

## ECO FRIENDLY EXTRACT OF PORTULACA QUADRIFIDA AS CORROSION INHIBITOR FOR CARBON STEEL IN 1M HYDROCHLORIC ACID SOLUTION

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Article Received on  
01 Feb. 2018,

Revised on 22 Feb. 2018,  
Accepted on 12 March 2018  
DOI: 10.20959/wjpr20186-11530

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### ABSTRACT

Plant extracts as corrosion inhibitors are found as an alternative to synthetic organic compounds. The extract of Portulaca Quadrifida and its major active constituent namely, Kaempferol were investigated for their corrosion inhibition properties on mild steel in 1M hydrochloric acid solution using weight loss, electrochemical methods. The formulation consisting of 3mL of Portulaca Quadrifida Extract (PQE) and 50 ppm  $Zn^{2+}$  offers 95% inhibition efficiency to carbon steel immersed in 1M hydrochloric acid solution. Influence of duration of immersion on the Inhibition Efficiency of PQE- $Zn^{2+}$  has been evaluated. Potentiodynamic polarization investigations revealed that the inhibitors performed as mixed type inhibitors. The mechanistic

aspects of corrosion inhibition have been investigated by polarization study and AC impedance spectra. The surface morphology and the roughness of the metal surface have been analysed by atomic force microscopy. The FT-IR reveals that the protective film is formed on the metal surface consists of  $Fe^{2+}$  - PQE complex and  $Zn(OH)_2$ .

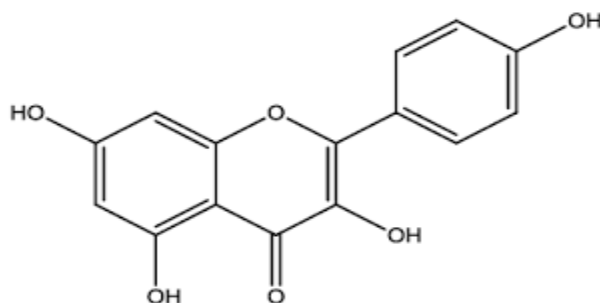
**KEYWORDS:** Carbon steel, Synergism Parameter, Portulaca Quadrifida, Kaempferol, Protective film.

### 1. INTRODUCTION

Corrosion and its devastating effects in the industry is a major concern. Efforts geared toward ameliorating the menace of corrosion is an additional major concern for industrialists and researchers.<sup>[1]</sup> Several efforts have been made to control the menace of corrosion in which the

use of corrosion inhibitors plays a prominent role.<sup>[2]</sup> Corrosion inhibitors are substances added in a minute quantity to an electrochemical system to reduce the rate of deterioration of the metal. Foremost amongst the inhibitors are organic compounds. Previous studies have shown that most organic inhibitors act by adsorption at the metal/solution interface.<sup>[3]</sup> This phenomenon could take place either as electrostatic attraction between the charged metal and the charged inhibitor molecules; dipole-type interaction between uncharged electron pairs in the inhibitor with the metal; the  $\pi$ -electrons bonds interaction with the metal and combination of all of the above.<sup>[4-6]</sup> Heterocyclic organic compounds containing atoms of oxygen, nitrogen, sulphur, and phosphorus as heteroatoms have been used as corrosion inhibitors.<sup>[7-9]</sup> These inhibitors are highly efficient due to their excellent adsorption onto the metal surface. In addition, several factors like the functional groups, steric factors, molecular structures, aromaticity and electron density at donor atoms as well as temperature and pH of the corrosion medium influence the adsorption of these inhibitors on the metal surface. There are various types of organic inhibitors that have been reported.<sup>[3,10-14]</sup> In the various works adsorption has been shown to depend on certain physicochemical properties of the inhibitor group, such as functional groups, electron density at the donor atom,  $\pi$ -orbital character, and the electronic structure of the molecule. The work of shows that the adsorption process is influenced by the electronic characteristics of the inhibitor, the nature of the metal surface, steric effect, temperature and pressure of reaction, multilayer adsorption as well as varying degree of surface site activity.<sup>[15]</sup> Of recent, the use of synthetic organic inhibitors has been limited as a result of their high costs and environmental threats posed by their use. This has therefore motivated an alternative in the natural organic compounds.<sup>[10]</sup> Plants have been found to be repository of several thousands of organic compounds some of which bear resemblance with the commonly used organic corrosion inhibitors.<sup>[3,15-17]</sup> Extracts and constituents of plants have been used by several corrosion practitioners to alleviate the menace of corrosion. Naturally occurring substances are cheap and renewable, biodegradable and do not contain heavy metals or other toxic chemicals and are therefore eco-friendly and hence ecologically acceptable.<sup>[18]</sup> Extracts of tobacco plant<sup>[19]</sup> have been reported to show remarkable corrosion inhibition of aluminium and steel in both salt and acidic solutions. Extracts from *Lanneacoromandelica* leaves<sup>[20]</sup>; *Nauclealatifolia*<sup>[21]</sup>; *Piper longa*<sup>[22]</sup> *Coriandrum sativum* L<sup>[23]</sup>; *Medicago sativa*<sup>[24]</sup>; *Tinosporacripisa*<sup>[25]</sup>; *Sida acuta*<sup>[26]</sup>; Ginko leaves<sup>[12]</sup>; Thyme leaves<sup>[27]</sup>; Apricot juice<sup>[28]</sup>; *Jasminum nudiflorum* Lindl<sup>[29]</sup>; Coffee senna<sup>[30]</sup> and several other plants have also been studied and found to be effective as corrosion inhibitors. The active components of various plant extracts have also been studied for

