Bioinhibition of Corrosion of Mild Steel in 1 M NaOH by Ethanolic Extract of *Dialium guineense* Leaves Using Different Corrosion Techniques

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ABSTRACT

This work assessed the efficacy of *Dialium guineense* leaf extract (DGE) in corrosion inhibition of mild steel in 1 M NaOH medium utilizing various corrosion methods like gravimetric, potentiodynamic polarization techniques, etc. The leaf extract was characterized by Fourier transform infrared spectroscopy, gas chromatography-mass spectrometry, and phytochemical analysis. Polished mild steel after being immersed in the leaf extract was characterized by scanning electron microscopy methods to assess the surface effect of the inhibitor on the mild steel. Gravimetry, electrochemical impedance spectroscopy, and potentiodynamic polarization methods were employed in studying the adsorption, kinetics, and thermodynamics behavior of corrosion inhibition of mild steel at different temperatures (303 K, 323 K, and 343 K) and varied inhibitor concentrations (0.2, 0.4, 0.6, 0.8, and 1.0 g/L). Response surface methodology was employed to optimize the inhibition efficacy. The gravimetric results revealed that the DGE was more efficient at higher concentrations but less efficient at lower temperatures. The potentiodynamic polarization results, on the other hand, indicate that the DGE is a mixed-type inhibitor. Electrochemical impedance spectroscopy results revealed that the addition of the inhibitor increased the charge-transfer resistance of the corrosion process and hence the suppression performance. The DGE exhibited good corrosion resistance performance; hence, it can serve as a suitable corrosion inhibitor for mild steel in NaOH and other alkaline media.

Keywords: corrosion inhibition, mild steel, *Dialium guineense*, corrosion techniques, RSM, optimization

Abbreviations

FTIR	Fourier transform infrared spectroscopy
GC-MS	Gas chromatography–mass spectrometry
SEM	Scanning electron microscopy
mg CE	milligram Catechin equivalents
GAE	Gallic acid equivalents
Conc.	Concentration
SCE	Standard calomel electrode
EIS	Electrochemical Impedance Spectroscopy

ANOVA	Analysis of variance
Std. Dev.	Standard deviation
BIC	Bayesian information criterion
AIC	Akaike information criterion

INTRODUCTION

Nowadays, mild steel is extensively utilized in industrial piping, automobiles, structural fabrication, aircraft, metal components of machines, bridges, railways, domestic tools, etc. Industrial processes such as prickling (for removing the undesired scales, impurities like oxides and other contaminants) as well as washing metals with acids often involve contact between the metal and a destructive solution, therefore making the metal vulnerable to corrosion (Sharma & Sharma, 2016). Corrosion is the degradation of these metallic equipment and components by chemical or electrochemical reactions with their environments. Mild steel, being a ferrous metal, is very susceptible to corrosion attack. One of the greatest empirical methods of checking mild steel corrosion in an aggressive medium is by employing a corrosion inhibitor (Chaubey, Savita, et al., 2017). A corrosion inhibitor is a material that successfully decreases the corrosion speed of a metal exposed to corrosion agents on addition of a little amount to such metal's environment (Buchweishaija, 2009). The ability of various organic compounds having nitrogen, oxygen, sulfur, phosphorus, and multiple bonds or aromatic rings in their structures to form a protective film on a metal surface has revealed that such can be good corrosion inhibitors (Gopal et al., 2013). However, the use of conventional inhibitors has been reduced in recent times due to their price and harmful effects on the environment (Dehghani et al., 2020). Plant extracts are now considered better corrosion inhibitors manufactured organic than compounds because they are cheap, handy, harmless, inexhaustible, and environmental friendly (Prabakaran et al., 2016). The phytochemicals (alkaloids and flavonoids) found in plant extracts have heteroatoms (N, S, O, and π -

electrons, aromatic ring), which aid their adsorption on active sites of the metal surface and consequently resist corrosion (Chaubey, Yadav, et al., 2017).

This work investigates the use of *Dialium* guineense leaf extract (DGE) to reduce the degradation rate of mild steel in 1 M NaOH using some corrosion techniques. The taxonomic or scientific classification of velvet tamarind (*Dialium guineense*) is as follows:

Kingdom	-	Plantae (plants)
Division	-	Tracheophyta (vascular
		Plants)
Class	-	Magnoliopsida
Order	-	Fabales
Family	-	Fabaceae (legumes)
Genus	-	Dialium
Species	-	D. guineense
Binomial		
Name	-	Dialium guineense Willd

MATERIALS AND METHODS

Materials

Mild steel; Reagents: NaOH, acetone, distilled water, each of analytical grade.

Plant leaf extract: Dialium guineense

Equipment: (a) Fourier transform infrared spectroscopy (FTIR) Shimadzu, Model: IRAffinity-1; S/N: A2137470136 SI)

(b) Gas chromatography-mass spectrometry (GC-MS) GCMS-QP2010 PLUS, Shimadzu, Japan)

(c) Scanning electron microscopy (SEM) model: Phenom Prox, Phenom World Eindhoven, Netherlands

(d)Potentiostat/galvanostat 263 electrochemical system workstation

(e) Design expert software

(f) Glassware, electronic weighing balance, water bath, Memmert oven, stopwatch

(g) Others: knife, plastic bucket, grinding machine, filter paper, thread, masking tape, emery papers, etc.

Preparation of the Bioinhibitor

The method used here is similar to those of Omotioma and Onukwuli (2016). Leaves of Dialium guineense were sourced from Isuaniocha, Anambra State, Nigeria. These leaves were identified at the Botany Department, Nnamdi Azikiwe University, Awka. The leaves were dried under the sun for three days, ground, and stored in a closed container. Twenty grams of the sample was measured and soaked in 500 ml of ethanol (99.7% v/v) for 24 hr. The mixture was filtered to obtain the desired filtrate, a mixture of ethanol and the bioinhibitor. The solvent, ethanol, was recovered by evaporation, while the desired bioinhibitor was weighed and stored for corrosion bioinhibition study.

Preparation of Mild Steel Coupons

The method adopted here is similar to that of Omotioma and Onukwuli (2015, 2017). The mild steel was size reduced to 5 cm \times 4 cm \times 0.1 cm to obtain the coupons. The coupons were washed and smoothened with emery paper to reveal a polished surface. Oil and organic impurities were removed from the coupons by degreasing with acetone, washing with distilled water, drying in air, and finally storing in desiccators. The initial weight of the coupons was obtained using an electronic weighing balance.

