



Methanolic Extracts of *Adansonia digitata* (Baobab) Fruit Pulp and Seeds as Potential Green Inhibitors for Mild Steel Corrosion in 0.5 M H₂SO₄ Solution

Petro Novert Karungamye, H. C. Ananda Murthy

Department of Chemistry, College of Natural and Mathematical Sciences, The University of Dodoma, Dodoma, P.O. Box 259, Dodoma, Tanzania.

Received 11th August 2017; Revised 25th August 2017; Accepted 28th August 2017

ABSTRACT

The corrosion inhibition of mild steel (MS) in 0.5 M H₂SO₄ solution by the methanolic extracts of *Adansonia digitata* (baobab) fruit pulp extract (ADPE) and *A. digitata* (baobab) fruit seeds extract (ADSE) was studied by gravimetric, potentiodynamic polarization, electrochemical impedance spectroscopic, and scanning electron microscopy (SEM) methods. The weight loss and polarization studies reveal that the corrosion inhibition efficiency increases with increase in the concentrations of inhibitors ADSE and ADPE. ADSE exhibited high corrosion inhibitor efficiency (74.5%) for MS. Tafel plots show that baobab fruit extracts act as efficient mixed-type corrosion inhibitors. The double-layer capacitance (C_{dl}) and charge transfer resistance (R_{ct}) values derived from Nyquist plots proved the anticorrosive nature of extracts. The inhibition of corrosion is possibly due to adsorption of the extracts on MS surface. The adsorption obeys Langmuir adsorption isotherm. The low free energy of adsorption (ΔG_{ads}) values for both the extracts confirmed physisorption on MS surface. The SEM images confirmed severe surface deterioration of MS exposed to H₂SO₄ solution in the absence of inhibitors. The ADSE exhibited high efficiency as green and eco-friendly corrosion inhibitor for MS in acidic medium.

Key words: Mild steel, Green inhibitor, *Adansonia digitata*, Acid corrosion.

1. INTRODUCTION

Mild steel (MS) has widespread applications in chemical and allied industries due to its low cost, ease of fabrication, and good tensile strength in addition to its other desirable properties. MS corrosion has been a serious problem of global concern since many decades with the enhancement of its application in various fields such as automobiles, aviation, agriculture, building construction, power plants, and oil and gas industry.

The MS corrosion in acidic media has gained significance in the recent past, due to increased industrial applications of MS in acidic solutions such as acid pickling, acid descaling, industrial cleaning, and oil well acidizing [1]. Degradation of MS during service conditions has created a limitation in industries. Therefore, the protection of MS from corrosion is of paramount significance.

The corrosion damage of MS on exposure to the acidic environment and consequent environmental pollution can be retarded considerably by the use of corrosion inhibitors [2]. The corrosion inhibition method of protecting MS has gained much importance recently

among all the other protection methods for economical and practical reasons [3]. The use of inhibitors has been well documented as an effective method of protecting metallic materials from corrosion [4]. Synthetic organic inhibitors have shown efficiency in corrosion inhibition, but they have a high cost of production, toxicity, and non-biodegradability properties which stimulate search for green corrosion inhibitors [5].

Green corrosion inhibitors are biodegradable and do not contain heavy metals or other toxic compounds. In the recent times, there has been serious search for better green corrosion inhibitors for MS so that the environment is protected. A large number of researchers have explored the natural plant extracts as effective corrosion inhibitors such as *Hunteria umbellata* [6], *Ligularia fischeri* [7], *African perquetina* [8], *Nicotian atabacum* [9], *Psidium guajava* [10], *Aquilaria crassna* [11], *Aloe barbadensis* [12], *Adenopus breviflorus* [13], *Musa paradisiaca* [14], and *Hibiscus sabdariffa* [15].

The phytochemical investigation of *Adansonia digitata* (baobab) fruit seed extract (ADSE) and

*Corresponding Author:

E-mail: petrokarungamye@gmail.com

A. digitata (baobab) fruit pulp extract (ADPE) revealed the presence of organic components such as flavonoids, terpenoids, phytosterols, amino acids, carbohydrates, lipids, vitamins, and minerals. Methanol extract of the pulp of the fruits of *A. digitata* contains catechin and various epicatechins [16], while the seed oil contains the compounds such as campesterol, cholesterol, isofucosterol, β -sitosterol, stigmaterol, and tocopherol [17]. The presence of these effective organic compounds in baobab fruit, which contain N, O heteroatoms, -OH group, and π electrons in their structures, shows their ability to be corrosion inhibitors. However, this baobab fruit pulp and seed extracts have not yet been investigated for their corrosion inhibition properties.

The present work was aimed to investigate the efficiency of methanolic extracts of *A. digitata* fruit pulp and seeds as green and eco-friendly corrosion inhibitors for MS in 0.5 M H_2SO_4 solution by gravimetric, polarization, electrochemical impedance, and scanning electron microscopy (SEM) techniques.

2. EXPERIMENTAL

2.1. Materials and Sample Preparation

The MS plate of grade JIS G 3132 having the composition (wt.%) of C (0.18), Si (0.35), Mn (0.60), P (0.040), S (0.040), Cr (0.14), and remaining Fe was used to prepare the coupons for this study. The MS coupons of dimension 76.2 mm \times 22.23 mm \times 3.18 mm with a hole drilled 6 mm from one side were used for weight loss measurements, and for electrochemical studies, the square rod of the same material with dimension 10 mm \times 10 mm \times 30 mm coated with epoxy resin to give an exposed area of 1 cm² was used. For surface studies by SEM, the MS coupons of dimension 30 mm \times 30 mm \times 3 mm were used. Before each experiment, the coupons were mechanically polished with emery papers of grades 600, 800, and 1000 rinsed with distilled water, degreased in acetone, air dried, and stored in desiccators. The corrosive medium 0.5 M H_2SO_4 solution was prepared by diluting analytical grade sulfuric acid with distilled water.

2.2. Preparation of Plant Fruit Extracts

Dry baobab (*A. digitata*) fruits were collected from the villages around the University of Dodoma. The fruit pulp was separated from the seeds by manual grinding and sieving to remove the fibers. The collected powder was allowed to dry at room temperature and then stored in airtight polythene bags. The baobab fruits pulp is shown in Figure 1.

