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Adsorption ability, stability and corrosion inhibition mechanism of phoenix dactylifera extrat on mild steel

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#### Abstract

Adsorption ability, stability and corrosion inhibition of *phoenix dactylifera* (date palm) seed extract (PDSE) as a natural corrosion inhibitor were studied on mild steel (MS) in 1 M HCl solution after different exposure times. Linear polarization resistance (LPR), potentiodynamic polarization (PP) and electrochemical impedance spectroscopy (EIS) techniques were utilized to define the inhibiting performance of the extract on the rate of corrosion. The stability of the organic film formed over the metal surface was investigated with the help of chronoamperometry (CA) technique. The MS surface was characterized using scanning electron microscopy (SEM), x-ray diffraction (XRD) and contact angle measurements. Surface charge of the metal after exposing to the solution was determined by measuring the potential of zero charge (PZC) using the EIS technique and an adsorption mechanism was proposed. The results of the electrochemical measurements showed that PDSE reduces sufficiently the rate of MS corrosion. The SEM studies showed that the inhibitor strictly attached to the metal surface and form a protective film over the metal surface. The average inhibition efficiency determined from LPR, EIS and PP techniques was found to be 97.3%, which is quite efficient for the practical applications.

# 1. Introduction

Corrosion is one of the most serious problems in the iron and steel industries [1, 2]. Acid solutions such as HCI and H<sub>2</sub>SO<sub>4</sub>, which are commonly used in the steel pickling, cause corrosion of metals [3, 4]. Unfortunatelly, there is no method to completely eliminate the corrosion process. On the other hand, many approaches have been made to slow down the rate of corrosion. Among them, the most practical and common method is the use of inhibitors to protect metals against corrosion [5–10]. When inhibitors are added to corrosive media in small amounts, the corrosion rate of metals may significantly reduces. Organic compounds are generally preferred for this aim. The organic compounds bearing active adsorption centres such as oxygen, nitrogen or sulphur atoms as well as, containing n electrons in conjugated double bonds or triple bonds are reported to be effective for protecting metals [11–13]. However, most of organic inhibitors suggested for this aim have some disadvantages, such as low efficiency, high cost and hazardous effects on human or environment, which restrict their practical usage. In order to overcome these drawbacks, it is needed to find new and applicable corrosion inhibitors. In this sense, researchers have focused on eco-friendly, and renewable natural waste resources to be used for protecting metals against corrosion. Plant-based natural wastes contain many functional organic compounds including tannins, organic acids, alkaloids, saponins, terpenoids and flavonoids, and are called green inhibitors [14]. Green inhibitors, which do not contain heavy metals or toxic compounds, have been reported as corrosion inhibitors for different metals in acidic solution [15-19]. The reported studies indicated that the tested inhibitors could slow down the corrosion rate of metals in alkaline or acidic environments.

Table 1. Electrochemical parameters calculated from PP data for MS in 1 M
HCl solution in the absence and presence 2000 ppm PDSE after 6 h and
compersion with the literature findings.

	E <sub>corr</sub> (V, Ag/AgCl)	$i_{corr}$ (mA cm <sup>-2</sup> )	W (mm year <sup>-1</sup> )	η%
MS	-0.486	1.74	15.57	_
PDSE	-0.505	0.020	0.31	98.8
PD leaf [23]	-0.481	0.048	_	79.9
Terminalia catappa leaves [29]	—	—	~20.2	
Eucalyptus leaf [30]	-0.540	0.14	_	85.0
Borageflower [31]	-0.589	0.34	16	48.5
Glycinemax [32]	-0.522	4.99	8.9	94.0
Cuscuta reflexa [32]	-0.507	16.06	15.9	80.9
Spirogyra [32]	-0.514	21.93	15.8	73.9

**Table 2.** Electrochemical parameters calculated from EIS and LPR data for MS in 1 M HCl solution in the absence and presence 2000 ppm

 PDSE after 6 h and compersion with the literature findings.