corrosion inhibition in which the phytochemical constituents of plants have shown varying level of corrosion inhibition. Arbutin, an active principle from *Artemisia pallens*<sup>[31]</sup>, alkaloid extracts of *Oxandraasbeckii*<sup>[32]</sup>, Henna plant<sup>[33]</sup> and its constituents, lawsone, gallic acid  $\alpha$ -D-glucose and tannic acid were shown to inhibit corrosion of mild steel in hydrochloric acid solution. Punicagranatum peel and its main constituents, ellagicacid and tannic acid<sup>[34]</sup> were also found to be effective corrosion inhibitors on mild steel in acidic solutions; *Anibarosaeodora* plant<sup>[35,36]</sup> with anibine as the major alkaloid has also been studied. The rhizomes of *A. galanga*, a plant belonging to the Zingiberaceae family, commonly called greater galangal is selected in this study. The plant is known to possess antioxidant properties<sup>[36, 37]</sup> and have been used as an herb for medical purposes.<sup>[38]</sup> Extracts of turmeric and ginger both belonging to the same family of Zingiberaceaeas *A. galanga* have previously been investigated as green corrosion inhibitors.<sup>[39,40]</sup> The major active compound in *Portulaca Quadrifida* Extract (PQE) is Kaempferol(IUPAC: 3,5,7- Trihydroxy-2-(4-hydroxyphenyl)-4H-chromen4-one)with structure in figure 1.



**Figure 1: Structure of Kaempferol.**

**(IUPAC: 3,5,7- Trihydroxy-2-(4-hydroxyphenyl)-4H-chromen4-one)**

The present study aimed at investigating the inhibitive properties of *Portulaca Quadrifida* Extract (PQE) on the corrosion of carbon steel in 1M HCl solution

## 2. MATERIALS AND METHODS

### 2.1. Preparation of the specimen

Carbon steel specimens of size 1.0 cm  $\times$  4.0 cm  $\times$  0.2 cm and chemical composition 0.026% Sulphur, 0.06% Phosphorous, 0.4% Manganese, 0.1% Carbon and the rest iron were polished to a mirror finish and degreased with trichloroethylene and used for the weight loss method and surface examination studies.

## 2.2. Preparation of Portulaca Quadrifida Extract (PQE)

An aqueous extract of Portulaca Quadrifida Extract (PQE) was prepared by grinding 10g of Portulaca Quadrifida, with distilled water, filtering the suspending impurities, and making up to 100 ml. The extract was used as corrosion inhibitor in the present study.

## 2.3. Corrosion medium

The corrosion solution of 1 M HCl used was prepared by dilution of analytical reagent grade 37% HCl with distilled water. From this stock solution 100 mL each of standard solutions are prepared with and without different concentrations of the inhibitor. The 1 M HCl also served as the blank solution in the experiments.

## 2.4. Weight-loss method

Carbon steel specimens were immersed in 100 ml of 1M hydrochloric acid solution containing various concentrations of the inhibitor Portulaca Quadrifida Extract (PQE) in the absence and presence of  $Zn^{2+}$  for one day. The weights of the specimens before and after immersion were determined using a Digital Balance (Model AUY 220SHIMADZU). From the change in weight of the specimens, corrosion rates (CR) were calculated with the help of the following relationship.

$$CR = \frac{\Delta m}{A * T}$$

Where,

CR - corrosion rate

$\Delta m$  - loss in weight (mg)

A - Surface area of the specimen ( $dm^2$ )

T - Period of immersion (days)

The inhibition efficiency (IE) was then calculated using the equation:

$$IE \% = \left( \frac{W_1 - W_2}{W_1} \right) \times 100$$

Where,  $W_1$  is the weight loss value in the absence of inhibitor and  $W_2$  is the weight loss value in the presence of inhibitor.

## 2.5. Potentiodynamic Polarization

Polarization studies were carried out in a CHI- electrochemical work station with impedance model 660A. It was provided with IR compensation facility. A three electrode cell assembly

was used. The working electrode was carbon steel. A SCE was the reference electrode. Platinum was the counter electrode. From polarization study corrosion parameters such as corrosion potential ( $E_{\text{corr}}$ ), corrosion current ( $I_{\text{corr}}$ ), Tafel slopes anodic =  $b_a$  and cathodic =  $b_c$  were calculated and polarization study was done. The scan rate (V/S) was 0.01. Hold time at ( $E_{\text{fcs}}$ ) was zero and quiet time (s) was two.