After removing the pulp, the seeds were washed properly with running tap water, sun dried, ground into powder, and stored in dry airtight containers. 500 g each of dried pulp powder and seeds powder were each extracted separately with 2.5 L of 80% (V/V) aqueous methanol for 24 h at room temperature.



Figure 1: Baobab fruits pulp.

Selection of the solvent was based on the efficiency of extraction. When compared to aqueous ethanol, aqueous methanol is more effective in extraction of polar and moderately polar components from different plant materials as discussed elsewhere [18,19]. After double filtration, cleaned first with a fabric and then with Whatman filter papers to remove the residues. The extracts were concentrated using warm air evaporator to get the crude extracts [16]. ADPE and ADSE were stored in glass bottles for corrosion studies.

2.3. Gravimetric Method

Gravimetric (weight loss) experiments were carried out as described by ASTM practice standard G-31. The weighed MS coupons (76.2 mm \times 22.23 mm \times 3.18 mm) were immersed in 200 ml of 0.5 M H_2SO_4 acid solutions containing different concentrations of ADSE and ADPE inhibitors for immersion periods of 24 h, 48 h, and 72 h at room temperature according to the reported studies [20-23]. After the experiments, the coupons were removed from the corrosive acid solution and immersed in 70°C mixtures of 200 g/L of NaOH and 20g/L of zinc metal dust and left for 45 min to remove the corrosion product from the surface of MS coupons. From the hot solution, coupons were then cleaned using the brush in running tap water, rinsed with distilled water, cleaned in acetone, dried, and reweighed. The mean of weight loss values of two identical coupons was used to calculate the surface coverage (θ), percentage inhibition efficiency (% IE), and corrosion rate (CR) in millimeters per year (mmpy) using the following formula:

$$\text{Surface coverage } (\theta) = \frac{w_0 - w_1}{w_0} \quad (1)$$

$$(\% \text{ IE}) = \frac{w_0 - w_1}{w_0} \times 100 \quad (2)$$

$$\text{Corrosion rate } (\rho) = \frac{87.6W}{\rho At} \quad (3)$$

Where,

w_0 =Average weight loss without inhibitor,

w_1 =Average weight loss with inhibitor,

w =Weight loss (mg),

ρ =Density (g/cm^3)=7.86 (MS),

A =Area of the MS coupon (cm^2),

t =Time (h).

2.4. Electrochemical Measurements

The electrochemical measurements were carried out using Autolab potentiostat/galvanostat model Aut50665, and the data were collected with NOVA 1.11 software. A three-electrode cell assembly in which MS square rod with exposed area of 1 cm^2 as the working electrode, the platinum electrode as an auxiliary (counter) electrode, and the saturated calomel electrode as a reference electrode was used. All experiments were conducted at room temperature using 200 ml of 0.5 M H_2SO_4 with different concentrations of ADSE and ADPE inhibitors. Each experiment was repeated at least three times to check the reproducibility, and the good reproducible results were reported. Before each experiment, the electrode was allowed to corrode freely for 20 min for potential stabilization [24,25]. After this time, the potential corresponding to the corrosion potential (E_{corr}) of the working electrode was recorded with applied potential $E=E_{\text{corr}}\pm 200 \text{ mV}$, with a scan rate of 1.0 mV s^{-1} [25,26]. The Tafel curves were extrapolated to obtain corrosion current densities (i_{corr}), corrosion potential, and corrosion rate [27]. The IE was calculated from the measured i_{corr} values using the following formulas [28,29]:

$$(\% \text{ IE}) = \frac{i_{\text{corr}}^0 - i_{\text{corr}}^1}{i_{\text{corr}}^0} \times 100 \quad (4)$$

Where,

i_{corr}^0 = Corrosion current density without inhibitor,

i_{corr}^1 = Corrosion current density with inhibitor.

In case of electrochemical impedance spectroscopy (EIS), experiments were carried out at open-circuit potential over a frequency range of 0.1 Hz-100 kHz [30] using AC signals of amplitude 10 mV peak to peak at the open-circuit potential. The

double-layer capacitance (C_{dl}) and charge transfer resistance (R_{ct}) values were derived from Nyquist plots which were obtained using the impedance data plotted in EIS analyzer software. From the charge transfer resistance values, the IE of the inhibitor was calculated using the equation below [7]:

$$(\% \text{ IE}) = \frac{R_{\text{ct}}^i - R_{\text{ct}}^0}{R_{\text{ct}}^i} \times 100 \quad (5)$$

Where,

R_{ct}^i = Charge transfer resistance with inhibitor,

R_{ct}^0 = Charge transfer resistance without inhibitor.

2.5. Surface Analysis

The surface of polished MS coupons immersed in 0.5 M H_2SO_4 for 3 h in the presence and absence of inhibitor was immediately examined using SEM COXEM MODEL CX200.

3. RESULTS AND DISCUSSION

3.1. Gravimetric Measurements

3.1.1. Effect of inhibitor concentration

The corrosion inhibition behavior of different concentrations of the extracts (300, 600, and 900 ppm) on MS in 0.5 M H_2SO_4 was studied for various immersion periods of 24, 48, and 72 h using weight loss method. The corrosion rate, surface coverage, and IE were calculated using equations (1-3). The data obtained are given in Table 1. It is clear from the results that the % IE increases with increase in the concentration of inhibitors.

This confirms the dependence of inhibiting effect on phytoconstituents of fruit extracts. When the inhibitor molecules accumulate on the surface of MS, they reduce the interaction between MS surface and aggressive medium by increasing in coverage of MS surface leading to a compact and coherent film on the surface of MS [31].

The effect of inhibitor efficiency on the inhibitor concentrations is shown in Figure 2. Increasing the concentration of inhibitor from 300 to 900 ppm increases % IE from 51.61% to 69.90% for ADPE and 54.68% to 74.53% for ADSE. ADSE exhibited high corrosion inhibitor efficiency (74.5%) for MS.

The degree of protection increases with the increasing surface coverage by adsorbed molecules [32].