	EIS $R_p(\Omega \text{ cm}^2)$	$CPE(\operatorname{sn} \Omega^{-1} \operatorname{cm}^{-2})$	п	$\eta\%$	LPR $R_p(\Omega \text{ cm}^2)$	$\eta\%$
	P			,	P	,
MS	2.6	721	818		4.6	_
PDSE	98.5	812	850	97.6	108.0	95.7
PD leaf [23]	566.3	152.7	910	88.0	271.1	85.7
Borageflower [32]	498.8	47	940	91.8	_	_
Glycinemax [36]	70.98	70.1	860	86.6	_	_
Cuscuta reflexa [36]	120.9	82.36	800	80.7	_	_
Spirogyra [36]	174.8	83.62	600	86.6	_	_

Corrosion inhibition effect of aqueous seed extract of phoenix dactylifera against MS corrosion was reported in 2 M H<sub>2</sub>SO<sub>4</sub> solution using mass loss and hydrogen evolution techniques [20]. It was found that the inhibition effect of the inhibitor changes with the inhibitor concentration, immersion time and temperature. Yamuna and Anthony [21] reported the inhibition effect of *citrus medica* leaf for corrosion of carbon steel using electrochemical methods. The researchers showed that citrus medica leaf has a good inhibition performance (81.75%) at 300 ppm. Inhibition performance of the extracts increases with increasing the extract concentration. In another study, fenugreek leaves and lemon peel as a green corrosion inhibitor for mild steel was studied in 1 M HCl solution using loss method and potentiodynamic polarization techniques [22]. Umeron et. all [23] reported the inhibition effect of leaf extract of date palm for corrosion of carbon steel using electrochemical methods. The researchers showed that the leaf extract of PD has a good inhibition performance (88.5% after 1 h). The inhibition performance of the extracts increases with increasing the extract concentration but decreases with increasing temperature. In another study of the same research group [24], the seed extract of PD in acidic solutions was studied by weight loss and electrochemical methods. The authors obtained plant extracts from an acidic solution. In addition to these specific studies, many researchers have investigated the inhibitory activity of bark, stem and leaf isolates of various plants as green inhibitors. Also, the corrosion inhibition effects of extracts of ginger [25], prunus dulcis peels [26], the extract of olive leaves [27], palm oil from seed [28], pomegranate peel [28] have been reported in the literature. A comperative data with this study are sumamrized in tables 1 and 2.

As it is explained above, PDSE was extracted in distilled water [20] and acidic solutions [23]. But, it must be pointed that the type of extraction solution or solvent can affect the chemical content of the extract, which significantly change the adsorption or corrosion protection ability of the obtained isolate. The content of the isolate can also affects the adsorption ability as well as the stability of inhibitor films formed over metal surfaces and their corrosion protection ability. Therefore, we have obtained extract of PDSE from a special organic solution, methanol:dichloromethane solvent system (1:1; v:v) in order to obtain more adsorbtive components and provide better protection ability. To our best knowladge, a mixure of solvents having different dipol characters has not been applied to this plant yet and will be reported first time. Many electrochemical and surface characterization techniques were used to characterize surface or the film as well as protection performance of the extract.

# 2. Experimental

#### 2.1. Preparation of inhibitor and test solution

The natural compound used for MS protection were obtained from a local market in Bingöl, Turkey. The samples were dried on unprinted papers in a sun-free environment. At the end of the drying process, the seeds were milled in a laboratory mill and passed through a 30 mesh analysis sieve. The powdered seeds (100 g) were put into the maceration container. 2 Lof methanol: dichloromethane solvent system (1:1; v- v) was added each time. The mixture was stirred in an orbital shaker for 48 hours under laboratory conditions. This process continued until the transition of organic matter was completed. A total of 6 L of solvent was used for maceration. Then, the isolate was filtered through Whatman no:1 filter paper. The resulting isolate solutions were combined and the solvent was removed by rotary evaporation under reduced pressure at 40 °C to give dry PDSE. The obtained isolate was taken into an amber glass bottle and stored in a refrigerator (+4 °C) for further analysis and measurements.

All corrosion tests were carried out in 1 M HCl solution without and with the addition of the extract. The temperature of the test solutions was kept at 298 K during the electrochemical measurements.

#### 2.2. Preparation of electrodes

MS working electrodes were prepared as specified in reference [4]. Their chemical composition was (wt%) C (1.720), O (0.115), Al (0.173), Si (0.133), P (0.052), Cu (0.144), Cr (0.057), Mn (0.704), Sn (0.126), Mo (0.204), Ni (0.115), and Fe (remainder). The exposed surface area of the MS electrodes was 0.785 cm<sup>2</sup>. The surface of MS electrode, which was exposed to the test solution was polished with different emery papers, which ended with 1200 grit before the experiments. Then, the electrodes were washed with distilled water, degreased with ethanol, washed with distilled water once again and finally dried with napkin paper. After cleaning electrode surface, the electrode was exposed to the test solutions as soon as possible. A platinum sheet (Pt) with 2 cm<sup>2</sup> total surface area and a commerically purchased Ag/AgCl (3.0 M KCl) were used as counter and the reference electrodes, respectively for all electrochemical experiments.