## 2.6. AC impedance spectra

The instrument used for polarization study was used to record AC impedance spectra also. The cell set up was also the same. The real part ( $Z'$ ) and imaginary part ( $Z''$ ) of the cell impedance were measured in ohms at various frequencies. Values of charge transfer resistance ( $R_{\text{ct}}$ ) and the double layer capacitance ( $C_{\text{dl}}$ ) were calculated. AC impedance spectra were recorded with initial  $E(\text{v}) = 0$ , high frequency (Hz) =  $1 \times 10^5$ , low frequency (Hz) = 1, amplitude (V) = 0.005 and quiet time (s) = 2. The inhibition efficiency of PQE for the carbon steel electrode can be calculated from the charge-transfer resistance as follows.

$$IE \% = \frac{R'_{\text{ct}} - R_{\text{ct}}}{R'_{\text{ct}}} \times 100$$

The values of charge transfer resistance,  $R_{\text{ct}}$  and the double layer capacitance,  $C_{\text{dl}}$  were calculated.

$$R_{\text{ct}} = (R_s + R_{\text{ct}}) - R_s$$

where  $R_s$  is solution resistance

$$C_{\text{dl}} = \frac{1}{2\pi f_{\text{max}} R_{\text{ct}}}$$

where  $f_{\text{max}}$  is maximum frequency.

## 2.7. Surface examination study

The carbon steel specimens were immersed in various test solutions for a period of 1 day. After 1 day, the specimens were taken out and dried. The nature of the film formed on the surface of the metal specimen was analyzed by various surface analysis techniques.

### 2.7.1. Fourier transform infrared spectra

These spectra were recorded in a Perkin-Elmer-1600 spectrophotometer using KBr pellet. The FTIR spectrum of the protective film was recorded by carefully removing the film, mixing it with KBr and making the pellet.

### 2.7.2. Atomic Force Microscopy characterization (AFM)

The carbon steel specimen immersed in blank and in the inhibitor solution for a period of one day was removed, rinsed with double distilled water, dried and subjected to the surface examination. Atomic force microscopy (Veecodinnova model) was used to observe the samples' surface in tapping mode, using cantilever with linear tips. The scanning area in the images was  $5 \mu\text{m} \times 5 \mu\text{m}$  and the scan rate was 0.6 HZ /second.

## 3. RESULTS AND DISSCUSSION

### 3.1. Analysis of results of weight - loss study

The calculated Inhibition efficiencies (IE) and corresponding corrosion rates (CR) of an aqueous extract of *Portulaca Quadrifida* (PQE) in 1M HCl solution the corrosion of carbon steel immersed in the presence and absence of  $\text{Zn}^{2+}$  has been evaluated by weight loss method. The results are given in Table 1.

**Table 1: Corrosion rates (CR) and inhibition efficiency of carbon steel immersed in an aqueous solution in the absence and presence of inhibitors Inhibitors: *Portulaca Quadrifida* (PQE) +  $\text{Zn}^{2+}$  Period of immersion: 1 day.**

PQE (mL)	$\text{Zn}^{2+}$ (0 ppm)		$\text{Zn}^{2+}$ (25 ppm)		$\text{Zn}^{2+}$ (50 ppm)	
	IE %	CR (mmpy)	IE %	CR (mmpy)	IE %	CR (mmpy)
0	-	0.8387	14	0.5242	22	0.3186
1	55	0.4666	56	0.3890	64	0.2612
2	68	0.3315	62	0.2696	79	0.2278
3	79	0.1757	89	0.1133	95	0.0512
4	71	0.3003	63	0.2484	83	0.1757
5	63	0.3833	59	0.3421	72	0.2906

It is observed that when the carbon steel is immersed in 1M HCl solution of *Portulaca Quadrifida* Extract (PQE) only shows 60% inhibition efficiency (IE) (in the absence of  $\text{Zn}^{2+}$ ). This inhibition efficiency is found to be enhanced in the presence of  $\text{Zn}^{2+}$  ion. When  $\text{Zn}^{2+}$  (50 ppm) is added IE also increases and gives maximum 95% IE at 3mL of PQE and 50 ppm of  $\text{Zn}^{2+}$  shows that synergistic effect exists between  $\text{Zn}^{2+}$  and the active principles present in PQE. When the concentration of  $\text{Zn}^{2+}$  increases from 25 ppm to 50 ppm the IE slightly increases. This may be due to the fact that, when the concentration of  $\text{Zn}^{2+}$  increases, the  $\text{Zn}^{2+}$ -PQE complex formed in the bulk of the solution. When the concentration of PQE was increased the IE decreased. This due to the fact that when higher concentrations of PQE are

added the protective film ( $\text{Fe}^{2+}$ - PQE Complex) formed on the metal surface goes into solution and thus destroying the protective film. It may be considered that the protective film formed may go into transpassivestate, where the film is broken. Hence the IE decreases, similar observation was made with Hibiscus Rosa-Sinensis Al at pH 12<sup>[41]</sup>, Euphorbia<sup>[42]</sup>, Henna.<sup>[43]</sup>

