. Lahbib; Y.B. Amor; A. Erto; M. Balsamo and Y. Benguerba. (2020). Computational and Experimental Studies on the Efficiency of *Rosmarinus officinalis* Polyphenols as Green Corrosion Inhibitors for XC48 Steel in Acidic Medium. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 606: 125458

Berrissoul, A.; A. Onarhach; F. Benhiba; A. Romane; A. Zarrouk; A. Guenbour; B. Dikici and A. Dafali. (2020). Evaluation of *Lavandula mairei* Extract as Green Inhibitor for Mild Steel Corrosion in 1M HCl Solution – Experimental and Theoretical Approach. Journal of Molecular Liquids, 313: 113493

Chaudhary, S. and Tak, R. K. (2022). Natural Corrosion Inhibition and Adsorption Characteristics of *Tribulus terrestris* Plant Extract on Aluminum in Hydrochloric Acid Environment. Biointerface Research and Applied Chemistry 12 (2): 2603-2617.

Chen, S.; S. Chen; B. Zhu; C. Huang and W. Li. (2020). *Magnolia grandiflora* Leave Extracts as a Novel Environmentally Friendly Inhibitor for Q235 Steel Corrosion in 1M HCl: Combining Experimental and Theoretical Researches. Journal of Molecular Liquids, 311: 113312

Dohare, P.; K. Ansari; M.A. Quraishi and I. Obot. (2017). Pyranpyrazole Derivatives as Novel Corrosion Inhibitors for Mild Steel Useful for Industrial Pickling Process: Experimental and Quantum Chemical Study. Journal of Industrial and Engineering Chemistry, 52: 197-210.

Fang, Y.; B. Suganthan and R.P. Ramasamy. (2019). Electrochemical Characterization of Aromatic Corrosion Inhibitors from Plant Extracts. J. Electroanal. Chem. 840: 74-83.

Ishak, A.; F.V. Adams; J.O. Madu; I.V. Joseph and P.A. Olubambi. (2019). Corrosion Inhibition of Mild Steel in 1M Hydrochloric Acid using *Haematostaphis barteri* Leaves Extract, Procedia Manufacturing, 35: 1279-1285

Magu, T.O.; V.M. Bassey; B.E. Nyong; O.E. Obono; N.A Nzeata-Ibe and O.U. Akakuru. (2017). Inhibition Studies of *Spondias mombin* L. in 0.1 HCl Solution on Mild Steel and Verification of a New Temperature Coefficient of Inhibition Efficiency Equation for Adsorption Mechanism Elucidation. World News of Natural Sciences, 8: 15-26

Marzorati, S.; L. Verotta and S.P. Trasatti. (2019). Green Corrosion Inhibitors from Natural Sources and Biomass Wastes. Molecules, 24: 48.

Muthukumarasamy, K.; Pitchai, S.; K. Devarayan and L. Nallathambi. (2020). Adsorption and Corrosion Inhibition Performance of Tunbergia fragrans Extract on Mild Steel in Acid Medium. Materials Today: Proceedings, 23-31.

Obi-Egbedi, N.O.; I.B. Obot and S.A. Umoren. (2012). *Spondias mombin* L. As a Green Corrosion Inhibitor for Aluminium in Sulphuric Acid: Correlation Between Inhibitive Effect and Electronic Properties of Extracts Major Constituents Using Density Functional Theory. Arabian Journal of Chemistry, 5(3): 361-373.

Obot, I.B.; I.B. Onyeachu; N. Wazzan and A.H. Al-Amri. (2019). Theoretical and Experimental Investigation of Two Alkyl Carboxylates as Corrosion Inhibitor for Steel in Acidic Medium. Molecular Liquids 279: 190–207.

Onyeachu, I.B.; I.B. Obot; A. Alamri and C.A. Eziukwu. (2020). Effective Acid Corrosion Inhibitors for X60 Steel under Turbulent Flow Conditions Based on Benzimidazoles: Experimental, Theoretical, SEM, ATR-IR and XPS Investigations. European Physical Journal Plus 135: 129

Oguike, R. S. and O. Oni. (2019). Natural Products for Material Protection: Passivation Enhancing Potentials of *Spondias mombin* as AISI 316L Corrosion Inhibitor in 3.5% NaCl Solution. Global Journal of Science Frontier Research (B), 19: 33-44.

Palaniappan, N.; L. Cole; F. Caballero-Briones; S. Manickam; K.J. Thomas and D. Santos. (2020). Experimental and DFT Studies on the Ultrasonic Energy-assisted Extraction of the Phytochemicals of *Catharanthus roseus* as Green Corrosion Inhibitors for Mild Steel in NaCl Medium. RSC Advances, 10: 5399-5411.

Sidikat, I.K.; A. Abiodun; R.A. Olayide; O.A. Nurudeen; F.A. Alex and O.A. Hezekiah. (2018). Inhibitive Action of Water Extract of *Spondias mombin* on Corrosion of Low Carbon Steel in 0.5 M Sulphuric Acid. FUOYE Journal of Engineering and Technology, 3(1): 42-47.