#### 2.3. Electrochemical measurments

A CHI6096E Electrochemical Workstation was used for all electrochemical experiments. Prior to each measurements, the electrodes were immersed in a corrosive test solution for 6 h. Polarization curves were obtained with a scan rate of 1 mV s<sup>-1</sup> in the potential range from -0.6 V to -0.2 V (Ag/AgCl). EIS measurements were performed at open circuit potentials ( $E_{ocp}$ ) between 100 kHz and 0.01 Hz by applying 5 mV amplitude. LPR measurements were carried out by recording the electrode potential  $\pm$  10 mV around  $E_{ocp}$  with 1 mV s<sup>-1</sup> scan rate.

The stability of the inhibitor film assembled on the steel surface was examined with the help of CA. The CA measurements were made by applying constant anodic or cathodic overpotentials for 1 h and 6 h in the absence and presence of the inhibitor. The PZC of MS was determined in 1 M HCl solution in the presence of 2000 ppm PDSE with the help of EIS measurements after 6 h immersion.

#### 2.4. Surface characterization measurements

The surfaces of the steel samples after exposing to 1 M HCl solution in the absence and presence of 2000 ppm PDSE for 1 h and 6 h were examined by SEM (Joel 6510). The hydrophobic/hydrophilic properties of MS, which was exposed to 1 M HCl solution without and with the addition of 2000 ppm PDSE, were investigated by contact angle measurements, which were performed using sessile water drop method using a contact angle measuring system XRD studies. The MS was immersed in 1 M HCl solutions with 2000 ppm of PDSE extract for 1 h and 6 h. The product formed over the steel surface were analysed by XRD.

# 3. Results and discussion

#### 3.1. Potentiodynamic polarization measurements

The MS specimen was treated to 1 M HCl solution containing 2000 ppm PDSE and PDSE-free solution at room temperature for 6 h and PP measurements were obtained. The curves obtained are presented in figure 1. Some electrochemical parameters such as corrosion potential ( $E_{corr}$ ), corrosion current density ( $i_{corr}$ ), corrosion rate (W) and percentage inhibition efficiency ( $\eta$ %) values were calculated from these curves and the data calculated are listed in table 1.

 $i_{corr}$  values were calculated by extrapolating the linear part (Tafel region) of the curves to their corresponding  $E_{corr}$ . The W was calculated from to the following equation (1) [4];



**Figure 1.** Polarization curves of MS obtained in 1 M HCl solution in the absence ( $\bigcirc$ ) and presence of 2000 ppm PDSE (•) after 6 h exposure.

$$w = \frac{i_{corr} x t x M}{F} \tag{1}$$

In this equation, *t* is exposure time, M is the molar weight of iron and F is Faraday constant. The  $\eta$ % values were determined using the equation given below [33];

$$\eta\% = \frac{i' - i}{i'} x100$$
 (2)

where i' and i are corrosion current densities of MS in the uninhibited and inhibited acid solutions, respectively.

As it is seen from figure 1, both anodic and cathodic semi-logarithmic polarization curves of MS electrode are almost parallel. This behaviour suggests that the corrosion mechanism of the steel does not change with the addition of the inhibitor to the aggressive solution. As it is clearly seen from from figure 1 and table 1, the addition of PDSE to HCl solution shifts  $E_{corr}$  towards more negative potential with respect to inhibitor-free solution (from -0.486 V to -0.505 V versus Ag/AgCl). Therefore, PDSE could be classified as mixed-type corrosion inhibitor with predominant control of the cathodic reaction [34, 35].

Both anodic and cathodic current densities also reduce after the addition of inhibitor to the corrosive solution;  $i_{corr}$  slowers significantly, which is dependent on the inhibitor concentration. The reduction in  $i_{corr}$  after the addition of the inhibitor may be arises from the formation of a protective inhibitor layer assembled on the metal surface.

According to data presented in table 1, W and related  $i_{corr}$  values decrease more and more when PDSE is added to 1 M HCl solution. The inhibition efficiency at 2000 ppm PDSE is 98.80%. Pramudita and co-workers [29] found that *Terminalia catappa* leaves decreases corrosion rate of MS in 1 M H<sub>2</sub>SO<sub>4</sub> within 6 hours immersion period. However, the corrosion rate of the steel in the case of this extract is high with respect to PDSE. The similar data were obtained for some other natural products, which are summarized in tables 1 and 2. The comperative data provided in these tables indicates that the inhibitory performance of PDSE is good [30–32].