Preparation of Alkaline Solution

The alkaline solution was prepared with the aid of an electronic weighing balance, a volumetric flask, and a beaker; 1 M NaOH was prepared by dissolving 40 g of NaOH in 1 L of distilled water.

Characterization of the DGE *FTIR analysis*

This analysis involves using а spectrophotometer to identify the type of bonding especially functional groups existing in an organic compound (El Ouariachi et al., 2010). DGE contains organic compounds that are adsorbed on the metal surface to provide protection against corrosion. Therefore, the FTIR analysis can be suitable in predicting whether organic inhibitors are adsorbed or not. The DGE and the protective film that is formed over the steel surface by the inhibitor molecule were analyzed separately using FTIR spectroscopy using the KBr pellet method. The specimen (mild steel) was immersed in the corrosive medium consisting of 0.2–1.0 g/L of the inhibitor for 8 hr, which gave rise to the formation of a fine protective film over the mild steel surface. Further, the film was carefully scratched from the mild steel surface and analyzed by FTIR spectroscopy. The analysis was carried out PerkinElmer System FTIR using а instrument (Erebugha et al., 2014).

$$\Delta w = w_i - w_f \tag{1}$$

$$CR = \frac{w_i - w_f}{At} \tag{2}$$

$$IE\% = \frac{\omega_0 - \omega_1}{\omega_0} * 100 \tag{3}$$

$$\theta = \frac{\omega_0 - \omega_1}{\omega_0} \tag{4}$$

$$\omega_0$$
 (4)

where w_i and w_f are the initial and final weight of metal samples, respectively; ω_1 and ω_0 are the weight loss values in presence and absence of inhibitor, respectively; A is the total area of the specimen; and t is the immersion time. The reaction number (RN) was also evaluated using Equation 5 (Eddy et al., 2012).

$$RN = \frac{T_{\rm m} - T_{\rm i}}{t} \tag{5}$$

where $T_{\rm m}$ and $T_{\rm i}$ are the maximum and initial temperatures (in degrees Celsius), respectively, and *t* is the time in minutes elapsed to reach $T_{\rm m}$.

The inhibitor efficiency was determined using Equation 6:

$$IE\% = (1 - \frac{RN_{add}}{RN_{free}}) * 100$$
 (6)

where RN_{free} and RN_{add} are the reaction numbers for the metal dissolution in free and inhibited corrosive medium, respectively.

Weight loss method using response surface method

The method used here is similar to that of Ezeugo et al. (2017). Using the response surface method (RSM), $_{\mathrm{the}}$ inhibitor concentration, temperature, and time were the considered factors while weight loss, CR, and IE were the expected responses of the study. The RSM was used to analyze the responses, and the graphical analyses of the inhibition efficiencies were equally carried out. The mathematical models in terms of coded form were obtained. The models in terms of coded factors were used to make predictions about the response for given levels of each factor. The high levels of the factors were coded as +1, and the low levels of the factors were coded as -1.

Potentiodynamic measurements

The method used here is similar to that of Ezeamaku et. al. (2019).Potentiodynamic/galvanostat corrosion system with the EChem software was used for the potentiodynamic polarization experiment. A graphite rod was used as counter electrode, and a saturated calomel electrode (SCE) was used as reference electrode. The latter was connected via a Luggin capillary. Impedance measurements were performed in aerated and unstirred solutions at the end of 1,800 s at $30 \pm 1^{\circ}$ C. The studies were carried out in the potential range ± 250 mV versus corrosion potential at a scan rate of 0.333 mVs⁻¹. The test was run in triplicate to verify the repeatability of the data. The experiments

were carried out in freshly prepared solution at a temperature of 30 ± 1 °C (Chidiebere et al., 2012; Oguzie et al., 2010). The IE was determined using Equation 7:

$$IE\% = \frac{i_{\text{corr(uninh)}} - i_{\text{corr(inh)}}}{i_{\text{corr(uninh)}}} \times 100$$
(7)

where $i_{\text{corr(uninh)}}$ and $i_{\text{corr(inh)}}$ are the corrosion current density values without and with the inhibitor, respectively.

Electrochemical measurements

The method used here is similar to that of Ezeamaku et al. (2019). This experiment was conducted in a three-electrode corrosion cell using a VersaSTAT 300 complete DC voltammetry and corrosion system with V3 studio software for electrochemical impedance spectroscopy. A graphite rod was used as counter electrode, and an SCE was used as reference electrode. The latter was connected via а Luggin capillary. Impedance measurements were performed in aerated and unstirred solutions at the end of 1,800 s at $30 \pm 1^{\circ}$ C. Impedance measurements were made at corrosion potentials (E_{corr}) over a frequency range of 100 KHz-0.1 Hz with a signal amplitude perturbation of 5 mV (Ihebrodike et al., 2012; Oguzie et al., 2012). The inhibition efficiencies (IE%) for different inhibitor concentrations were calculated from Nyquist plots using the following equation:

$$IE\% = \left(\frac{R_{\rm ct(inh)} - R_{\rm ct}}{R_{\rm ct(inh)}}\right) \times 100$$
 (8)

where $R_{\rm ct}$ and $R_{\rm ct(inh)}$ denote charge transfer resistance in the absence and presence of the inhibitor.

Effect of Temperature on CR

Based on the work done by Ezeugo et al. (2017), the effect of temperature on the CR was described using the Arrhenius equation:

$$CR = Ae^{-E_{a}/_{RT}}$$
(9)

Equation (9) can be linearized.

$$\ln(CR) = \ln A - \left(\frac{E_a}{R}\right)\left(\frac{1}{T}\right) \tag{10}$$

Considering the CRs of the metal at T_1 and T_2 as CR_1 and CR_2 , then Equation 10 can be expressed by Equation 11 (Nnanna et al., 2013; Nwabanne & Okafor, 2011; Octave, 2003).

$$\ln \left(\frac{CR_2}{CR_1} \right) = \left(\frac{E_a}{2.303R} \right) \left(\frac{1}{T_1} - \frac{1}{T_2} \right) \tag{11}$$

Thermodynamic Parameter for the Adsorption Process

Ebenso et al. (2008) and Nwabanne and Okafor (2011) evaluated the heat of adsorption (Q_{ads} ; kJmol⁻¹) using Equation 12.

$$Q_{\text{ads}} = 2.303 \text{R} \left[\log \left(\frac{\theta_2}{1 - \theta_2} \right) - \log \left(\frac{\theta_1}{1 - \theta_1} \right) \right] * \frac{T_2 \cdot T_1}{T_2 - T_1}$$
(12)

where R is the gas constant; θ_1 and θ_2 are the degree of surface coverage at temperatures T_1 and T_2 , respectively; and Q_{ads} is the heat of adsorption.