### 3.2. Influence of immersion period on the inhibition efficiency of Portulaca Quadrifida Extract (PQE)

The influence of duration of immersion on the IE of PQE (3 mL) -  $\text{Zn}^{2+}$  (50ppm) system is given in Table 2. When the immersion period increases the inhibition efficiency decreases and the corrosion rate increases this shows that the protective film formed on the metal surface, was broken by the corrosive environment and the film was dissolved, this same result is shown in Phyllanthusamarus extract.<sup>[44]</sup>

**Table 2: Influence of duration of immersion on the inhibition efficiency of PQE- $\text{Zn}^{2+}$  system.**

Immersion Period (days)	Corrosion Rate (CR) in the absence of the inhibitor (mmpy)	Corrosion Rate (CR) in the presence of the inhibitor PQE (3ml)+ $\text{Zn}^{2+}$ (mmpy)	Inhibition Efficiency (IE%)
1	0.2504	0.0510	95
3	0.4737	0.1926	63
5	0.6734	0.3644	48
7	0.8909	0.5277	35

### 3.3. Synergism Parameter ( $S_I$ )

Synergism parameter is calculated to evaluate the synergistic effect existing between inhibitors. Synergism parameter is calculated using the relation.

$$S_I = (1 - I_{1+2}) / (1 - I'_{1+2})$$

Where,  $I_1$  is the surface coverage of inhibitor (PQE),

$I_2$  is the surface coverage of inhibitor ( $\text{Zn}^{2+}$ ) and

$I_{1+2}$  is the combined surface coverage of inhibitors (PQE) and ( $\text{Zn}^{2+}$ )

**Table 3: Synergism Parameter for PQE- Zn<sup>2+</sup> (25 ppm)system in carbon steel immersed in 1M HCl water for one days.**

PQE (mL)	Zn <sup>2+</sup> (25 ppm)	I <sub>1</sub>	I <sub>2</sub>	(I' <sub>1+2</sub> )	S <sub>I</sub>	IE%
1	25	0.48	0.14	0.56	0.9439	56
2	25	0.54	0.14	0.62	1.0584	62
3	25	0.60	0.14	0.89	1.6418	89
4	25	0.55	0.14	0.63	1.0391	63
5	25	0.51	0.14	0.59	0.9642	59

**Table 4: Synergism Parameter for PQE- Zn<sup>2+</sup> (50 ppm)system in carbon steel immersed in 1MHCl water for one days.**

PQE (mL)	Zn <sup>2+</sup> (50 ppm)	I <sub>1</sub>	I <sub>2</sub>	(I' <sub>1+2</sub> )	S <sub>I</sub>	IE%
1	50	0.48	0.22	0.64	0.9750	64
2	50	0.54	0.22	0.79	1.1885	79
3	50	0.60	0.22	0.95	3.2760	95
4	50	0.55	0.22	0.83	1.3305	83
5	50	0.51	0.22	0.72	1.0307	72

When  $S_I > 1$ , synergistic effect exist between the two inhibitors. In case of  $S_I < 1$ , negative interaction takes place between the two inhibitors, (i.e, CR increases). The calculated synergism parameter values for PortulacaQuadrifida Extract (PQE) and Zn<sup>2+</sup> synergism are given in the table 3 and 4.

Synergism Parameter ( $S_I$ ) for the formulation consisting of 3mLofPQE and 50 ppm of Zn<sup>2+</sup> ions are 3.2760 which is greater than one. This shows that the synergistic effect exists between PQE and Zn<sup>2+</sup>.

### 3.4. Analysis of polarization curve

The potentiodynamic polarization curves of carbon steel immersed in 1M HCl solution in the absence and presence of inhibitors (PortulacaQuadrifida Extract (PQE) and Zn<sup>2+</sup>) are shown in Fig.2. The corrosion parameters namely corrosion potential ( $E_{corr}$ ), Tafel slopes ( $b_c$  = cathodic,  $b_a$  = anodic), linear polarization resistance (LPR) and corrosion current ( $I_{corr}$ ) are given in Table 5.