#### 3.2. Electrochemical impedance spectroscopy measurements

In the EIS measurements, we determined the corrosion protection ability of PDSE (2000 ppm) in 1 M HCl solution after 6 h immersion. Nyquist and Bode plots of the steel electrode are shown in figure 2. As it can be seen from figure 2(a) the Nyquist plot of MS electrode in 1 M HCl solution consisted of a single depressed capacitive semi-circle shape and only one time-constant is appeared at the Bode plots (figure 2(b) and (c)). The addition of the inhibitor to the corrosive solution does not affect appearance of the plots. These observations demonstrate that the corrosion mechanism does not change with the addition of the extract to the acidic solution. The depressed semicircle from ideal appearance is generally explained by inhomogeneities of the electrode surface, impurities and distributions of active sites on the solid surface [35, 29–32, 36]. These observations indicate that the corrosion process of MS in 1 M HCl solution in the absence and presence of PDSE is activation-controlled.

MS/solution interface is modelled with the electrical equivalent circuit diagram proposed in figure 2(a) as inset. In this model, polarization resistance ( $R_p$ ) and constant phase element (*CPE*) are connected in parallel with each other and solution resistance ( $R_s$ ) in series with both. Some electrochemical parameters, such as  $R_p$ , *CPE* and *n* (degree of surface inhomogeneity) values were determined from fitting experimental data to this model via the ZView software programme and given on table 2. The  $\eta$  values of the inhibitor were calculated from EIS data according to the following formula:





$$\eta\% = \frac{R'_{\rm p} - R_{\rm p}}{R'_{\rm p}} x100 \tag{3}$$

where  $R'_{p}$  and  $R_{p}$  are the polarization resistances of MS obtained in the uninhibited and inhibited acid solutions, respectively [37].

Data are given in figure 2 and table 2 clearly indicate that when the inhibitor was added to aggressive solution, the values of  $R_p$  increases most probably adsorption of more inhibitor molecules over the steel surface or increasing quality/thickening film since more PDSE molecules presence in the solution [37]. The resulting inhibitor film is acting as a barrier between the metal and the corrosive solution, which prevent the metal against corrosion.

The interface of MS/solution does not behave as an ideal capacitor because of the roughness or unstable current distributions on the electrode surface. The data presented in table 2 indicate that *CPE* values decrease

with addition of the inhibitor in the corrosive solution. This is due to a decrease in dielectric constant or an increase in electrical double layer thickness. This type of behaviour is observed in systems where inhibition occurs due to the adsorption of the inhibitor molecules on metal surfaces by forming a protective surface film [37] 95.7% inhibition efficiency was achieved when 2000 ppm PDSE is added to 1 M HCl solution for 6 h.

#### 3.3. Linear polarization measurements

The LPR is a suitable electrochemical technique to determine resistance appeared at the metal/solution interface at limited potential range around open circuit potential. The  $R_p$  of MS in 1.0 M HCl solution with and without 2000 ppm of PDSE was also studied by LPR technique. From the current-potential curves,  $R_p$  was calculated and provided on table. The  $\eta$  was calculated from equation (3) and given on the same table. As it is seen from table 2, EIS and LPR results are very comparable; the addition of PDSE inhibits corrosion of the steel which is enhanced more and more with the increase compared to inhibitor free solution.

Electrochemical data clearly indicate that the isolate obtained from the special organic solvent mixture applied in this study performs better corrosion protection ability with respect to the isolates obtained from distilled water [38] and acidic aqueous solutions [39].

#### 3.4. Chronoamperimetry measurements

In order to determine the stability of the assembled film over the metal surface CA measurements were performed. For this aim 100 mV anodic or cathodic overpotentials ( $E_{corr} \pm 100$  mV) were applied to the system for 3600 s and the current densities observed were plotted against operation time (figure 3). As a reference points, the similar measurements were also performed for a blank solution and the data obtained are comparatively given on figure 3. The data presented in figure 3 show that anodic current density in the absence of the inhibitor increases sharply during the initial of the operation, which can be assigned to access dissolution of the steel and thus increases real surface area [40, 41]. But, the cathodic current density is almost constant during the electrolysis. However, when PDSE is added to the aggressive solution, both anodic and cathodic current densities decrease significantly. Increasing anodic current density during the initial of the electrolysis presented here indicate that the inhibitor film formed over the steel surface is electrochemically stable in acidic media, which is an advantage for the practical applications.