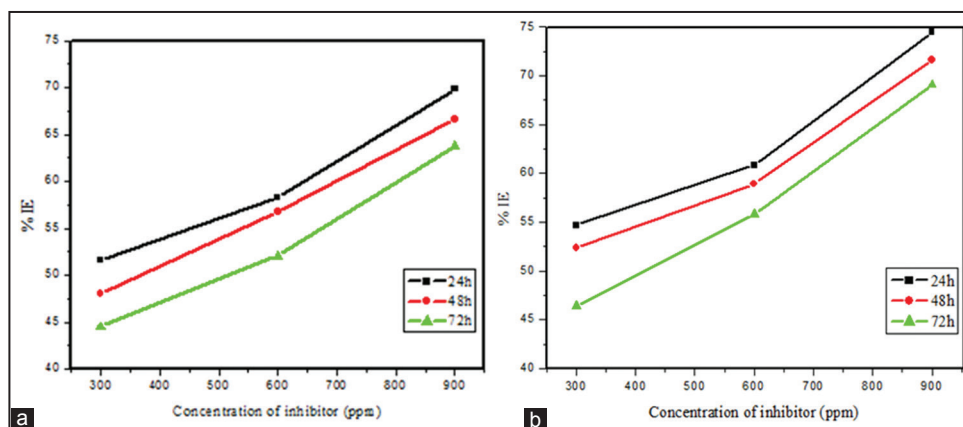
3.1.2. Effect of immersion period

The variation of weight loss with % IE at various immersion periods is shown in Figure 3. It is obvious from the plots that the weight loss of MS decreases

Table 1: The gravimetric parameters for MS in 0.5 M H₂SO₄ in the presence and absence of *Adansonia digitata* extract with different concentrations at various time of immersion at 298 K.

Inhibitor	Time (h)	Concentration (ppm)	θ	% IE	CR (mmpy) E-3
ADPE	24	Blank			31.401
		300	0.516	51.607	15.207
		600	0.583	58.250	13.119
		900	0.699	69.903	9.458
	48	Blank			28.220
		300	0.480	48.013	14.671
		600	0.567	56.720	12.214
		900	0.666	66.645	9.413
	72	Blank			25.329
		300	0.445	44.500	14.058
		600	0.521	52.050	12.145
		900	0.637	63.749	9.182
ADSE	24	Blank			31.401
		300	0.547	54.675	14.232
		600	0.609	60.854	12.292
		900	0.745	74.529	7.998
	48	Blank			28.220
		300	0.524	52.387	13.436
		600	0.589	58.918	11.593
		900	0.717	71.657	7.998
	72	Blank			25.364
		300	0.464	46.387	13.599
		600	0.558	55.843	11.200
		900	0.691	69.098	7.838

ADPE=*Adansonia digitata* (baobab) fruit pulp extract, ADSE=*A. digitata* (baobab) fruit seeds extract, MS=Mild steel, IE=Inhibition efficiency, CR=Corrosion rate

**Figure 2:** Inhibition efficiency plots against concentration of inhibitor *Adansonia digitata* pulp extract (a) and *A. digitata* seeds extract (b) for mild steel corrosion in 0.5 M H₂SO₄.

with immersion period which is possibly due to the increased thickness of the adsorbed layer containing phytoconstituents and corrosion products at the MS surface.

The interaction of ADPE and ADSE with MS may be a result of the presence of polysaccharides and protein molecules in their structures. These molecules form a linkage with the metal surface by donating a

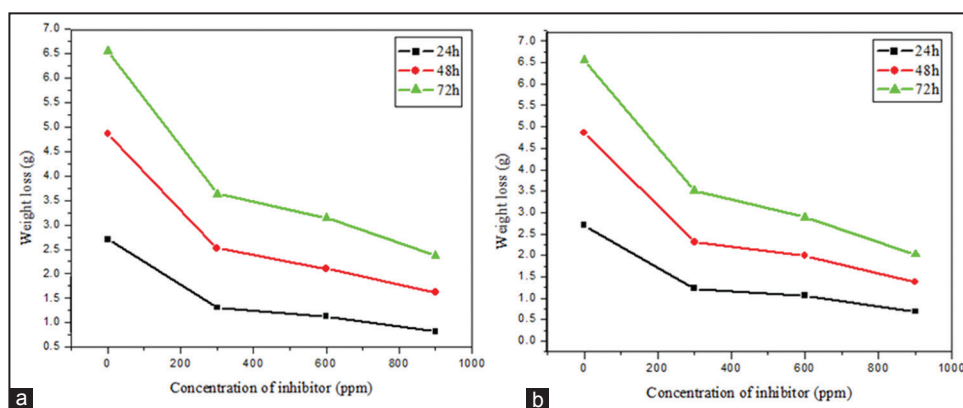


Figure 3: Plots of weight loss of *mild steel* against concentration of inhibitor *Adansonia digitata* pulp extract (a) and *A. digitata* seeds extract (b) in 0.5 M H_2SO_4 .

Table 2: Potentiodynamic polarization parameters for the corrosion inhibition of MS in 0.5 M H_2SO_4 in the presence and absence of inhibitor.

Inhibitor	Concentrated (ppm)	$-E_{corr}$ (mV)	i_{corr} (A/cm ²)	% IE	CR (mm/year)
ADPE	Blank	461.80	306.25		3.5586
	300	453.90	145.14	52.607	2.4339
	600	451.94	129.37	57.756	1.6207
	900	438.83	103.88	66.081	1.331
ADSE	Blank	461.80	306.25		3.558
	300	456.28	139.66	54.398	2.266
	600	453.71	121.08	60.462	1.478
	900	452.60	80.18	73.818	0.909

ADPE=*Adansonia digitata* (baobab) fruit pulp extract, ADSE=*A. digitata* (baobab) fruit seeds extract, MS=Mild steel, IE=Inhibition efficiency, CR=Corrosion rate

lone pair of electrons. IE decreases with immersion time possibly due to the formation of insoluble film/corrosion product on the MS surface which lowers the interaction of the MS with the aggressive medium [33].

The decrease in corrosion rate with increasing inhibitor concentration, as shown in Figure 4, suggests that the inhibitor molecules act by adsorption on the metal surface. Consequently, the increase in inhibitor efficiency was attributed to the increase in surface coverage by extract molecules [34].

3.2. Potentiodynamic Polarization Measurements

Corrosion inhibition is achieved by altering the anodic process, cathodic process, or both, which results reduced rate of the corrosion process [35]. The corrosion current density (i_{corr}) and corrosion potential (E_{corr}) were obtained from the intersection point of anodic and cathodic current curves in the Tafel plots. Potentiodynamic polarization parameters for the corrosion inhibition of MS in 0.5M H_2SO_4 in the presence and absence of inhibitor are given in Table 2. The corrosion current density i_{corr} values decrease markedly with increasing extract concentration from

306.25 to 103.88 A/cm² for ADPE, similarly for ADSE, i_{corr} decreases from 306.25 to 80.18 A/cm². Tafel constants b_a and b_c markedly altered in the presence of extract.