Adsorption Isotherms

According to Omotioma and Onukwuli (2016), the data obtained for the degree of surface coverage were used to test for the applicability of different adsorption isotherms such as Langmuir, Frumkin, Temkin, and Flory–Huggins isotherms.

Langmuir isotherm

The Langmuir isotherm can be expressed by Equation 13 (Li & Deng, 2012; Nwabanne & Okafor, 2011; Patel et al., 2013).

$$\frac{c}{\theta} = \frac{1}{\kappa} + C \tag{13}$$

where *C* is the concentration of the inhibitor, *K* is the adsorption equilibrium constant, and θ is the degree of surface coverage.

Linearizing Equation 13 gives

$$\log \frac{c}{\theta} = \log C - \log K \tag{14}$$

Frumkin isotherm

The Frumkin adsorption isotherm can be expressed according to Equation 15 (Nwabanne & Okafor, 2011).

$$\log\left((C) * \left(\frac{\theta}{1-\theta}\right)\right) = 2.303 \log K + 2\alpha\theta \qquad (15)$$

where K is the adsorption-desorption constant and α is the lateral interaction term describing the interaction in adsorbed layer.

Temkin isotherm

The Temkin isotherm can be expressed by Equation 16 (Nwabanne & Okafor, 2011):

$$\theta = -\frac{2.303 \log K}{2a} - \frac{2.303 \log C}{2a}$$
(16)

where *K* is the adsorption equilibrium constant, *a* is the attractive parameter, θ is the degree of surface coverage, and *C* is the concentration of the inhibitor.

Flory–Huggins isotherm

The Flory–Huggins isotherm can be expressed by Equation 17 (Alinnor & Ejikeme, 2012; Nwabanne & Okafor, 2011).

$$\log(\frac{\theta}{c}) = \log K + x \log(1 - \theta)$$
(17)

where x is the size parameter and is a measure of the number of adsorbed water molecules substituted by a given inhibitor molecule.

The free energy of adsorption (ΔG_{ads}) was calculated according to Equation 18 (Alinnor & Ejikeme, 2012; Nwabanne & Okafor, 2011).

$$\Delta G_{ads} = -2.303 RT \log(55.5K) \tag{18}$$

where R is the gas constant, T is temperature, K is the equilibrium constant for the adsorption process, and 55.5 represents the concentration of water in the alkaline solution.

RESULTS AND DISCUSSION

Characterization of the Extract and Coupons

Fourier transform infrared spectrometer analysis

The peaks, intensities, and assignments of the FTIR analyses of the pure plant extract and corrosion product with the plant extract are presented in Table 1. The shift/disappearance of some functional groups observed in the scratched metal oxide film shown in the Table 1 was as a result of the active functional groups that actually inhibit the metal's corrosion process. Table 1 presents the analysis of DGE and scratched mild steel oxide film. The FTIR spectra of the adsorbed protective layer formed on a mild steel surface after immersion in 1 M NaOH containing 0.4 g/L of DGE proves that the adsorption of the inhibitors took place via –OH stretching, N–H bending, C–O stretching, as well as –C, C– H:C–H bending and C–C stretching.

<i>Dialium guineense</i> Leaves Extract			Scratcl	ned Mild Ste	eel Oxide Film
Peak (cmol²/kJ²)	Intensity	Assignment	Peak (cmol²/kJ²)	Intensity	Assignment
581.64	1.5377	C=C-H, Ar-H	613.36	1.8791	C=C-H, Ar-H bend
		bend out of plane			out of plane
763.08	2.1753	C=C-H, Ar-H	613.36	2.908	C≡C-H, C-H bend
		bend out of plane			
887.88	2.964	C=C-H, Ar-H	860.24	2.0199	C=C-H, Ar-H bend
		bend out of plane			out of plane
1,195.08	2.4171	C-H bend in plane	983.68	3.7293	C=C-H, Ar-H bend
					out of plane
1,319.88	2.1638	C-H bend in plane	937.39	2.6214	C=C-H, Ar-H bend
					out of plane
1,442.76	2.6399	N-O asymmetric	1,292.28	2.1001	N-O symmetric
		stretch			stretch
1,633.80	1.9191	C=C stretch, C=N	1,662.6	2.2599	C=C stretch, C=N
		stretch			stretch
1,873.80	2.8225	C=O stretch	1,724.32	2.0579	C=O stretch
			1,878.62	2.4582	
2,244.36	2.8358	$C \equiv C$ stretch, $C \equiv N$	2,187.22	2.0436	$C \equiv C$ stretch, $C \equiv N$
		stretch	2,310.66	2.5063	stretch
3,623.88	1.9735	O-H stretch	3,483.34	2.4463	O-H stretch
			3,575.92	2.3126	

Table 1. Peak, Intensity, and Assignment of FTIR Analysis of Dialium gu	ineense
Leaves Extract and Scratched Mild Steel Oxide Film in NaOH	

GC-MS analysis

The volatile or semi-volatile phytocomponents present in the leaf ethanolic extract of DGE were identified by GC-MS analysis at a GC-MS running time of 40 min. The active compounds in the leaf ethanolic extract of the plant, the retention time, and the molecular formula are provided in **Table** 2. The aqueous extract of DGE revealed several peaks that represent different compounds as shown in the table. The peaks in the chromatogram were integrated and were compared with the database of spectrum of known components stored in the GC-MS library.

