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# A Study of *Eruca vesicaria*, *Bromelia hemisphaerica* and *Erythrina americana* as Green Corrosion Inhibitors for Carbon Steel in Sulfuric Acid

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## Abstract

**A study of *Eruca vesicaria*, *Bromelia hemisphaerica* and *Erythrina americana* as eco-friendly corrosion inhibitors for 1018 carbon steel in 0.5 M $H_2SO_4$ has been carried out by using weight loss tests, potentiodynamic polarization curves and electrochemical impedance spectroscopy measurements. Results have shown that the three extracts performed as good corrosion inhibitors, but the *Eruca vesicaria* exhibited the best performance followed by *Erythrina americana*. The three inhibitors formed a protective, passive film which protected the steel from corrosion. This was because they contain antioxidants present in their molecular structure with heteroatoms such as N, C and O like phenols, amino acids, etc., which react with metal and environment to form the protective film.**

## Keywords

**Acid Corrosion, Green Inhibitors, Electrochemical Techniques**

## 1. Introduction

Corrosion causes big economic looses to the industry and is a cause of big accidents. In industrial processes such

as acid pickling, well oil acidizing, metals and alloys are exposed to corrosive environments such as sulfuric acid ($H_2SO_4$), hydrochloric acid (HCl) and phosphoric acid ($H_3PO_4$) among others, which causes corrosion [1]-[3]. Among the different ways to protect metals against corrosion, the use of corrosion inhibitors is one of the most widely used methods [4]-[6]. However, most of the used, synthetic inhibitors are toxic, expensive and harmful for living species [7] [8]. Some plants had been studied as corrosion inhibitors such as *Salvia officinalis* [9], *Musa paradisica* [10], *Capsicum anum* [11], *Adhotada vasica* [12], and many others [13]-[22]. It was found that all these plant extracts act as good corrosion inhibitors for metal corrosion in acidic media. The corrosion inhibition of these compounds has been attributed to the presence of active compounds present in their structure. These organic compounds usually contain polar functions with nitrogen, sulphur or oxygen atoms and have triple or conjugated double bonds with aromatic rings in their molecular structures, which are the major adsorption centres to protect metal form further corrosion [23].

*Eruca vesicaria subsp. sativa* (syn. *E. sativa*), *Bromelia hemisphaerica* and *Erythrina* americana are plants widely used in Mexico because they are excellent source of antioxidants, enzimes or sedative and calming effects [24]-[26]. For instance, *Eruca vesicaria* contains phenolic compounds, carotenoids, glucosinolates, whereas *Eruca vesicaria* contains enzymes such as proteases which have been increased in their use in pharmaceutic, photographic, waste disposal, medicine, and the food industry. Finally, *Erythrina americana* contains alkaloids such as Erisopine, Erisodine, $\alpha$-Erythridine, $\beta$-Erythridine, and non-proteins aminoacids, lectines and trispenes [26]-[29] containing heteroatoms such as C, O and N, with good antioxidant properties. Since corrosion is an oxidative process, the use of these plants and their antioxidants properties make them good candidates to be used as corrosion inhibitors for 1018 carbon steel in 0.5 M $H_2SO_4$.

## 2. Results and Discussion

Material tested in this work was 1018 carbon steel containing 0.14% C, 0.90% Mn, 0.30% S, 0.030% P and as balance Fe, encapsulated in commercial epoxic resin with an exposed area of 1.0 cm$^2$. The aggressive solution, 0.5 M $H_2SO_4$ was prepared by dilution of analytical grade chemical in distilled water. *Eruca vesicaria*, *Bromelia hemisphaerica and Erythrina americana* were obtained from a local market.For the extraction, dried leafs of the plants were soaked in methanol during 21 days obtaining a solid, which was weighted and dissolved in methanol and used as a stock solution and used then for preparation of the desired concentrations by dilution. Used concentrations included 0, 200, 400, 600, 800 and 1000 ppm. To characterize the obtained extracts, FTIR technique was used. The IR spectra were recorded with KBr pellets on a Tensor 27 Bruker spectrophotometer between 400 and 4000 cm$^{-1}$. For the corrosion tests, both gravimetric and electrochemical techniques were used.