Polarization (Tafel) curves for MS in 0.5 M H_2SO_4 solution at room temperature in the absence and presence of different concentrations of inhibitors are given in Figure 5. From the figure, it is obvious that the two extracts alter the electrochemical processes on MS by reducing the anodic reaction rates by reducing the corrosion current densities on both sides of the polarization curves. It can be concluded from Tafel slopes that the green inhibitor follows mixed-type inhibition mode [36] as the shift in E_{corr} values for blank and inhibitor is less than 85 mV.

It is also seen from the plots that no significant change occurred for cathodic curves when compared with anodic curves which confirms that the inhibitor is more of anodic nature. The interaction between metal surface and lone pair of electrons of oxygen/nitrogen atoms of the extract decreases the anodic dissolution of MS due to adsorption.

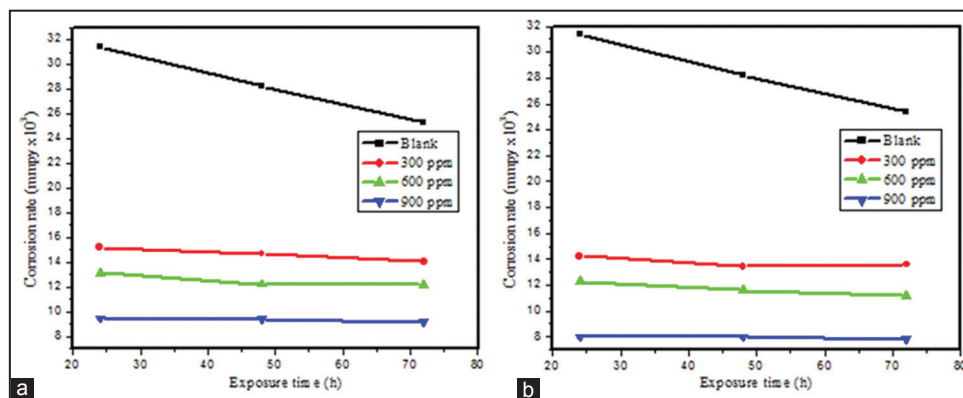


Figure 4: Corrosion rate plots for mild steel against concentration of inhibitor *Adansonia digitata* pulp extract (a) and *A. digitata* seeds extract (b) in 0.5 M H_2SO_4 .

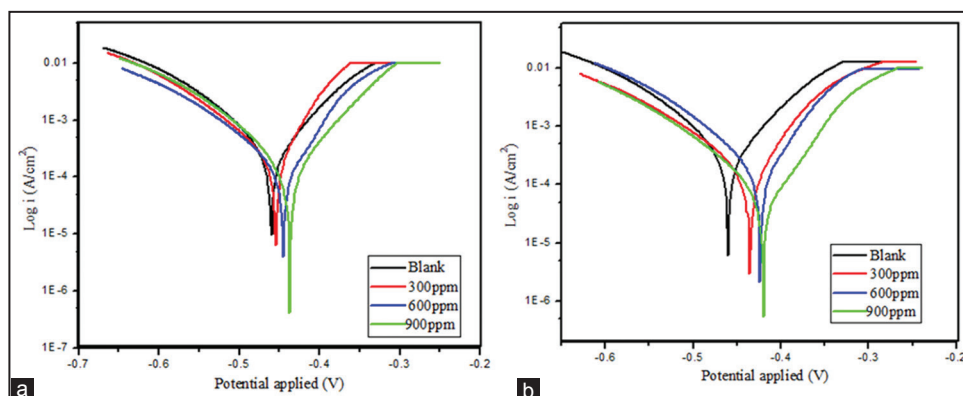


Figure 5: Tafel plots for mild steel corrosion in 0.5 M H_2SO_4 solution with different concentrations of inhibitor *Adansonia digitata* pulp extract (a) and *A. digitata* seeds extract (b).

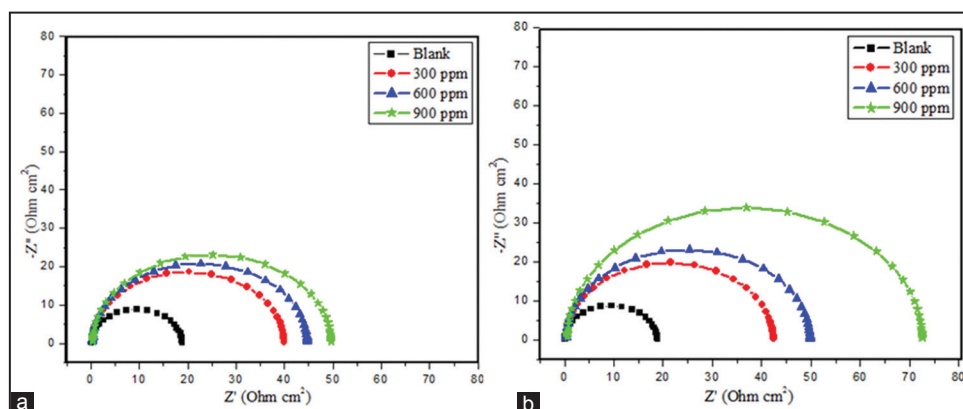


Figure 6: Nyquist plots (EIS) of mild steel in 0.5 M H_2SO_4 in the absence and presence of different concentrations of inhibitor *Adansonia digitata* pulp extract (a) and *A. digitata* seeds extract (b).

3.3. EIS Measurements

The inhibition processes of ADPE and ADSE were also studied by EIS technique. The formation of film on metal surface is proved by impedance spectra. Basically, corrosion process involves two steps, at first metal, undergo oxidation and metal ions diffuse into the solution phase in the second step. Extract molecules get adsorbed at the surface of MS, thereby preventing the metallic dissolution. Formation of the protective layer on the surface of MS boosts the charge transfer resistance and

diminishes the double-layer capacitance [9]. It is clear from the Nyquist's plots (Figure 6) Bode and phase plots (Figure 7) that charge transfer resistance and inhibitor efficiency increase with inhibitor concentration.