Peak	Name of Compound	Molecular I	Retention
1	n-Hexadecanoic acid	$C_{16}H_{39}O_{2}$	32 3716
2	15-Hydroxypentadecanoic acid	$C_{15}H_{30}O_{3}$	32.7906
3	n-Hexadecanoic acid	$C_{16}H_{32}O_2$	33.0809
4	Tetradecanoic acid	$C_{14}H_{28}O_2$	33.1148
5	Glycidyl palmitate	$C_{19}H_{36}O_{3}$	36.9148
6	Tetradecanoic acid	$\mathrm{C}_{14}\mathrm{H}_{28}\mathrm{O}_2$	37.0637
7	Octadecanoic acid, 2-hydroxy-1, 3- propanediyl ester	$C_{39}H_{76}O_5$	39.8625
8	Glycidyl palmitate	$C_{19}H_{36}O_{3}$	40.6906
9	Octadecanoic acid, 2-hydroxy-1, 3- propanediyl ester	$C_{39}H_{76}O_5$	40.9025
10	cis-Vaccenic acid	$C_{18}H_{34}O_2$	42.0927
11	Oleic acid	$C_{18}H_{34}O_2$	42.8762
12	Cyclopentadecanone, 2-hydroxy-	$C_{15}H_{28}O_2$	42.9755
13	9-Octadecenal, (Z)-	$C_{18}H_{34}O$	43.7866
14	trans-13-Octadecenoic acid	$C_{18}H_{34}O_2$	43.9923
15	15-Hydroxypentadecanoic acid	$\mathrm{C_{15}H_{30}O_{3}}$	44.1598
16	Lauric anhydride	$C_{24}H_{46}O_3$	44.2778
17	Lauric acid, 3, 4-dichlorophenyl ester	$C_{10}H_{10}C_{12}O_2$	44.5425
18	Carazolol	$C_{18}H_{22}N_2O_2$	44.6384
19	Dodecanoic acid, 1-(hydroxymethyl)-1, 2- ethanediyl ester	$C_{35}H_{68}O_5$	44.8747
20	Dodecanoic acid, 1-(hydroxymethyl)-1, 2- ethanediyl ester	$C_{35}H_{68}O_5$	45.1196
21	Nonacosan-14-one	$C_{29}H_{58}O$	46.2486
22	Lauric acid, 3, 4-dichlorophenyl ester	$C_{10}H_{10}C_{l2}O_{2}\\$	46.9733

Table 2. Gas Chromatography-Mass Spectrometry Analysis of DGE

Metal surface study using scanning electron microscopy (SEM)

Scanning electron microscopy (SEM) gives a visual image of the metal surface studied to understand the nature of the surface film in the control and in the presence of the inhibitor and the degree of corrosion of the metals. The digital images of the corroded metal, in NaOH medium, in the absence and presence of the plant extract are presented in Figure 1. Close observation of the images shows that there is remarkable difference in the metal surface in the absence and presence of the bioinhibitor. The images revealed that the metal surface in Figure 1a was greatly degraded due to pitting corrosion in the control, but in the presence of the bioinhibitor (Fig. 1b), there is a mild degradation of the metal surface. The reason behind this is that the bioinhibitor formed a protective layer on the mild steel surface (Omotioma & Onukwuli, 2017; Shanthi & Rajendran, 2013). The images have close correlation with the results obtained from the weight loss method. This is in agreement with the previous studies by Ezeugo et al. (2017) and Loto and Popoola (2012). The nature of the images shows that the DGE reduced the CR.



Figure 1. The micrograph of corroded mild steel surface in NaOH, (a) without DGE and (b) with DGE.

Phytochemical results

In Table 3, the qualitative analysis of the DGE shows that the phytochemicals alkaloids, cardiac glycosides, flavonoids, phenolics, phytates, saponins, and tannins are present in it at different levels. The qualitative results of the phytochemicals of the DGE are denoted with symbols: +++ (very strong), ++ (strong), + (in minute), and - (not present or too little to be observed qualitatively). Table 3 also indicates the amount/quantity of each phytochemical present in 1 ml of the extract. The presence of a reasonable amount of the phytochemicals (alkaloids and flavonoids) shows that DGE could make a good corrosion inhibitor because these components contain heteroatoms that aid their adsorption on the active sites of the metal and, as a result, inhibit corrosion.

Table	3.	Qualitative	and 6	Juantitative	Analysis	of the	DGE
Laste	••	quantuutive	ana y	Launinani	r indi y DiD		DOL

Parameters	Quality	Quantity (mg/100 g)
Alkaloids	+	83.3
Cardiac	+	70.0
glycosides Flavonoids (mg CE/100	++	365.0
g) Phenolics (GAE/g)	++	24.9
Phytates	+	50.0
Saponins	++	11.7
Tannins	++	270.0

Note. mg CE = milligram catechin equivalents, GAE = Gallic acid equivalents.

Weight Loss Results Effect of inhibitor concentration and temperature on weight loss and CR

The results of the weight loss after 8 hours is shown in Table 4 below. The inhibitor concentration of 0.0 represents the uninhibited mild steel, which served as the control experiment. It can be observed that weight loss is at maximum in the absence of the inhibitor but decreases alongside the CR with an increase in inhibitor concentration. Temperature rise, on the other hand, does not favor weight loss cum CR.

Temperature (K)	Inhibitor Concentration	Weight Loss (g)	Corrosion Rate (mg/cm ² hr)
()	(g/L)		(9:)
303	0.0	0.037	0.231
	0.2	0.027	0.169
	0.4	0.027	0.169
	0.6	0.017	0.106
	0.8	0.017	0.106
	1.0	0.013	0.081
323	0.0	0.053	0.331
	0.2	0.040	0.250
	0.4	0.033	0.206
	0.6	0.030	0.188
	0.8	0.027	0.169
	1.0	0.027	0.169
343	0.0	0.057	0.356
	0.2	0.047	0.294
	0.4	0.037	0.231
	0.6	0.037	0.231
	0.8	0.030	0.188
	1.0	0.030	0.188

Table 4. Variation of Weight Loss and Corrosion Rate With Inhibitor Concentration
and Temperature

Effect of inhibitor concentration and temperature on IE%

From Figure 2 below, there is rise in IE with increase in DGE concentration and decrease in temperature. The highest IE, 78%, was obtained at the inhibitor concentration of 1.0 g/L and at a lower temperature of 303 K.

This means that corrosion inhibition is more favored at room temperature than at higher temperatures. This is suggestive of physical adsorption mechanism, which agrees with what was obtained by Labjar et al. (2011).



Figure 2. Effect of inhibitor concentration and temperature on inhibition efficiency (IE) .

Potentiodynamic Polarization Measurements

From the polarization curves shown in Figure 3, it is clear that the mild steel, while showing active dissolution, showed no sign of moving to passivation in the alkaline solution. The electrochemical variables, namely, the corrosion potential (E_{corr}) , corrosion current densities (I_{corr}) , and the cathodic (b_c) and anodic (b_a) current values obtained from polarization curves, are presented in Table 5. Close inspection of the plot in Figure 3 shows that increase in the concentration of DGE suppresses both the dissolution of the metal in the anode and the evolution of hydrogen in the cathode. The corrosion potential $E_{\rm corr}$ shifts were not significant enough to either the negative or noble direction. According to Chidiebere et al. (2012), if the displacement of $E_{\rm corr}$ is more than 85 mV as earlier stated, we may say that the inhibitor is cathodic or anodic type. However, our results show that $E_{\rm corr}$ values are within the range of 15 mV to 53 mV. Hence, DGE can be regarded as a mixed-type inhibitor in this environment under study. This result agrees with Mistry et al. (2012) and Elmsellem et al. (2014). Generally, the corrosion current density (I_{corr}) is reduced with an increase in DGE concentration (from 196.2 μ A/cm² to 24.1 μ A/cm²). According to Chidiebere et al. (2012), the IE from polarization data as presented in Equation 7 can be estimated from the figures obtained for the corrosion current density in the absence $(i_{\text{corr,bl}})$ and presence of the inhibitor ($i_{\text{corr,inh}}$). The values obtained are presented in Table 5. The highest IE obtained for 1,000 mg/L of DGE in 1 M NaOH is 87.7%.