It is observed that in the absence of inhibitors the corrosion potential is -500m V vs. SCE, in the presence of inhibitors (Portulaca Quadrifida Extract (PQE) and Zn<sup>2+</sup>) the corrosion potential is shifted to -482mV vs SCE .This suggests that this formulation controls the anodic reaction and cathodic reaction to an equal extent. So we can conclude that this inhibitor acts



as mixed type of inhibitor. The LPR value increases from  $48.9 \Omega \text{ cm}^2$  to  $159.4 \Omega \text{ cm}^2$  further the corrosion current decreases from  $4.284 \times 10^{-4} \text{ A/cm}^2$  to  $1.512 \times 10^{-4} \text{ A/cm}^2$ . This suggests that a protective film is formed on the metal surface.<sup>[45-49]</sup>

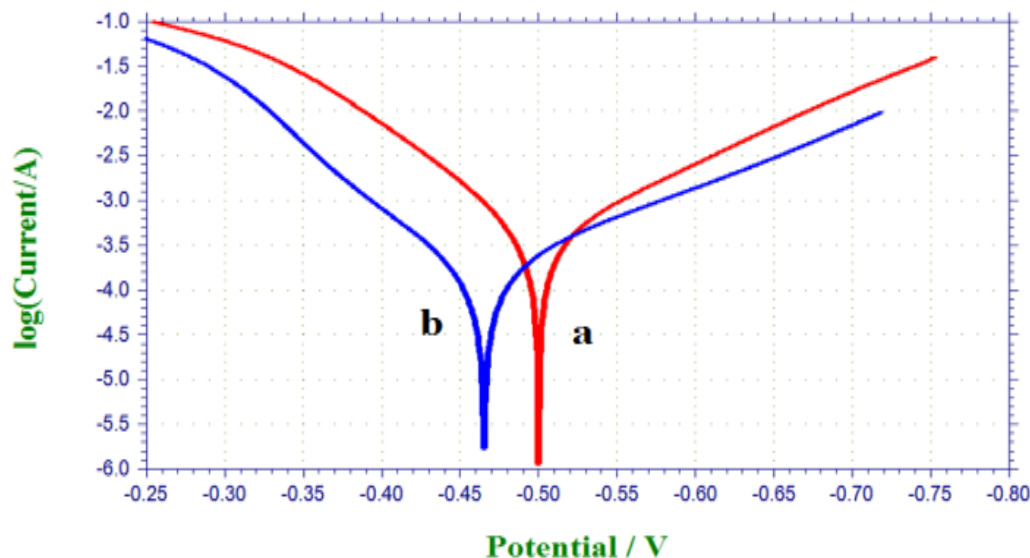


Figure 2. Polarization curves of carbon steel immersed in 1M HCl solution

- a) 1M HCl solution  
b) 3mL PQE + 50 ppm of  $\text{Zn}^{2+}$  + 1M HCl

Table 5: Corrosion parameters of carbon steel immersed in 1M HCl in the presence and absence of inhibitor obtained by polarization method.

PQE (mL)	$\text{Zn}^{2+}$ (ppm)	$E_{\text{corr}}$ (mV vs SCE)	$I_{\text{corr}}$ ( $\text{A/cm}^2$ )	$b_a$ ( $\text{mV dec}^{-1}$ )	$b_c$ ( $\text{mV dec}^{-1}$ )	LPR ( $\Omega \text{ cm}^2$ )
0	0	-500	$4.284 \times 10^{-4}$	81.3	118.4	48.9
3	50	-482	$1.512 \times 10^{-4}$	89.3	146.1	159.4

### 3.5. Analysis of AC Impedance spectra

The AC impedance spectra of carbon steel immersed in various solutions are shown in Figure 3 (Nyquist plot). The AC impedance parameters namely, charge transfer resistance ( $R_{\text{ct}}$ ) and double layer capacitance ( $C_{\text{dl}}$ ) are given in Table 6. When carbon steel immersed in 1M HCl solution, the charge transfer resistance  $R_{\text{ct}}$  value is  $31.5 \Omega \text{ cm}^2$  and  $C_{\text{dl}}$  value is  $4.7210 \times 10^{-4} \text{ F/cm}^2$ . when the formulation consisting of PQE (3 ml) and 50 ppm  $\text{Zn}^{2+}$  is added, the  $R_{\text{ct}}$  value increases from  $31.5 \Omega \text{ cm}^2$  to  $134.7 \Omega \text{ cm}^2$ . The  $C_{\text{dl}}$  value decreases from  $4.7210 \times 10^{-4} \text{ F/cm}^2$  to  $0.9865 \times 10^{-4} \text{ F/cm}^2$ , this confirms that a protective film is formed on the metal surface.