Weight loss experiments were carried out with carbon steel rods 2.5 cm length and 0.6 cm diameter abraded with fine emery paper until 1200 grade, rinsed with acetone, and exposed to the aggressive solution during 72 h. After a total time of exposition of 72 hours, specimens were taken out, washed with distilled water, degreased with acetone, dried and weighed accurately. Tests were performed by triplicate at room temperature (25°C). Corrosion rates, in terms of weight loss measurements, $\Delta W$, were calculated as follows:

$$\Delta W = (m_1 - m_2)/A \tag{1}$$

where $m_1$ is the mass of the specimen before corrosion, $m_2$ the mass of the specimen after corrosion, and $A$ the exposed area of the specimen. For the weight loss tests, inhibitor efficiency, I.E., was calculated as follows:

$$\text{I.E.}(\%) = 100(\Delta W_1 - \Delta W_2)/\Delta W_1 \tag{2}$$

where $\Delta W_1$ is the weight loss without inhibitor, and $\Delta W_2$ the weight loss with inhibitor. Specimens were weighed in an analytical balance with a precision of 0.1 mg.

Electrochemical techniques employed included potentiodynamic polarization curves and electrochemical impedance spectroscopy measurements, EIS. In all experiments, the carbon steel electrode was allowed to reach a stable open circuit potential value, E$_{corr}$. Polarization curves were recorded at a constant sweep rate of 1 mV/s at the interval from −1000 to +1000 mV respect to the E$_{corr}$ value. Measurements were obtained by using a conventional three electrodes glass cell with two graphite electrodes symmetrically distributed and a saturated calomel electrode (SCE) as reference. Corrosion current density values, i$_{corr}$, were obtained by using Tafel extrapolation. Electrochemical impedance spectroscopy tests were carried out at E$_{corr}$ by using a signal with an amplitude of 10 mV in a frequency interval of 100 mHz - 20 kHz. An ACM potentiostat controlled by a desk top computer was

used for the polarization curves, whereas for the EIS measurements, a model PC4 300 Gamry potentiostat was used.
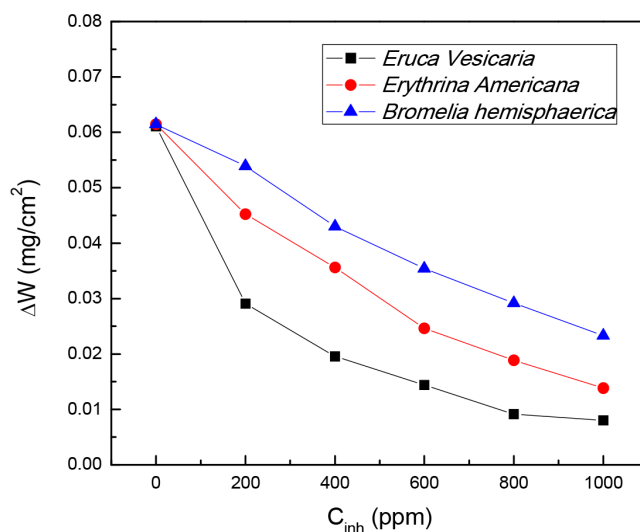
## 3. Results and Discussion

### 3.1. Weigh Loss Tests

The effect of *Eruca vesicaria*, *Bromelia hemisphaerica* and *Erythrina americana* concentration on the weight loss of 1018 carbon steel in 0.5 M $H_2SO_4$ is shown in **Figure 1**, where it can be seen that in all cases, the weight loss decreases as the inhibitor concentration increases. The lowest weight loss was obtained with the addition of *Eruca vesicaria*, whereas with the addition of *Bromelia hemisphaerica* the steel had highest weight loss values. In a similar way, the inhibitor efficiency increased with increasing its concentration, obtaining the highest values, between 40% and 80%, when *Eruca vesicaria* was added, whereas the lowest values were obtained with the addition of *Bromelia hemisphaerica*, obtaining values between 18% and 50%, **Figure 2**. This decrease in the corrosion rate is due to the adsorcion of the different inhibitors on the steel surface, and the fact that its efficiency values increase with an increase in its concentration is due to an increase in the surface area covered by the inhibitor.
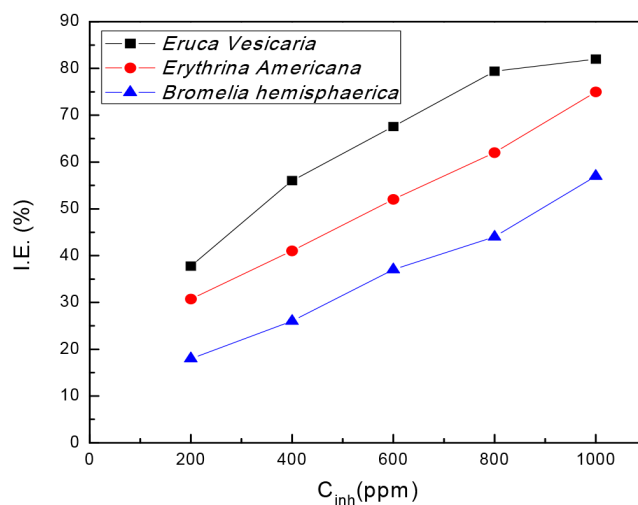
### 3.2. Polarization Curves