All impedance experimental data were tested in different circuit models to get an excellent fit with lower error which agreed with the circuit Figure 8. The impedance parameters such as solution resistance (R_s), charge transfer resistance (R_{ct}), and double-layer

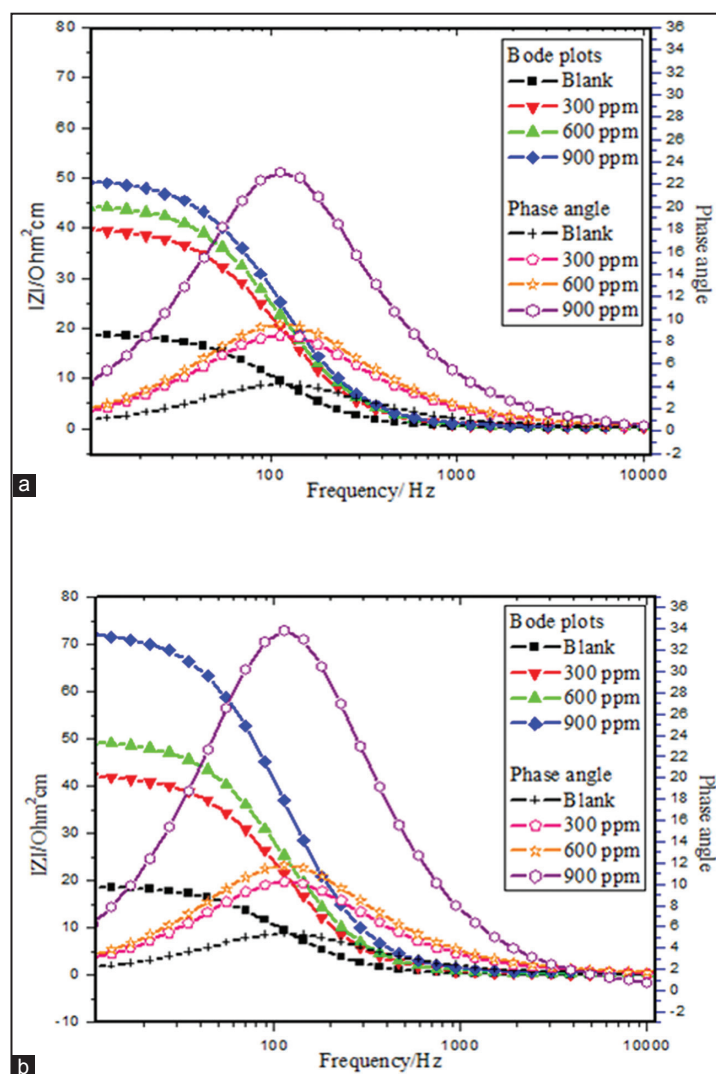


Figure 7: Bode and phase angle plots of mild steel in 0.5 M H_2SO_4 in absence and presence of different concentrations of inhibitor *Adansonia digitata* pulp extract (a) and *A. digitata* seeds extract (b).

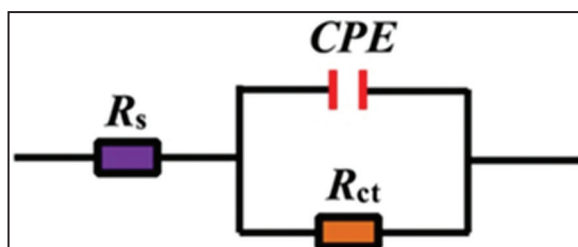


Figure 8: Equivalent circuit model used to fit the impedance spectral data.

capacitance (C_{dl}) were used to calculate the % IE using the formula (5).

The diameter of Nyquist plots increased on increasing the concentration of ADPE and ADSE which shows that these extracts strengthen the inhibitive film.

From the impedance data given in Table 3, the charge transfer resistance (R_{ct}) values increase with inhibitor

concentration which shows that a charge transfer process mainly controlling the corrosion of MS in acidic media. Values of double-layer capacitance (C_{dl}) decrease with increase of inhibitor concentration due to the adsorption of the inhibitor on the metal surface leading to the formation of film or complex from acidic solution [37].

The decrease in C_{dl} values generally related to the adsorption of organic molecules on the metal surface and then leads to a decrease in the local dielectric constant and/or an increase in the thickness of the electrical double layer. The % IE of the extracts determined by three different methods such as gravimetric, polarization, and EIS, as a function of concentration is in coherence with each other.

3.4. Adsorption Isotherms

Adsorption isotherm is used to provide useful insight into the mechanism of corrosion inhibition. The

Table 3: EIS data for corrosion of MS in 0.5 M H₂SO₄ with and without inhibitors.

Inhibitor	Concentrated (ppm)	C _{dl} (μFcm ⁻²)	R _s (Ωcm ²)	R _{ct} (Ωcm ²)	% IE
ADPE	Blank	77.721	0.137	18.342	
	300	36.790	0.288	38.729	52.645
	600	32.866	0.323	43.359	57.702
	900	29.591	0.359	48.164	61.922
ADSE	Blank	77.721	0.137	18.342	
	300	34.641	0.306	41.140	55.421
	600	29.484	0.360	48.339	62.060
	900	20.235	0.524	70.458	73.970

ADPE=*Adansonia digitata* (baobab) fruit pulp extract, ADSE=*Adansonia digitata* (baobab) fruit seeds extract, MS=Mild steel, IE=Inhibition efficiency

experimental data from weight loss measurements were applied to different adsorption isotherm equations to fit the values of surface coverage (θ) to get an isotherm with higher regression coefficient. Langmuir isotherm was tested by the plot between C/θ and C according to following equation:

$$\frac{C}{\theta} = \frac{1}{K_{ads}} + C \quad (6)$$

Most commonly applied adsorption isotherms are Temkin, Langmuir, and Frumkin isotherms [38,39]. In Langmuir isotherm, it is assumed that all sites have equal possibility for adsorption, and it is not affected by activity at nearby sites [40].

Langmuir isotherm (Figure 9) gave straight line with the slope of the unit, where the regression coefficient R² values for Langmuir isotherm were 0.9996 and 0.9998 for ADPE and ADSE, respectively, as given in Table 4. Adsorption depends on chemical composition of extract which showed the presence of various compounds such as flavonoids, terpenoids, phytosterols, amino acids, carbohydrates, lipids, and vitamins [41]. This inhibitor obeys the Langmuir adsorption isotherm [42,43].