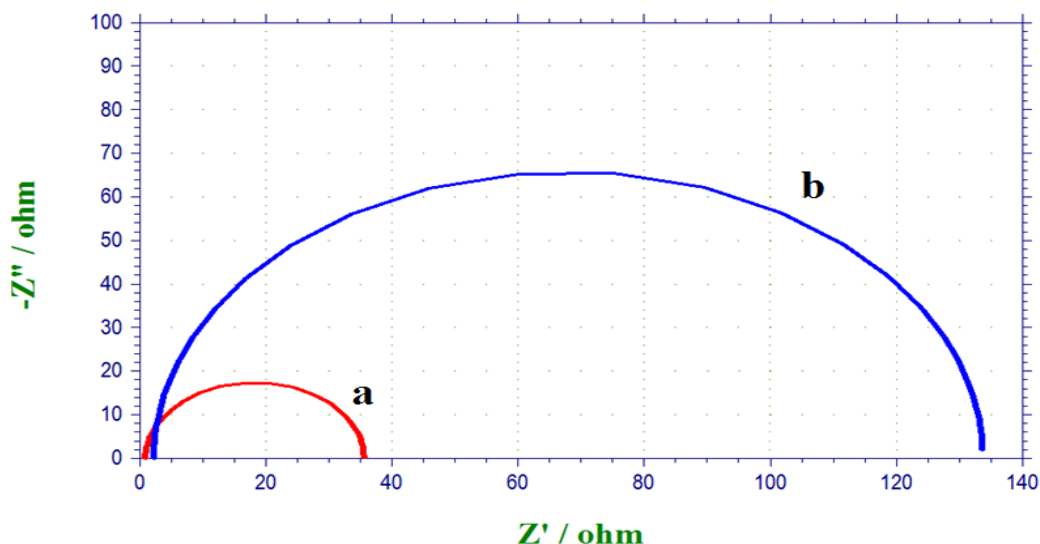


Figure 3: AC impedance of carbon steel immersed in 1M HCl solution.

a) 1M HCl solution

b) b) PQE(3mL)+ 50 ppm of  $Zn^{2+}$  + 1M HCl.

Table 6: Electrochemical impedance parameters for mild steel in the absence and presence of PortulacaQuadrifida Extract in 1M HCl solution

PQE (mL)	$Zn^{2+}$ (ppm)	$R_{ct}$ ( $\Omega \text{ cm}^2$ )	$C_{dl}$ ( $F/\text{cm}^2$ )
0	0	31.5	$4.7210 \times 10^{-4}$
3	50	134.7	$0.9865 \times 10^{-4}$

### 3.6. Analysis of FTIR spectra

FTIR spectra have been used to analyze the protective film formed on metal surface. A few drops of an aqueous extract of PortulacaQuadrifida was dried on a glass plate. A solid mass was obtained. Its FTIR spectrum is shown Fig. 3a. The C=O stretching frequency appears at  $1653 \text{ cm}^{-1}$ . The -OH stretching frequency appears at  $3391 \text{ cm}^{-1}$ . The asymmetric C-O-C stretching frequency appears at  $1237 \text{ cm}^{-1}$ . The symmetric C-O-C stretching frequency appears at  $1061 \text{ cm}^{-1}$ .<sup>[50]</sup> The FTIR spectrum of complex prepared by mixing PortulacaQuadrifida Extract and  $Fe^{2+}$  is shown in Fig 3b. The C=O stretching frequency shifts from  $1653 \text{ cm}^{-1}$  to  $1644 \text{ cm}^{-1}$ . The -OH stretching frequency shifts from  $3391 \text{ cm}^{-1}$  to  $3377 \text{ cm}^{-1}$ . The asymmetric C-O-C stretching frequency shifts from  $1237 \text{ cm}^{-1}$  to  $1234 \text{ cm}^{-1}$ . The symmetric C-O-C stretching frequency shifts from  $1061 \text{ cm}^{-1}$  to  $1059 \text{ cm}^{-1}$ . These frequency shifts show the formation of complex between and  $Fe^{2+}$  and PQE. These shifts confirm that the formation

of  $\text{Fe}^{2+}$  - PQE complex on the anodic sites of the metal surface. The peak at  $1384\text{ cm}^{-1}$  is due to  $\text{Zn}(\text{OH})_2$  formed on the cathodic sites of the metal surface.<sup>[51, 52]</sup>

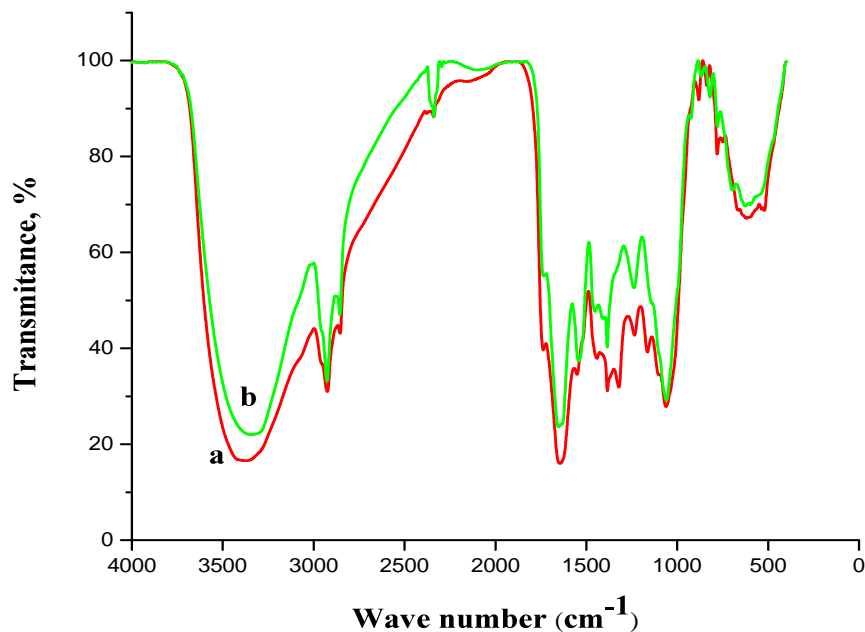


Fig. 4. FT-IR spectra of.