The effect of *Eruca vesicaria* concentration in the polarization curves for 1018 carbon steel in 0.5 M $H_2SO_4$ is given in **Figure 3**, where it can be seen that with or without inhibitor, steel displays an active-passive behaviour.

The $E_{corr}$ value shifts towards nobler values as soon as the *Eruca vesicaria* is added to the solution, and the $i_{corr}$ values decrease with the addition of the inhibitor for one order of magnitude up to 800 ppm, **Table 1**, and then it decreases with a further increase in the inhibitor concentration. This could be because *Eruca vesicaria* reacts with iron ions released during the corrosion process to form corrosion products which can be either protective or non-protective. For concentrations lower than 800 ppm, these corrosion products are protective and adherent, whereas for doses higher than 800 ppm, the formed corrosion products could be non-adherent, non-protective, which are detached from the metal surface, increasing, thus, the corrosion rate of the steel. Inhibitor efficiency values increase with the increase in the inhibitor concentration, reaching its highest value, 86%, when 1000 ppm of *Eruca vesicaria* was added to the solution. Both anodic and cathodic Tafel slopes were decreased with the addition of the inhibitor, especially the cathodic one, indicating that *Eruca vesicaria* is a mixed type of inhibitor, decreasing both the anodic dissolution of iron and the cathodic hydrogen evolution reaction, since in an acidic environment, it is the dominant cathodic reaction. The potential where the passivation starts,



**Figure 1.** Effect of *Eruca vesicaria*, *Bromelia hemisphaerica* and *Erythrina americana* concentration on the weight loss results for 1018 carbon steel in 0.5 M $H_2SO_4$.

**Figure 2.** Effect of *Eruca vesicaria*, *Bromelia hemisphaerica* and *Erythrina americana* concentration on the inhibitor efficiency values for 1018 carbon steel in 0.5 M H$_2$SO$_4$.
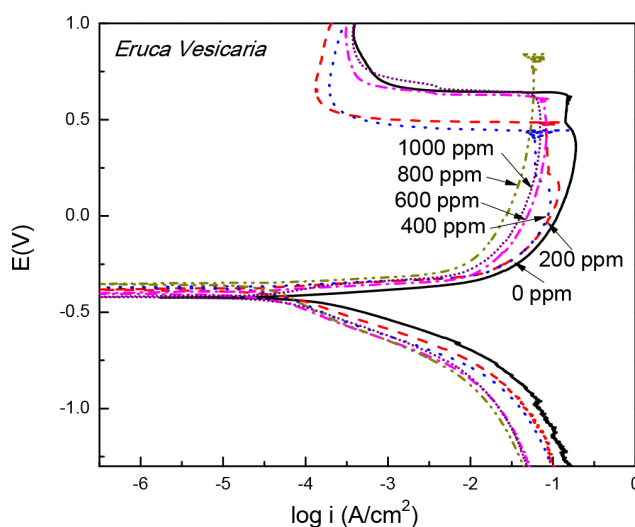


**Figure 3.** Effect of *Eruca vesicaria* concentration on the polarization curves for 1018 carbon steel in 0.5 M H$_2$SO$_4$.
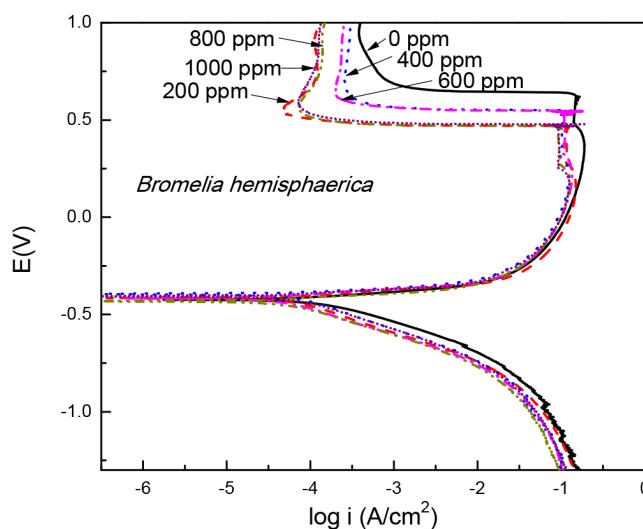
**Table 1.** Electrochemical parameters obtained from polarization curves in *Eruca vesicaria*.