This explains the monolayer formation of the inhibitor on the surface of MS [38]. Thermodynamic parameters (Table 5) for the adsorption of both extracts on the MS are calculated using the following equation:

$$\Delta G_{ads} = -RT \ln(55.5K_{ads}) \quad (7)$$

In general, it is accepted that when ΔG_{ads} values are about 20 kJ mol⁻¹ or lower, and adsorption is regarded as physisorption. For this, the inhibition is said to act through electrostatic interaction between the charged molecules and the charged metal. Furthermore, for the

Table 4: Langmuir adsorption isotherm data for MS in 0.5 M H₂SO₄ for ADPE and ADSE.

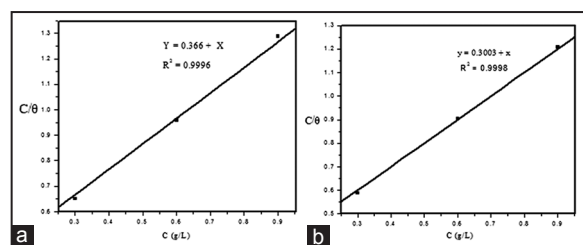
Media	Concentrated (g/L)	(θ)	C/θ	R ²
ADPE	0.3	0.516	0.581	0.9996
	0.6	0.583	1.029	
	0.9	0.699	1.288	
ADSE	0.3	0.547	0.548	0.9992
	0.6	0.609	0.985	
	0.9	0.745	1.208	

ADPE=*Adansonia digitata* (baobab) fruit pulp extract, ADSE=*Adansonia digitata* (baobab) fruit seeds extract, MS=Mild steel

Table 5: Langmuir thermodynamic parameters for ADPE and ADSE.

Inhibitor	K _{ads}	ΔG _{ads} (kJmol ⁻¹)
ADPE	2.732	-12.441
ADSE	3.330	-2.932

ADPE=*Adansonia digitata* (baobab) fruit pulp extract, ADSE=*Adansonia digitata* (baobab) fruit seeds extract

**Figure 9:** Langmuir adsorption isotherm plot for mild steel in 0.5 M H₂SO₄ with *Adansonia digitata* pulp extract (a) and *A. digitata* seeds extract (b) at 298 K.

values around 40 kJ mol⁻¹ or higher, the interactions are seen as chemisorption in which charge sharing or a charge transfer from the inhibitor molecules to the

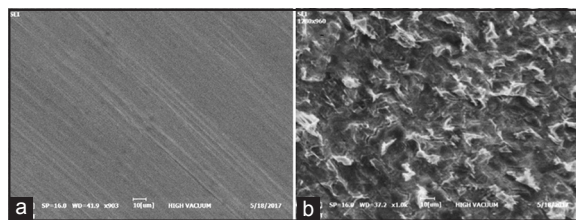


Figure 10: Scanning electron microscopy images of mild steel surface before immersion (a) and after immersion in 0.5M H₂SO₄ without inhibitor (b).

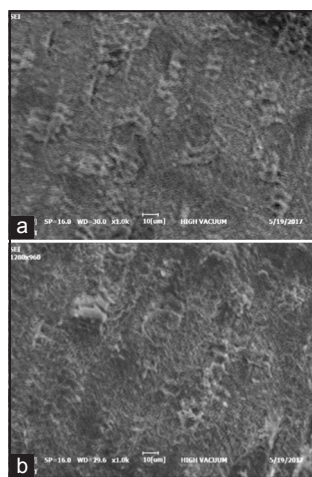


Figure 11: Scanning electron microscopy images of mild steel surface after immersion in 0.5M H₂SO₄ with inhibitors *Adansonia digitata* pulp extract (a) and *A. digitata* seeds extract (b).

metal surface occurs to form covalent bond [38]. In the present study, the values of free energy of adsorption for both ADPE and ADSE were around $-12.441 \text{ kJ mol}^{-1}$ and $-12.932 \text{ kJ mol}^{-1}$, respectively. This means that both inhibitors are physically adsorbed on the surface of MS.

3.5. SEM Analysis

SEM images were recorded to know the surface deterioration before and after MS corrosion on exposure to the 0.5 M H₂SO₄ solution in the absence and presence of ADPE and ADSE inhibitors. SEM images for MS surface before immersion and after immersion in 0.5 M H₂SO₄ without inhibitor are shown in Figure 9. SEM images for MS surface before immersion and after immersion in 0.5M H₂SO₄ without inhibitor are shown in Figure 10 (a) and (b) respectively where as in the presence of inhibitors ADPE and ADSE, as the surface conditions were comparatively better, as seen in Figure 11a and b, respectively.

This shows that the inhibitor molecules hinder the dissolution of MS by forming surface adsorbed layer, and thereby reducing the corrosion rate. It also confirms that the inhibitors effectively control the corrosion phenomenon by blocking the active corrosion causing sites on the MS surface. Metal surface was highly

covered with the protective layer formed by the green inhibitor which prevents the metal from further attack of acid media [36].

It is observed from Figure 11 that the surface deterioration is more in case of MS exposed to ADPE in acidic solution than that exposed to ADSE which could be attributed to the presence of higher proportions of active phytoconstituents in seeds than in pulp of baobab fruits.

4. CONCLUSION

The ADSE and ADPE proved to be effective green and eco-friendly inhibitors for MS corrosion in 0.5 M H₂SO₄ medium. The gravimetric analysis revealed that both inhibitors ADSE and ADPE found to follow mixed-type inhibition mode even though anodic reaction influence was predominant.

The inhibitor efficiency of extracts was found to increase with an increase in the inhibitor concentration. ADSE exhibited higher % IE compared to that of ADPE which could be attributed to the presence of higher percentage of active compounds in baobab seeds. The corrosion current density obtained from Tafel plots was found to be lowest for corrosive acid medium with high inhibitor concentration. Corrosion rate of MS was found to decrease with increase in extract concentrations.

This inhibitor obeys the Langmuir adsorption isotherm. Adsorption was effective due to the presence of various active compounds such as flavonoids, terpenoids, phytosterols, amino acids, carbohydrates, lipids, and vitamins in the extracts.

The EIS study shows that charge transfer resistance (R_{ct}) increases and double-layer capacitance (C_{dl}) decreases with increase in the inhibitor concentrations.