Figure 3. Potentiodynamic polarization curves of mild steel in 1 M NaOH in the control and presence DGE.

Table 5. Polarization Parameters for Mild Steel in 1 M NaOH in the Control

	and Presence of	DI DGE	
States	$E_{ m corr}$	$I_{ m corr}$	IE
System	(mV vs SCE)	(µA/cm²)	%
1 M			
NaOH	500		
200	-529	196.2	70
mg/L	-356	57.6	10. C
1,000	-476	24.1	0 97
mg/L			01. 7
-			1

Note. SCE = standard calomel electrode.

Electrochemical Impedance Spectroscopy Studies

Figures 4a–c show the impedance plots for mild steel in the control and in the presence of DGE, respectively. One time constant in the Bode plots corresponds to the single depressed capacitive loop in the Nyquist plots. Addition of DGE increases the magnitude of the semicircle (increase in charge transfer resistance) in Figure 4a, in the impedance of the interface in Figure 4b, and also in the highest phase angle in Figure 4c, respectively. The observation shows that inhibition of the corrosion process is taking place at the mild steel/NaOH interface, and the level of charge transfer resistance is seen to increase with an increase in the concentration of DGE indicating the presence of a thin film layer formed/adsorbed on the mild steel surface. According to Chidiebere et al. (2012), to obtain the quantitative values of the different impedance parameters presented in Table 6, the impedance spectra were examined by fixing to the equivalent circuit model $R_{
m s}$ $(Q_{\rm dl}R_{\rm ct})$, which has been earlier used to adequately model the mild steel/NaOH interface. Table 5 in agreement with the work done by Chidiebere et al. (2012), work clearly shows that DGE enhanced the R_{ct} at all concentrations, which corresponds to an increase in the diameter of the Nyquist semicircle and in the magnitude of the impedance modulus in the Bode plots, confirming the corrosion inhibiting effect. Also, the IE from the impedance data (IE%) was estimated by comparing the values of the charge transfer resistance in the control $(R_{\text{ct,bl}})$ and presence of the inhibitor $(R_{\text{ct,inh}})$ using Equation 8. The figures of the double-layer capacitance (C_{dl}) shown in Table 6, still in agreement with the work done by Chidiebere et al. (2012), were obtained at the frequency at which the imaginary component of the impedance is highest $(Z_{im(max)})$ using the following equation:

$$Z_{(\text{im})\text{max}} = \frac{1}{2\pi C_{\text{dl}} R_{\text{ct}}}$$
(19)

The parameter C_{dl} was modified in the presence of A yielding a lower value than observed in the uninhibited corrodent.

Equally in agreement with the work done by Chidiebere et al. (2012), lower C_{dl} values agree with the decreased interfacial capacitance, which, according to the Helmholtz model, results from a decline in the dielectric constant (e) or a rise in the double-layer thickness (δ) due to species adsorption at the double-layer capacitance given by $C_{dl} = \varepsilon \varepsilon_0 A/\delta$, where ε is the dielectric constant of the medium, ε_0 is the vacuum permittivity, A is the electrode area, and δ is the thickness of the interfacial layer. The reduction in C_{dl} value calculated from our electrochemical impedance spectroscopy (EIS) measurements proves that the DGE was adsorbed on the corroding mild steel surface. According to Chidiebere et al. (2014), the reduction in interfacial capacitance could be due to displacement of water molecules on mild steel surface by the organic compound, which has lower dielectric constants compared to water. Secondly, an increment in the thickness of the double layer due to adsorption of the DGE on the steel surface also gives rise to depletion of interfacial capacitance. The increase in resistance atа particular inhibitor concentration is in agreement with the results obtained from Chidiebere et al. (2015) and suggests the enhancement of adsorption of organic molecules on the mild steel surface and covering of the steel surface efficiently. Our results show that the inhibitor under investigation is efficient for inhibiting mild steel corrosion in 1 M NaOH solution.



Adsorption Properties for the Corrosion Inhibition





Figure 4. Electrochemical impedance spectra of mild steel in 1 M NaOH solution in the absence and presence of DGE: (a) Nyquist, (b) Bode phase angle, and (c) Bode modulus.

Table 6. Electrochemical Parameters for Uninhibited and Inhibited Mild Steel in 1 M NaOH

			• •		
		Dial	ium guinee	nse	
System	$R_{ m L1}(\Omega { m cm}^2)$	Rs (Ωcm^2)	$R_{ m ct}$ ($\Omega m cm^2$)	С _{d1} (µFст ⁻²)	IE%
1 M NaOH	6.2	2.13	98.7	3.12	
200 mg/L	412	3.23	342.2	1.54	71.2
1,000 mg/L	1988	3.67	812.5	1.02	87.9

Results of the Weight Loss Method Using RSM

The response (inhibition efficiencies) to the factors (inhibitor concentration, temperature, and time) for the bioinhibition of the corrosion of mild steel is presented in Table 7. A total of 30 experiments were used for the RSM modeling. The data show the variation of IE with NaOH/inhibitor concentrations, temperature, and time for the corrosion inhibition of mild steel. The IE obtained varied between 31.11% and 79.33%, showing an increment with a rise in concentration and time of immersion in DGE but a fall with temperature rise. These observations are in agreement with previous studies of El Ouariachi et al. (2010), Ndibe et al. (2011), and Abdulwahab et al. (2012).