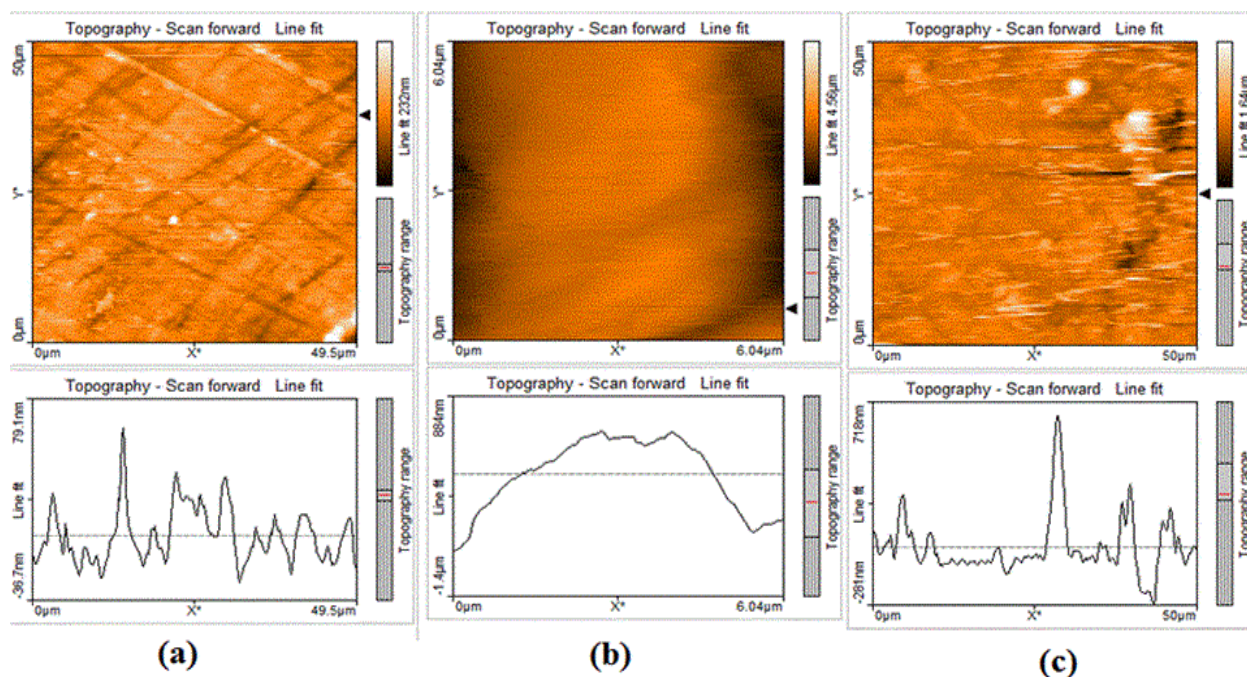
#### Pure Portulaca Quadrifida Extract (PQE)

b) protective film formed on the surface of the metal immersed in 1M HCl solution containing 3mL of Portulaca Quadrifida Extract (PQE) and 50 ppm of  $\text{Zn}^{2+}$ .

#### 3.7. Atomic Force Microscopy Characterization

AFM is a powerful technique to investigate the surface morphology at nano- to micro-scale and has become a new choice to study the influence of inhibitor on the generation and the progress of the corrosion at the metal/solution interface.<sup>[54]</sup> The three dimensional (3D) AFM morphologies and the AFM cross-sectional profile for polished carbon steel surface (reference sample), carbon steel surface immersed in 1M HCl solution (blank sample) and carbon steel surface immersed in 1M HCl solution containing the formulation of 3ml of PQE and 50 ppm of  $\text{Zn}^{2+}$  are shown as Fig.5 images (a, d), (b, e), (c, f) respectively. AFM image analysis was performed to obtain the average roughness,  $R_a$  (the average deviation of all points roughness profile from a mean line over the evaluation length), root-mean-square roughness,  $R_q$  (the average of the measured height deviations taken within the evaluation length and measured from the mean line) and the maximum peak-to-valley (P-V) height