The surface analysis by SEM confirms the presence of protective film on MS surface in the presence of inhibitors.

5. ACKNOWLEDGMENT

The authors are grateful to the University of Dodoma, for providing funds toward this research project, and thankful to the Nelson Mandela Institute of Science and Technology, Arusha, for providing the instrumental facilities.

6. REFERENCES

1. M. Finsgar, J. Jackson, (2014) Application of corrosion inhibitors for steels in acidic media for the oil and gas industry: A review, *Corrosion Science*, **86**: 17-41.
2. E. E. Oguzie, (2006) Studies on the inhibitive effect of occimum viridis extract on the acid corrosion of mild steel, *Materials Chemistry and Physics*, **99**: 441-446

3. M. Chigondo, F. Chigondo, (2016) Recent natural corrosion inhibitors for mild steel: An overview, *Journal of Chemistry, Hindawi Publishing Corporation*, **2016**: 7.
4. K. K. Alaneme, S. J. Olusegun, (2012) Corrosion inhibition performance of lignin extract of sun flower (*Tithonia diversifolia*) on medium carbon low alloy steel immersed in H₂SO₄ solution, *Leonardo Journal of Sciences*, **20**: 59-70.
5. P. B. Raja, A. A. Rahim, H. Osman, K. Awang, (2011) Inhibitive effect of *Xylopi ferruginea* extract on the corrosion of mild steel in 1M HCl medium, *International Journal of Minerals, Metallurgy and Materials*, **18(4)**: 413-418.
6. K. K. Alaneme, S. J. Olusegun, O. T. Adelowo, (2016) Corrosion inhibition and adsorption mechanism studies of *Hunteria umbellata* seed husk extracts on mild steel immersed in acidic solutions, *Alexandria Engineering Journal*, **55**: 673-681.
7. M. Prabakaran, S. H. Kim, K. Kalaiselvi, V. Hemapriya, I. M. Chung, (2016) Highly efficient *Ligularia fischeri* green extract for the protection against corrosion of mild steel in acidic medium: Electrochemical and spectroscopic investigations, *Journal of the Taiwan Institute of Chemical Engineers*, **59**: 553-562.
8. A. I. Caroline, A. S. Abdulrahman, I. H. Kobe, K. A. Ganiyu, S. M. Adams, (2015) inhibitive performance of bitter leaf root extract on mild steel corrosion in sulphuric acid solution, *American Journal of Materials Engineering and Technology*, **2**: 35-45.
9. J. Bhawsar, P. K. Jain, P. Jain, (2015) Experimental and computational studies of *Nicotiana tabacum* leaves extract as green corrosion inhibitor for mild steel in acidic medium, *Alexandria Engineering Journal*, **54(3)**: 769-775.
10. S. N. Victoria, R. Prasad, R. Manivannan, (2015) *Psidium guajava* leaf extract as green corrosion inhibitor for mild steel in phosphoric acid, *International Journal of Electrochemical Science*, **10(3)**: 2220-2238.
11. L. Y. S. Helen, A. A. Rahim, B. Saad, M. I. Saleh, P. B. Raja, (2014) *Aquilaria crassna* leaves extracts-a green corrosion inhibitor for mild steel in 1 M HCL medium, *International Journal of Electrochemical Science*, **9(2)**: 830-846.
12. G. Pankaj, J. Gargi, (2014) Corrosion inhibition by aloe barbadensis (*Aloe vera*) extract as green inhibitor for mild steel in HNO₃, *International Journal of Scientific Research and Reviews*, **3(4)**: 72-83.
13. A. Adewuyi, A. Göpfert, T. Wolff, (2014) Succinyl amide gemini surfactant from *Adenopus breviflorus* seed oil: A potential corrosion inhibitor of mild steel in acidic medium, *Industrial Crops and Products*, **5**: 439-449.
14. G. Ji, S. Anjum, S. Sundaram, R. Prakash, (2015) *Musa paradisica* peel extract as green corrosion inhibitor for mild steel in HCl solution, *Corrosion Science*, **90**: 107-117.
15. Z. V. P. Murthy, K. Vijayaragavan, (2014) Mild steel corrosion inhibition by acid extract of leaves of *Hibiscus sabdariffa* as a green corrosion inhibitor and sorption behavior, *Green Chemistry Letters and Reviews*, **7(3)**: 209-219.
16. A. A. Shahat, (2006) Procyanidins from *Adansonia digitata*, *Pharmaceutical Biology*, **44(6)**: 445-450.
17. M. Sundarambal, P. Muthusamy, R. Radha, S. A. Jerad, (2015) A review on *Adansonia digitata* Linn, *Journal of Pharmacognosy and Phytochemistry*, **4**: 12-16.
18. B. Sultana, F. Anwar, M. Ashraf, (2009) Effect of extraction solvent/technique on the antioxidant activity of selected medicinal plant extracts, *Molecules*, **14(6)**: 2167-2180.
19. R. P. F. Anwar, (2012) Effect of solvents extraction on total phenolics and antioxidant activity of extracts from flaxseed (*Linum usitatissimum* L), *Acta Scientiarum Polonorum Technologia Alimentaria*, **11**: 293-301.
20. K. K. Anupama, K. Ramya, A. Joseph, (2016) Electrochemical and computational aspects of surface interaction and corrosion inhibition of mild steel in hydrochloric acid by *Phyllanthus amarus* leaf extract (PAE), *Journal of Molecular Liquids*, **216**: 146-155.
21. K. Krishnaveni, J. Ravichandran, A. Selvaraj, (2013) Effect of *Morinda tinctoria* Leaves extract on the corrosion inhibition of mild steel in acid medium, *Acta Metallurgica Sinica (English Letters)*, **26(3)**: 321-327.
22. R. Rajalakshmi, S. Subhashini, S. Leelavathi, R. F. Mary, (2008) Efficacy of sprouted seed extracts of *Phaseolus aureus* on the corrosion inhibition of mild steel in 1M HCl, *Oriental Journal of Chemistry*, **24(3)**: 1085-1090.
23. A. S. Abdulrahman, M. Ismail, M. S. Hussain, (2007) Inhibition of corrosion of mild steel in hydrochloric acid by *Bambusa arundinacea* preparation of plant extracts, *International Review of Mechanical Engineering*, **5(1)**: 59-63.
24. M. Chevalier, F. Robert, N. Amusan, M. Traisnel, C. Roos, M. Lebrini, (2014) Enhanced corrosion resistance of mild steel in 1M hydrochloric acid solution by alkaloids extract from *Aniba rosaeodora* plant: Electrochemical, phytochemical and XPS studies, *Electrochimica Acta*, **131**: 96-105.
25. A. Singh, V. K. Singh, M. A. Quraishi, (2010) Aqueous extract of kalmegh (*Andrographis paniculata*) leaves as green inhibitor for mild steel in hydrochloric acid solution, *International Journal of Corrosion*, **2010**: 10.
26. M. H. Hussin, A. A. Rahim, M. N. M. Ibrahim,