Table 7. Experimental	Values of Factors and	Response Experiments
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		Factor 1	Factor 2	Factor 3	Factor 4	Response
Standard	Run	NaOH Concentration	Inhibitor Concentration	Time	Temperature	Inhibitor Efficiency
		(mol)	(g/L)	(hr)	(K)	(%)
14	1	2	0.025	6.25	333	36.11
18	2	2.5	0.04	4.5	323	47.84
11	3	1	0.055	2.75	333	67.67
25	4	1.5	0.04	4.5	323	56.6
16	5	2	0.055	6.25	333	61.6
27	6	1.5	0.04	4.5	323	57.02
23	7	1.5	0.04	4.5	303	66.67
9	8	1	0.025	2.75	333	66.67
17	9	0.5	0.04	4.5	323	70.97
1	10	1	0.025	2.75	313	67.44
19	11	1.5	0.01	4.5	323	66.67
15	12	1	0.055	6.25	333	57.5
6	13	2	0.025	6.25	313	66.67
7	14	1	0.055	6.25	313	51.06

28	15	1.5	0.04	4.5	323	59
22	16	1.5	0.04	8	323	54.37
5	17	1	0.025	6.25	313	79.33
24	18	1.5	0.04	4.5	343	58.45
8	19	2	0.055	6.25	313	66.67
30	20	1.5	0.04	4.5	323	60.19
10	21	2	0.025	2.75	333	31.11
13	22	1	0.025	6.25	333	64.37
12	23	2	0.055	2.75	333	61.33
3	24	1	0.055	2.75	313	50.45
20	25	1.5	0.07	4.5	323	71.67
2	26	2	0.025	2.75	313	40.19
26	27	1.5	0.04	4.5	323	61.11
21	28	1.5	0.04	1	323	43.84
4	29	2	0.055	2.75	313	56.67
29	30	1.5	0.04	4.5	323	58.6

Analysis of Variance (ANOVA)

The statistical sufficiency of this model was further investigated using analysis of variance (ANOVA), presented in Table 8. From the table, the individual results show that the factors base concentration and temperature, with high *p*-values (>0.05), are not important unlike the inhibitor concentration and time. However, they are important on interaction with other factors. The combined results of the factors on the efficacy of the inhibition are significant since the *p*-values are each <0.05 at the 95% confidence level ($\alpha = 0.05$). For instance, the interaction of base concentration and inhibitor concentration, AB, has a *p*-value of 0.0159, which is less than 0.05. This shows that the combined effect of the two factors on the inhibition efficiency is significant.

ANOVA for Response Surface Reduced Quadratic Model									
Analysis of variance table [partial sum of squares—type III]									
Source Sum of <i>df</i> Mean <i>F p</i> -Value									
Source	Squares	aj	Square	Value	(Probl	oility $> F$)			
Model	1,248.06	13	96.00	57.07	< 0.0001	Significant			
A-Base concentration	0.014	1	0.014	8.047E-	0.9296	Not			
				003		Significant			
B-Inhibitor concentration	29.28	1	29.28	17.41	0.0007	Significant			
C-Time	79.17	1	79.17	47.06	<0.0001	Significant			
D-Temperature	6.54	1	6.54	3.89	0.0662	Not			
						Significant			
AB	12.23	1	12.23	7.27	0.0159	Significant			
AC	64.76	1	64.76	38.49	<0.0001	Significant			
AD	374.33	1	374.33	222.50	<0.0001	Significant			
BC	210.18	1	210.18	124.93	<0.0001	Significant			
BD	93.27	1	93.27	55.44	<0.0001	Significant			
A^2	74.85	1	74.85	44.49	<0.0001	Significant			
B^2	125.99	1	125.99	74.89	<0.0001	Significant			
C^2	62.50	1	62.50	37.15	<0.0001	Significant			
D^2	93.67	1	93.67	55.68	<0.0001	Significant			
Residual	26.92	16	1.68						
Lack of fit	22.09	11	2.01	2.08	0.2164	Not			
						significant			
Pure error	4.83	5	0.97						
Corrected total	1,274.97	29							

 Table 8. ANOVA for RSM Model for the Factors-Interaction Response

Std. Dev.		R^2	0.9789
	1.30		
Mean	41.24	Adjusted R^2	0.9617
Coefficient of variation (%)	3.15	Predicted \mathbb{R}^2	0.9104
Predicted residual error sum of	114.21	Adequate	32.011
squares		precision	
-2 Log likelihood	81.88	BIC	129.50
		AIC	137.88

Note. RSM = response surface methodology, Std. Dev. = standard deviation, BIC = Bayesian information criterion, AIC = Akaike information criterion.

Graphical Analysis of the IE (%) Using RSM

The calculated plots against the observed plots as seen in fig. 5 show direct variation, indicating that the observed experimental values are consistent with the calculated values. Corrosion inhibition of mild steel in NaOH with various concentrations of DGE revealed that there is corresponding increase in the IE on increased DGE concentration. However, there is a fall in IE when temperature is increased. The above results are in agreement with previous studies by El Ouariachi et al. (2010), Ndibe et al. (2011), and Abdulwahab et al. (2012). The graphs of the IE versus concentration, temperature, and time are of second-degree polynomial.





Figure 5. IE (%) of DGE as bioinhibitor of mild steel corrosion in NaOH: (a) predicted against observed, (b) IE (%) against DGE concentration and NaOH concentration, (c) IE (%) against time and alkali concentration, (d) IE (%) against temperature and alkali concentration, (e) IE (%) against time and DGE concentration, and (f) IE (%) against temperature and DGE concentration.

Model Equation for the IE

 $\begin{array}{l} \text{IE}=+2550.66-286.91\text{A}-3916.83\text{B}+14.94\text{C}-1\\ 3.97\text{D}+116.58\text{A}^{*}\text{B}-2.30\text{A}^{*}\text{C}+097\text{A}^{*}\text{D}-138.07\\ \text{B}^{*}\text{C}+16.09\text{B}^{*}\text{D}-6.61\text{A}^{2}-9525.46\text{B}^{2}-0.49\text{C}^{2}+0\\ .02\text{D}^{2} \end{array}$

The model was obtained by employing RSM tools of design expert software. The

Optimum Conditions for the Corrosion Inhibition of Mild Steel

Table 9 displays the optimum inhibitor concentration, optimum temperature, and optimum time that led to the average model showed the variation among the IE, NaOH concentration (A), DGE concentration (B), time (C), and temperature (D). The regression model for IE of DGE as bioinhibitor of the mild steel corrosion in the NaOH is shown in Equation 20. This includes both significant and nonsignificant model parameters, which can be eliminated.

maximum IE for mild steel in the NaOH medium. The result shows that DGE has IE of 50.23% (with optimum inhibitor concentration of 0.027 g/L, temperature of 314.972 K, and time of 5.733 hr).