#### 3.5. Surface characterization measurements

Figure 4 shows the surface contact angles for MS electrode in 1 M HCl solution without and with the addition of 2000 ppm PDSE after exposing the MS to the test solutions for 6 h. The contact angle was determined as  $18.0^{\circ}$  in 1 M HCl solution. The addition of 2000 ppm PDSE increases contact angle from  $18.0^{\circ}$  to  $45.26^{\circ}$ . Therefore, it can be said that the hydrophobic character of the surface increases due to the adsorption of organic molecules over the surface [42–44].

The surface structures of the MS specimens after exposing to the test solutions for 6 h were examined with SEM measurements and the images obtained are shown in figure 5. As it is clearly seen from figure 5, the surface of MS electrode is strongly damaged in 1 M HCl solution most probably due to the excessive dissolution of steel; many cracks and pits distributed over the steel have appeared. However, after the addition of 2000 ppm PDSE to the corrosive solution, the MS surface looks much better. A very homogenous and adherent inhibitor film appears on the steel surface, which reduces the dissolution of the steel in corrosive media and provides significant prevention against corrosion. The data obtained here support the results of electrochemical measurements and suggest that this extract is a good corrosion inhibitor for mild steel ptotection in HCl solution.

#### 3.6. X-ray diffraction study

The surface of MS after exposing to corrosive solution in the presence of 2000 ppm plant extracts for 1 h and 6 h were examined with XRD. For comparison the XRD patterns of MS were also given in the same figure (figure 6). The comparison between the diffraction diagrams given on figure 6 clearly shows that there are not significant differences between the XRD pattern of un-corroded and corroded surfaces after exposing to 1.0 M HCl + 2000 ppm PDSE for 1 and 6 h. The strong peak intensity observed around  $45^{\circ}$  at  $2\theta$  are related to Fe phase and the peaks related to iron oxides are not observed. Therefore, we could that the inhibitor prevent MS dissolution significantly. The reduction in the peak intensity is indicative of the bonding between MS and molecules of inhibitor contained in PDSE, possibly due to metal complex formation [45].

#### 3.7. The potential of zero charge and the inhibition mechanism

Adsorption of organic species over the metal surfaces occurs by the adsorption of inhibitor molecules through the displacement of initially adsorbed water molecules on the metal surface as given below [46],





$$Inh_{(solution)} + nH_2O_{adsorption} \leftrightarrow Inh_{adsorption} + nH_2O_{solution}$$
(4)

In order to determine the excess surface charge of the metal, the potential of zero charge (PZC) determination studies were made after exposing the metal to the corrosiv media for 6 h in the acidic media with or without inhibitor. A plot of  $R_p$  versus applied potential was obtained and is shown on figure 7. The potential obtained at maximum point of the plot,  $R_p = -0.488$  V is called as  $E_{pzc}$ . On the other hand, the  $E_{ocp}$  in the same conditions is -0.507 V for inhibitor-free 1 M HCl solution. The  $E_{r,}$  Antropov's 'rational' potential of corrosion calculated from  $E_r = E_{ocp} - E_{pzc}$ .  $E_r$  was found to be -0.019 V, which indicates excess negative charge on the MS surface.



**Figure 5.** SEM images of the MS specimens immersed into 1 M HCl in the absence (a) and presence 2000 ppm PDSE (b) after 1 h (a), (b) and 6 h (a'), (b') exposure.



The PZC value was determined as -0.532 V in inhibitor containing medium and the  $E_{ocp}$  value is -0.512 V. In this case, the  $E_r$  was calculated as +0.020 V, which shows that the surface of the metal in this conditions has excess positive charge [47, 48].

When the metal surface posses positively charged in the corrosive media, negative species such as chlorine ions are adsorbed on the surface of the metal initially and attracts cationic forms and protonated water molecules. So close-packed triple-layer will form on the metal surface and inhibit MS dissolution [49–51].

# 4. Conclusions

In this study, adsorption ability, stability and corrosion inhibition of PDSE on MS was studied in 1 M HCl solution using various electrochemical techniques. According to the data obtained, following important points can be summarized;

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- 1. PDSE acts as a good corrosion inhibitor with high inhibition efficiency (more than 95%) in acidic solution after 6 h immersion.
- 2. The isolate obtained from an organic solvent mixture (applied in this study) performs better corrosion protection ability with respect to the isolates obtained from distilled water and acidic aqueous solutions reported in literature.
- 3. PP studies shown that PDSE reduces both anodic dissolution of metal and also the rate of cathodic hydrogen evolution reactions.
- 4. PDSE behaves as mixed-type corrosion inhibitor with predominant cathodic effectiveness.
- 5. The CA results indicated that the film assembled over the MS surface is stable.
- 6. PZC results showed that, the excess surface charge of the metal in the presence of inhibitor was positive.
- 7. The surface hydrophobicity increases by adding the PDSE to the aggresive solution.
- 8. The SEM and XRD studies showed that the surface inhibitor film reduces the corrosion rate of MS in HCl solution.