values (largest single peak-to-valley height in five adjoining sampling heights).<sup>[55]</sup> Table 7 is a summary of ( $R_q$ ), ( $R_a$ ), (P-V) value for carbon steel surface immersed indifferent environment. Fig.5 (a, d) displays the surface topography of un-corroded metal surface. The value of  $R_q$ ,  $R_a$  and P-V height for the polished carbon steel surface (reference sample) are 17.52 nm, 20.64nm and 105.97 nm respectively. The slight roughness observed on the polished carbon steel surface is due to atmospheric corrosion. Fig.5 (b, e) displays the corroded metal surface with few pits in the absence of the inhibitor immersed in 1M HCl solution. The( $R_q$ ), ( $R_a$ ), (P-V) height values for the carbon steel surface are 386.55nm, 447.5nm and 1529.40 nm respectively. These data suggests that carbon steel surface immersed in 1M HCl has a greater surface roughness than the polished metal surface, which shows that the unprotected carbon steel surface is rougher and was due to the corrosion of the carbon steel in 1M HCl environment. Fig.5 (c, f) displays the steel surface after immersion in 1M HCl solutioncontaining 3ml of PQE and 50 ppm of  $Zn^{2+}$ . The ( $R_q$ ), ( $R_a$ ), (P-V) height values for the carbon steel surface are 50.80nm, 75.55nm and 531.58nm respectively The ( $R_q$ ), ( $R_a$ ), (P-V) height values are considerably less in the inhibited environment compared to the uninhibited environment. These parameters confirms that the surface is smoother. The smoothness of the surface is due to the formation of a compact protective film of  $Fe^{2+}$  - PQE complex thereby inhibiting the corrosion of carbon steel.<sup>[56]</sup>



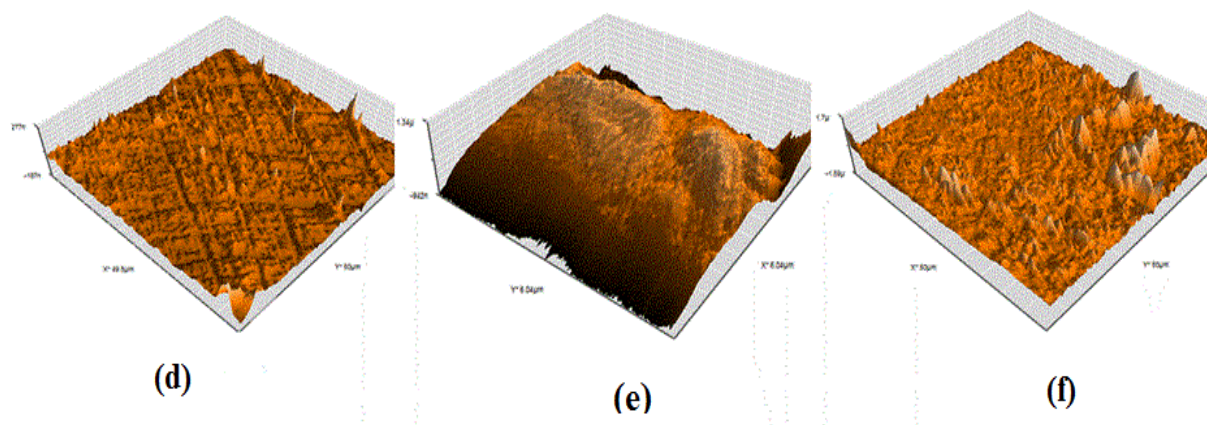


Fig 5: AFM Cross sectional image of the surface of.

- a) Polished carbon steel (control)
- b) Carbon steel immersed 1M HCl (blank)
- c) Carbon steel immersed in 1M HCl containing PQE (3mL) + Zn<sup>2+</sup> (50 ppm)

Three dimensional AFM image of the surface of

- c) Polished carbon steel (control)
- d) Carbon steel immersed 1M HCl (blank)
- f) Carbon steel immersed in 1M HCl containing PQE (3mL) + Zn<sup>2+</sup> (50 ppm)

Table 7: AFM data for carbon steel surface immersed in inhibited and uninhibited environment.

Sample	Average Roughness (R <sub>a</sub> ) (nm)	RMS Roughness (R <sub>q</sub> ) (nm)	Maximum Peak-to-valley height (nm)
1. Polished carbon steel	17.52	20.64	105.97
2. Carbon steel immersed in 1M HCl (blank)	386.55	447.51	1529.40
3. Carbon steel immersed 1M HCl containing PQE (3mL) + Zn <sup>2+</sup> (50ppm)	50.805	75.579	531.58

#### 4. CONCLUSION

The present study leads to the following conclusions. A synergistic effect exists between *Portulaca quadrifida* Extract (PQE) and Zn<sup>2+</sup> in controlling corrosion of carbon steel immersed in 1M HCl solution. The formulation consisting of 3 mL of *Portulaca quadrifida* Extract (PQE) and 50 ppm of Zn<sup>2+</sup> offers 95% Inhibition Efficiency. When immersion period increases corrosion rate also increases.

Polarization study suggests that the combination of PQE and  $Zn^{2+}$  functions as a mixed type inhibitor. AC impedance spectra reveal that a protective film is formed on the metal surface.

FTIR spectra reveal that the protective film consists of  $Fe^{2+}$ -PQE complex and  $Zn(OH)_2$ . AFM studies confirm that the surface is smoother. The smoothness of the surface is due to the formation of a compact protective film of  $Fe^{2+}$ -PQE complex on the metal surface thereby inhibiting the corrosion of carbon steel in 1M HCl solution.

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