			DGE			
Media	Inhibitor (Plant Extract)	NaOH (mols)	Inhibitor Concentration (g/L)	Time (hr)	Temperature (K)	Inhibition Efficiency (%)
NaOH	Dialium guineense leaves	1.122	0.027	5.733	314.972	50.257

Table 9. Optimum Conditions for Corrosion Inhibition of Mild Steel in NaOH Using

Note. DGE = *Dialium guineense* leaf extract

additional experiment was conducted with chosen conditions for the concentration, temperature, and time as shown in Table 10. The table also shows the predicted (from measured IE is close to the calculated value. This shows the suitability of RSM approach for enhancing the corrosion inhibition process.

Medi a	Inhibitor (Plant Extract)	Acid/Al kaline (mols)	Inhibitor Concent ration (g/L)	Tempera ture (K)	Time (hr)	Predicted Inhibitio n Efficienc y (%)	Measured Inhibitio n Efficiency (%)	Percenta ge Error (%)
NaOH	Dialium guineense leaves	1.122	0.027	313.000	2.750	50.26	51.19	0.18

Table 10. Result Validation for Corrosion Inhibition of Mild Steel in NaOH

CONCLUSION

In this work, the efficiency of DGE as a corrosion bioinhibitor in 1 M NaOH medium was assessed. Phytochemical analysis and the FTIR results revealed the presence of alkaloids and flavonoids in DGE, which confirmed it a good corrosion inhibitor. The SEM micrographs revealed the DGE was protective on the mild steel surface. Gravimetric measurements showed the inhibitive action of the DGE was favored by its increased concentration and at room temperature. Potentiodynamic polarization studies reveal that DGE is a mixed-type inhibitor since it retards the two corrosion reactions occurring at the cathode and anode. Based on the electrochemical impedance spectroscopy experiments, solution resistance increase in increases with the DGE concentration due to the increase in the double-layer capacitance. Isotherm studies that the Flory-Huggins indicate and Langmuir models best fitted the adsorption of the DGE on the mild steel surface at the temperatures of 303 and 343 K, respectively. The quadratic nature of the model equation from RSM revealed that a blending of the inhibitor's concentration and either temperature or time remarkably affected the efficacy of the DGE. RSM was used to optimize the IE. The calculated optimum inhibitor efficiency of 50.23% was obtained

from RSM with the optimal process parameters of 0.027 g/L of inhibitor concentration, temperature of 314.972 K, and time of 5.733 hr. The calculated plot against the observed plot gave a straight line graph indicating the observed experimental value is consistent with the calculated value.

REFERENCES

- Abdulwahab, M., Kasim, A., Bello, K. A., & Gaminana, J. O. (2012). Corrosion inhibition of multi-component aluminium alloy in hydrochloric acid solution by aqueous extract of bitter leaf (Verninia amygdalina) powder. Advanced Materials Research, 367, 319–325.
- Alinnor, I. J., & Ejikeme, P. M. (2012). Corrosion inhibition of aluminum in acidic medium by different extracts of Osmium gratissium. American Chemical Science Journal, 2(4), 122–135.
- Buchweishaija, J. (2009). Phytochemicals as green corrosion inhibitors in various corrosive media: A review. *Tanzania Journal of Science*, 35.
- Chaubey, N., Savita, Singh, V. K., & Quraishi, M. (2017). Corrosion inhibition performance of different bark extracts on aluminium in alkaline solution. Journal of the Association of Arab Universities for Basic and Applied Sciences, 22(1), 38–44.

- Chaubey, N., Yadav, D. K., Singh, V. K., & Quraishi, M. (2017). A comparative study of leaves extracts for corrosion inhibition effect on aluminium alloy in alkaline medium. Ain Shams Engineering Journal, 8(4), 673–682.
- Chidiebere, M. A., Ogukwe, C. E., Oguzie, K. L., Eneh, C. N., & Oguzie, E. E. (2012).
 Corrosion inhibition and adsorption behavior of *Punica granatum* extract on mild steel in acidic environments: Experimental and theoretical studies. *Industrial and Engineering Chemistry Research*, 51, 668–677.
- Chidiebere, M. A., Oguzie, E. E., Liu, L., Li, Y., & Wang, F. (2014). Corrosion inhibition of Q235 mild steel in 0.5M H₂SO₄ solution by phytic acid and synergistic iodide additives. *Industrial and Engineering Chemistry Research*, 53(18), 7670–7679.
- Chidiebere, M. A., Oguzie, E. E., Liu, L., Li, Y., & Wang, F. (2015). Adsorption and corrosion inibiting effect of riboflavin on Q235 mild steel corrosion in acidic environments. *Materials Chemistry and Physics*, 156, 95– 104.
- Dehghani, A., Bahlakeh, G., Ramezanzadeh, B., & Ramezanzadeh, M. (2020). Potential role of a novel green eco-friendly inhibitor in corrosion inhibition of mild steel in HCl solution: Detailed macro/micro-scale experimental and computational explorations. Construction and Building Materials, 245, 118464.
- Ebenso, E. E., Eddy, N. O., & Odiongenyi, A. O. (2008). Corrosion of inhibitive properties and adsorption behaviour of ethanol of *Piper guinensis* as a green corrosion inhibitor for mild steel in H₂SO₄. African Journal of Pure and Applied Chemistry, 2(11), 107-115.
- Eddy, N. O., Ita, B. I., Dodo, S. N., & Paul, E. D. (2012). Inhibitive and adsorption properties of ethanol extract of *Hibiscus* sabdariffa Calyx for the corrosion of mild steel in 0.1M HCl. Green Chemistry Letters and Reviews, 5(1), 43–53.
- El Ouariachi, E., Paolini, J., Bouklah, M., Elidrissi,
 A., Bouyanzer, A., Hammouti, B.,
 Desjobert, J. M., & Costa, J. (2010).
 Adsorption properties of *Rosmarinus* officinalis oil as green corrosion inhibitors on C38 steel in 0.5M H₂SO₄. Acta Metallurgica Sinica (English Letters), 23(1), 13–20.