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#### References

- Tian Y and Zheng M 2019 Inhibition effect of silicate and molybdate on the corrosion of SS 316 in neutral corrosive solution at high temperature Mater. Res. Express 6 1–15
- [2] Es'haghi M, Amjad A, Asghari S and Lotfi A 2018 Studying effect of plantain extract behavior as an eco-friendly corrosion inhibitor on the mild steel in 1 M HCl solution *Anti-Corrosion Methods and Materials* 65 310–6
- [3] Essien E A, Kavaz D, Ituen E B and Umoren S A 2018 Synthesis, characterization and anticorrosion property of olive leaves extracttitanium nanoparticles composite *J. Adhes. Sci. Technol.* **32** 1773–94
- [4] Solmaz R 2014 Investigation of adsorption and corrosion inhibition of mild steel in hydrochloric acid solution by 5-(4-Dimethylaminobenzylidene)rhodanine Corros. Sci. 79 169–76
- [5] Othman N K, Yahya S and Ismail M C 2019 Corrosion inhibition of steel in 3.5% NaCl by rices traw extract J. Ind. Eng. Chem. 70 299–310
- [6] Obot I B, Umoren S A and Ankah N K 2019 Pyrazine derivatives as green oil field corrosion inhibitors for steel J. Mol. Liq. 277 749–61
- [7] Zaferani S H, Sharifi M, Zaarei D and Shishesaz M R 2013 Application of eco-friendly products as corrosion inhibitors for metals in acid pickling processes—a review *Journal of Environmental Chemical Engineering* 1 652–7