- N. Brosse, (2016) The capability of ultrafiltrated alkaline and organosolv oil palm (*Elaeis guineensis*) fronds lignin as green corrosion inhibitor for mild steel in 0.5 M HCl solution, *Journal of the International Measurement Confederation*, **78**: 90-103.
27. A. K. Singh, S. Mohapatra, B. Pani, (2016) Corrosion inhibition effect of *Aloe vera* gel: Gravimetric and electrochemical study, *Journal of Industrial and Engineering Chemistry*, **33**: 288-297.
 28. R. S. Mayanglambam, V. Sharma, G. Singh, (2011) *Musa paradisiaca* extract as a green inhibitor for corrosion of mild steel in 0.5 m sulphuric acid solution, *Portugaliae Electrochimica Acta*, **29(6)**: 405-417.
 29. A. K. Satapathy, G. Gunasekaran, S. C. Sahoo, K. Amit, P. V. Rodrigues, (2009) Corrosion inhibition by *Justicia gendarussa* plant extract in hydrochloric acid solution, *Corrosion Science*, **51(12)**: 2848-2856.
 30. H. Cang, W. Shi, J. Shao, Q. Xu, (2012) Study of *Stevia rebaudiana* leaves as green corrosion inhibitor for mild steel in sulphuric acid by electrochemical techniques, *International Journal of Electrochemical Science*, **7(4)**: 3726-3736.
 31. ASTM International, (2004) Standard practice for laboratory immersion corrosion testing of metals 1, *Annual Book of ASTM Standards*, **3.2**: 108-115.
 32. K. Kanagavalli, (2014) *Caesalpinia pulcherrima* as corrosion inhibitor for mild steel in acid medium, *International Journal of Scientific and Engineering Research*, **5(10)**: 1411-1416.
 33. R. A. M. Saedah, S. R. Al-Mhyawi, (2014) Inhibition of mild steel corrosion using *Juniperus* plants as green inhibitor, *African Journal of Pure and Applied Chemistry*, **8(1)**: 9-22.
 34. H. Cang, Z. Fei, J. Shao, W. Shi, Q. Xu, (2013) Corrosion inhibition of mild steel by Aloes extract in HCL solution medium, *International Journal of Electrochemical Science*, **8(1)**: 720-734.
 35. M. Manickam, D. Sivakumar, B. Thirumalairaj, M. Jaganathan, (2016) Corrosion inhibition of mild steel in 1 mol L⁻¹ HCl using gum exudates of *Azadirachta indica*, *Advances in Physical Chemistry Hindawi Publishing Corporation*, **2016**: 12.
 36. B. Raja, M. G. Sethuraman, (2009) *Solanum tuberosum* as an inhibitor of mild steel corrosion in acid media, *Iranian Journal of Chemistry and Chemical Engineering*, **28(1)**: 77-84.
 37. M. Znini, G. Cristofari, L. Majidi, A. Ansari, A. Bouyanzer, (2012) Green approach to corrosion inhibition of mild steel by essential oil leaves of *Asteriscus graveolens* (Forssk.) in sulphuric acid medium, *International Journal of Electrochemical Science*, **7(5)**: 3959-3981.
 38. H. Z. Alkhatlan, M. Khan, M. M. S. Abdullah, A. M. Al-Mayouf, A. A. Mousa, Z. A. M. Al-Othman, (2014) *Launaea nudicaulis* as a source of new and efficient green corrosion inhibitor for mild steel in acidic medium: A comparative study of two solvent extracts, *International Journal of Electrochemical Science*, **9(2)**: 870-889.
 39. M. R. Singh, P. Gupta, K. Gupta, (2013) The litchi (*Litchi chinensis*) peels extract as a potential green inhibitor in prevention of corrosion of mild steel in 0.5M H₂SO₄ solution, *Arabian Journal of Chemistry*, **4(5)**: 6.
 40. S. K. Shukla, P. Dwivedi, S. Sundaram, E. E. Ebenso, (2012) Green capsicum annum fruit extract for inhibition of mild steel corrosion in hydrochloric acid solution, *International Journal of Electrochemical Science*, **7**: 12146-12158.
 41. E. E. Oguzie, (2005) Inhibition of acid corrosion of mild steel by *Telfaria occidentalis* extract, *Pigment and Resin Technology*, **34(6)**: 321-326.
 42. V. Namratha, P. Sahithi, (2015) Baobab: A review about 'the tree of life', *International Journal of Advanced Herbal Science and Technology*, **1(1)**: 20-26.
 43. M. Sidibe, J. T. Williams, A. Hughes, N. Haq, R. W. Smith, (2002) Baobab. *Adansonia digitata*, *International Centre for Underutilised Crops*, **2002**: 20.

*Bibliographical Sketch



Petro Novert Karungamye is a tutorial assistant in the Department of Chemistry, College of Natural and Mathematical Sciences, the University of Dodoma, Tanzania. He assists in teaching various chemistry courses including Solid state chemistry, Organic chemistry, Environmental chemistry and analytical chemistry. He obtained his bachelor degree (Bachelor of Science in Chemistry) from the University of Dodoma in the year 2012 which enabled him to work as a quality assurance officer in beverage industry and then laboratory technician in brewing industry where he got exposure to analytical methods, calibration, instrumentation, inspection of raw materials and products and generally good manufacturing practice and good laboratory practice. He is currently a graduate student in the University of Dodoma doing Masters of Science in Chemistry. His research interests include corrosion inhibition, biofuels, computational chemistry and water treatment technologies. He has some publications on corrosion inhibition of mild steel using green inhibitors. Email: petrokarungamye@gmail.com