- Elmsellem, H., Aouniti, A., Khoutoul, M., Chetouani, A., Hammouti, B., Benchat, N., Touzani, R., & Elazzouzi, M. (2014).
 Theoretical approach to the corrosion inhibition efficiency of some pyrimidine derivatives using DFT method of mild steel in HCl solution. Journal of Chemical and Pharmaceutical Research, 6(4), 1216–1224.
- Erebugha, A. Y., Owuama, K. C., & Ezeugo, J. O. (2014). Study of inhibitive effect of Dennattia tripattalla on aluminum in tetraoxosulphate (VI) acid medium. Journal of Emerging Technologies and Innovative Research, 8(10), 637–646.
- Ezeamaku, U. I., Iheaturu, N. C., Cike, K. O., & Onukwuli, O. D. (2019). Corrosion inhibition of mild steel by *Citrus sinensis* (orange) leaves extract in HCl/H₂SO₄ acid medium. *International Journal of Advanced Research in Chemical Science*, 6(7), 1–9.
- Ezeugo, J. N. O., Onukwuli, O. D., & Omotioma, M. (2017). Optimization of corrosion inhibition of *Picralima nitida* leaves extract as green corrosion inhibitor for zinc in 1.0 M HCl. World News of Natural Sciences, 15, 139–161.
- Gopal, J., Dwivedi, P., Sundaram, S., & Prakash,
 R. (2013). Inhibitive effect of Chlorophytum borivilianum root extract on mild steel corrosion in HCl and H2SO4 solutions. Industrial & Engineering Chemistry Research, 52, 10673–10681.
- Ihebrodike, M. M., Nwandu, M. C., Okeoma, K. B., Nnanna, L. A., Chidiere, M. A., Eze, F. C., & Oguzie, E. E. (2012). Experimental and theoretical assessment of the inhibiting action of Aspilia africana extract on corrosion of aluminum alloy AA 3003 in hydrochloric acid. Journal of Materials Science, 47, 2559–2572. https://doi.org/10.1007/s10853-011-6079-2
- Labjar, N., Bentiss, F., Lebrini, M., Jama, C., & El hajjaji, S. (2011). Study of temperature effect on the corrosion inhibition of C38 carbon steel using aminotris(methylenephosphonic) acid in hydrochloric acid solution. *International Journal of Corrosion*, 2011, 548528. https://doi.org/10.1155/2011/548528
- Li, X., & Deng, S. (2012). Inhibition effect of Dendrocalamus brandisii leaves extracts on aluminum in HCl, H₃PO₄ solutions. Corrosion Science, 65, 299–308.

- Loto, C. A., & Popoola, A. P. I. (2012). Plant extracts corrosion inhibition of aluminum alloy in H₂SO₄. *Canadian Journal of Pure* and Applied Sciences, 6(2), 1973–1980.
- Marcano, L., & Hasenawa, D. (1991). Analysis of phytochemicals in leaves and seeds. *Agronomy Journal*, 83, 445–452.
- Mayuri, P. N. (2012). Screening of Ailanthus excelsa Roxb for secondary metabolites. Journal of Current Pharmaceutical Research, 10(1), 19–219.
- Mistry, B. M., Patel, N. S., Sahoo, S., & Jauhari, S. (2012). Experimental and quantum chemical studies on corrosion inhibition performance of quinoline derivatives for MS in 1N HCl. Bulletin of Materials Science, 35(3), 459–469.
- Nagm, A. N., Kandile, N. G., Badr, E. A., & Mohammed, M. A. (2012). Gravimetric and electrochemical evaluation of environmentally friendly nonionic corrosion inhibitors for carbon steel in 1 M HCl. Corrosion Science, 65, 94–103.
- Ndibe, O. M., Menkiti, M. C., Ijomah, M. N. C., & Onukwuli, O. D. (2011). Corrosion inhibition of mild steel by acid extraction of Vernonia amygdalina in HCl and HNO₃. Electronic Journal of Environmental Agricultural and Food Chemistry, 10(9), 2847–2860.
- Nnanna, L. A., Owate, I. O., Nwadiuko, O. C., Ekekwe, N. D., & Oji, W. J. (2013). Adsorption and corrosion inhibition of *Gnetum africana* leaves extract on carbon steel. *International Journal of Materials* and Chemistry, 3(1), 10–16.
- Nwabanne, J. T., & Okafor, V. N. (2011). Inhibition of the corrosion of mild steel in acidic medium bv Vernonia amygdalina: Adsorption and thermodynamic study. Journal of Emerging Trends inEngineering Applied and Science (JETEAS), 2(4), 619-625.
- Octave, L., (2003). *Chemical reaction engineering* (3rd ed.). New York: John Wily and Sons.
- Oguzie, E. E., Enenebeaku, C. K., Akalezi, C. O., Okoro, S. C., Ayuk, A. A., & Ejike, E. N. (2010). Adsorption and corrosioninhibiting effect of *Dacryodis edulis* extract on low-carbon-steel corrosion in acidic media. *Journal of Colloid and Interface Science*, 349, 283–292.
- Oguzie, E. E., Adindu, C. B., Enenebeaku, C. K., Ogukwe, C. E., Chidiebere, M. A., & Oguzie, K. L. (2012). Natural products for

materials protection: Mechanism of corrosion inhibition of mild steel by acid extracts of *Piper guineense*. Journal of *Physical Chemistry*, 116, 13603–13615.

- Omotioma, M., & Onukwuli, O. D. (2015). Inhibitive and adsorption properties of leaves extract of bitter leaf (Vernonia amygdalina) as corrosion inhibitor of aluminium in 1.0M NaOH. Der Pharma Chemica, 7(11), 373–383.
- Omotioma, M., & Onukwuli O. D. (2017). Evaluation of pawpaw leaves extract as anti-corrosion agent for aluminium in hydrochloric acid medium. *Nigerian Journal of Technology*, *36*(2), 496–504.
- Omotioma, M., & Onukwuli O. D. (2016) Corrosion inhibition of mild steel in 1.0M HCl with castor oil extract as inhibitor. International Journal of Chemical Sciences, 14(1), 103–127.
- Patel, N. S., Jauhariand, S., Mehta, G. N., Al-Deyeb, S. S., Warad, I., & Hammouti, B. (2013). Mild steel corrosion inhibition by various plants extracts in 0.5M sulphuric acid. *International Journal of Electrochemical Science*, 8, 2635–2655.
- Prabakaran, M., Kim, S., Kalaiselvi, K., Venkatesan, H., & Chung, I. (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. https://dx.doi.org/10.1016/j.jtice.2015.08.0 23
- Rosaline-Vimela, J., Leema, R. A., & Raja, S. (2012). A study on the phytochemical analysis and corrosion inhibition on mild steal by Annona muricata L. leaves extract in 1N hydrochloric acid. Der Chemica Sinica, 3(3), 582–588.
- Shanthi, T., & Rajendran, S. (2013). Corrosion resistance of mild simulate concrete pore solution in presence of carboxy methyl cellulose. Journal of Chemical, Biological and Physical Sciences, 3(4), 2550-2556.
- Sharma, Y., & Sharma, S. (2016). Corrosion inhibition of aluminum by *Psidium* guajava seeds in HCl solution. *Portugaliae Electrochimica Acta*, 34(6), 365–382.