- [8] Raja P B and Sethuraman M G 2008 Natural products as corrosion inhibitor for metals in corrosive media a review Mater. Lett. 62 113–6
- [9] Salman T A, Al-Azawi K F, Mohammed I M, Al-Baghdadi S B, Al-Amiery A A, Gaaz T S and Kadhum A A H 2018 Experimental studies on inhibition of mild steel corrosion by novel synthesized inhibitor complemented with quantum chemical calculations *Results in Physics* 10 291–6
- [10] Singh D K, Ebenso E E, Singh M K, Behera D, Udayabhanu G and John R P 2018 Non-toxic Schiff bases as efficient corrosion inhibitors for mild steel in 1M HCl: electrochemical, AFM, FE-SEM and theoretical studies J. Mol. Liq. 250 88–99
- [11] Othman M H A, Al-Amiery A A, Al-Majedy Y K, Kadhum A A H, Mohamad A B and Gaaz T S 2018 Synthesis and characterization of a novel organic corrosion inhibitor for mild steel in 1 M hydrochloric acid *Results in Physics* 8 728–33
- [12] Tian H, Li W, Liu A, Gao X, Han P, Ding R, Yang C and Wang D 2018 Controlled delivery of multi-substituted triazole by metalorganic framework for efficient inhibition of mild steel corrosion in neutral chloride solution *Corros. Sci.* 131 1–16
- [13] Ma Q, Qi S, He X, Tang Y and Lu G 2017 1, 2, 3-Triazole derivatives as corrosion inhibitors for mild steel in acidic medium: experimental and computational chemistry studies Corros. Sci. 129 91–101
- [14] Sin H L Y, Rahim A A, Gan C Y, Saad B, Salleh M I and Umeda M 2017 Aquilaria subintergra leaves extracts as sustainable mild steel corrosion inhibitors in HCl Measurements 109 334–45
- [15] Ma X, Jiang X, Xia S, Shan M, Li X, Yu L and Tang Q 2016 New corrosion inhibitor acrylamide methyl ether for mild steel in 1 M HCl Appl. Surf. Sci. 371 248–57
- [16] Büyüksagis A, Dilek M and Kargioğlu M 2015 Corrosion inhibition of st37 steel in geothermal fluid by Quercus robur and pomegranate peels extracts Protection of Metals and Physical Chemistry of Surfaces 51 861–72
- [17] El-Bribri A, Tabyaoui M, Tabyaoui B, El-Attari H and Bentiss F 2013 The use of euphorbia falcata extract as eco-friendly corrosion inhibitor of carbon steel in hydrochloric acid solution *Mater. Chem. Phys.* 141 240–47
- [18] Obadoni B O and Ochuko P O 2001 Phytochemical studies and comparative efficacy of the crude extracts of some homeostatic plants in Edo and Delta States of Nigeria Global *Journal of Pure Applied Science* 8 203–8
- [19] Ostovari A, Hoseinieh S M, Peikari M, Shadizadeh S R and Hashemi S J 2009 Corrosion inhibition of mild steel in 1 M HCl solution by henna extract: a comparative study of the inhibition by henna and its constituents (Lawsone, Gallic acid, a-D-Glucose and Tannic acid) *Corros. Sci.* 51 1935–49
- [20] Al-Turkustania A M, Al-Sawata R M, Al-Hassania R H, Al-Ghamdia N S, AlHarbia E M, Al-Gamdia M A and Al-Solmi S A 2013 Corrosion behaviour of mild steel in acidic solution using the aqueous seed extract of Phoenix dactylifera L (Date seeds) *Journal of Chemica Acta* 2 53–61
- [21] Yamuna J and Anthony N 2015 Corrosion protection of carbon steel in neutral medium using citrus medica [CM] leaf as an inhibitor International Journal of Chem Tech Research 51 318–25
- [22] Agarwal K 2014 Fenugreek leaves and lemon peel as green corrosion inhibitor for mild steel in 1M HCl medium *Journal of Materials* Science and Surface Engineering 1 44–8
- [23] Umoren S A, Gasem Z M and Obot I B 2014 Date palm (Phoenix dactylifera) leaf extract as an eco-friendly corrosion inhibitor for carbon steel in 1 M hydrochloric acid solution Anti-Corrosion Methods And Materials 62 19–28
- [24] Umoren S A, Gasem Z M and Obot I B 2013 Natural products for material protection: inhibition of mild steel corrosion by date palm seed extracts in acidic media Ind. Eng. Chem. Res. 52 14855–65
- [25] Liu Y, Song Z, Wang W, Jiang L, Zhang Y, Guo M, Song F and Xu N 2019 Effect of ginger extract as green inhibitör on chloride-induced corrosion of carbon steel in simulated concrete pore solutions *Journal of Clear Production* 201 298–307
- [26] Pal S, Lgaz H, Tiwari P, Chung M, Ji G and Prakash R 2019 Experimental and theoretical investigation of aqueous and methanolicextracts of Prunus dulcispeels as green corrosion inhibitors of mild steelin aggressive chloride media J. Mol. Liq. 276 347–61
- [27] El-Etre A Y 2007 Inhibition of acid corrosion of carbon steel using aqueous extract of olive leaves *Journal Colloid Interface Science* **314** 578–83
- [28] Rashid K and Khadom A 2018 Evaluation of environmentally friendly inhibitor for corrosion of mild steel in phosphoric acid solution: unconventional approach Anti-Corrosion Methods and Materials 65 506–14
- [29] Pramudita M and Nasikin M 2018 Influence of tannin content in Terminalia catappa leaves extracts resulted from maceration extraction on decreasing corrosion rate for mild steel in 1M H<sub>2</sub>SO<sub>4</sub> Materials Science and Engineering 345 1–6
- [30] Dehghani A, Bahlakeh G and Ramezanzadeh B 2019 Green Eucalyptus leaf extract: a potent source of bio-active corrosion inhibitors for mild steel *Bioelectrochemistry* 130 1–10
- [31] Dehghani A, Bahlakeh G, Ramezanzadeh B and Ramezanzadeh M 2019 Potential of Borage flower aqueous extract as an environmentally sustainable corrosion inhibitor for acid corrosion of mild steel: electrochemical and theoretical studies J. Mol. Liq. 277 895–911
- [32] VermaD K, Khan F, Bahadur I, Salmane M, Quraishi M A, Verma C and Ebenso E E 2018 Inhibition performance of Glycine max, Cuscuta reflexa and Spirogyra extracts for mild steel dissolution in acidic medium: density functional theory and experimental studies *Results in Physics* 10 665–74
- [33] Solmaz R, Sahin A E and Kardas G 2011 Adsorption and corrosion inhibition effect of 2-((5-mercapto-1,3, 4-thiadiazol-2-ylimino) methyl)phenol Schiff base on mild steel Mater. Chem. Phys. 125 796–801
- [34] Pandey A, Verma C, Singh B and Ebenso E E 2018 Synthesis, characterization and corrosion inhibition properties of benzamidee2chloro-4-nitrobenzoic acid and anthranilic acide2- chloro-4-nitrobenzoic acid for mild steel corrosion in acidic medium J. Mol. Struct. 1155 110–22
- [35] Yılmaz N, Fitoz A, Ergun Ü and Emregül K A 2016 Combined electrochemical and theoretical study into the effect of 2-((thiazole-2ylimino)methyl)phenol as a corrosion inhibitor for mild steel in a highly acidic environment Corros. Sci. 111 110–20
- [36] Hamani H, Douadi T, Daoud D, Al-Noaimic M, Rikkouha R A and Chafa S 2017 1-(4-Nitrophenylo-imino)-1-(phenylhydrazono)propan-2-one as corrosion inhibitor for mild steel in 1M HCl solution: weight loss, electrochemical, thermodynamic and quantum chemical studies Jornal of Electroanalitical *Chemistry* 801 425–38
- [37] Solmaz R, Altunbaş E and Kardaş G 2011 Investigation of adsorption and corrosion inhibition effect of 1,1'-thiocarbonyldiimidazole on mild steel in hydrochloric acid solution *Protection of Metals and Physical Chemistry of Surfaces* 4752 264–71
- [38] Verma C, Olasunkanmi L O, Ebenso E E, Quraishi M A and Obot I B 2016 Adsorption behavior of glucosamine-based, pyrimidinefused heterocycles as green corrosion inhibitors for mild steel: experimental and theoretical studies J. Phys. Chem. C 120 11598–611
- [39] Sherif E M 2011 Effects of 5-(3-aminophenyl)-tetrazole on the inhibition of unalloyed iron corrosion in aerated 3.5% sodium chloride solutions as a corrosion inhibitor *Mater. Chem. Phys.* 129 961–7
- [40] Sherif E M, Erasmus R M and Comins J D 2010 In situ Raman spectroscopy and electrochemical techniques for studying corrosion and corrosion inhibition of iron in sodium chloride solutions *Electrochim. Acta* 55 3657–63

- [41] Abdel-Gaber A M, Abd-El-Nabey B A, Khamis E and Abd-El-Khalek D E 2011 A natural extract as scale and corrosion inhibitor for steel surface in brine solution *Desalination* 278 337–42
- [42] Lagrenee M, Mernari B, Bouanis M, Traisnel M and Bentiss F 2002 Study of the mechanism and inhibiting efficiency of 3, 5-bis(4methylthiophenyl)-4H-1, 2, 4-triazole on mild steel corrosion in acidic media Corros. Sci. 44 573–88
- [43] Salci A and Solmaz R 2018 Fabrication of rhodanine self-assembled monolayer thin films on copper: solvent optimization and corrosion inhibition studied Prog. Org. Coat. 125 516–24
- [44] Singh A, Lin Y, Ebenso E E, Liu W, Pan J and Huang B 2015 Gingko biloba fruit extract as an eco-friendly corrosion inhibitor for J55 steel in CO<sub>2</sub> saturated 3.5% NaCl solution *Journal of Indurstrial and Engineering Cemistry* 24 219–28
- [45] Prabakaran M, Kim S H, Kalaiselvi K, Hemapriya V and Chung I M 2016 Highly efficient Ligularia fischeri green extract for the protection against corrosion of mild steel in acidic medium: electrochemical and spectroscopic investigations J. Taiwan Inst. Chem. Eng. 59 553–62
- [46] Yüce O A and Kardas G 2012 Adsorption and inhibition effect of 2-thiohydantoin on mild steel corrosion in 0.1 M HCl Corros. Sci. 58 86–94
- [47] Popova A, Sokolova E, Raicheva S and Christov M 2003 AC and DC study of the temperature effect on mild steel corrosion in acidic media in the presence of benzimidazole derivatives *Corros. Sci.* 45 33–58
- [48] Antropov L I 1960 Kinetics of Electrode Processes and Null Points of Metals (New Delhi: Council of Scientific and Industrial Research)
- [49] El-Awady A A, Abd-El-Nabey B A and Aziz S G 1992 Thermodynamic and adsorptionisotherms analyses for the inhibition of the acid corrosion of steel by cyclic and open-chain amines *Journal of Electrochemical Society* 139 2149–54
- [50] Döner A and Kardas G 2011 N-Aminorhodanine as an effective corrosion inhibitor for mild steel in 0.5 M H<sub>2</sub>SO<sub>4</sub> Corros. Sci. 53 4223–32
- [51] Solmaz R, Kardas G, Çulha M, Yazıcı B and Erbil M 2008 Investigation of adsorption and inhibitive effect of 2-mercaptothiazoline on corrosion of mild steel in hydrochloric acid media *Electrochimical Acta* 53 5941–52