| C$_{inh}$ (ppm) | E$_{corr}$ (mV) | i$_{corr}$ (mA/cm$^2$) | $\beta_a$ (mV/dec) | $\beta_c$ (mV/dec) | I.E. (%) | E$_{pas}$ (mV) | i$_{pas}$ (mA/cm$^2$) |
|---|---|---|---|---|---|---|---|
| 0 | −426 | $1.94 \times 10^{-4}$ | 36 | 177 | --- | 680 | $7.8 \times 10^{-4}$ |
| 200 | −384 | $3.5 \times 10^{-5}$ | 27 | 142 | 82 | 536 | $5.94 \times 10^{-4}$ |
| 400 | −384 | $3.1 \times 10^{-5}$ | 24 | 136 | 84 | 535 | $3.94 \times 10^{-4}$ |
| 600 | −403 | $2.63 \times 10^{-5}$ | 22 | 131 | 86 | 678 | $2.44 \times 10^{-4}$ |
| 800 | −424 | $1.9 \times 10^{-5}$ | 21 | 122 | 90 | 760 | $7.64 \times 10^{-5}$ |
| 1000 | −356 | $2.8 \times 10^{-5}$ | 20 | 120 | 65 | -- | $8.74 \times 10^{-5}$ |

$E_{pas}$, as well as the passive current density value, $i_{pas}$, were decreased with the addition of *Eruca vesicaria*, indicating that a better passive film is formed on top of steel when *Eruca vesicaria* is present. Thus, *Eruca vesicaria* helps to improve the passive film properties of the steel.

Polarization curves for 1018 carbon steel at different concentrations of *Bromelia hemisphaerica* is shown in **Figure 4**, where it is clear the active-passive behaviour of the steel. The free corrosion potential value was only marginally shifted towards nobler values and the corrosion current density was decreased as the *Bromelia hemisphaerica* concentration increased obtaining its lowest value with the addition of 800 ppm, **Table 2**. Both the anodic and cathodic Tafel slopes were decreased, especially with the highest inhibitor concentrations, indicating the mixed character of *Bromelia hemisphaerica*. Inhibitor efficiency values increased with increasing the *Bromelia hemisphaerica* concentration, between 64% and 74%, but these values were smaller than those obtained with *Eruca vesicaria*. The $E_{pas}$ and $i_{pas}$ values were lowered with the addition of *Bromelia hemisphaerica*, lower even than those obtained with the addition of *Eruca vesicaria*, improving, thus, the film passive properties of the steel, even in a better way than *Eruca vesicaria* did.
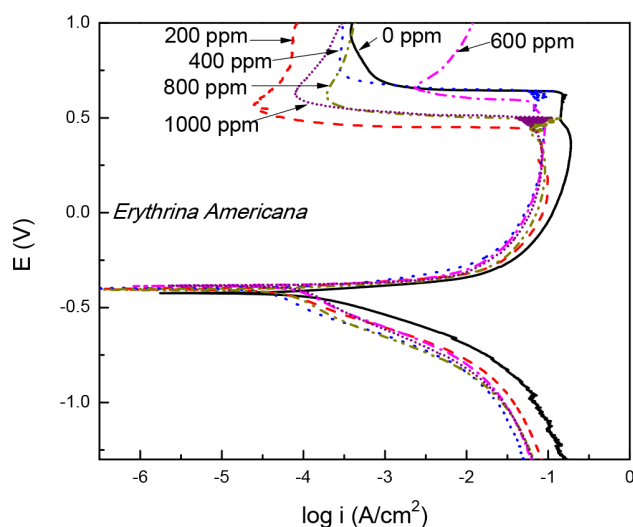
Finally, the effect of *Erythrina americana* concentration on the polarization curves for 1018 carbon steel in 0.5 M $H_2SO_4$ is shown in **Figure 5**. In this figure it can be seen that steel display an active-passive behaviour regardless of the *Erythrina americana* concentration. This time, the $E_{corr}$ value was shifted towards nobler values as the *Erythrina americana* concentration increased, **Table 3**, but the $i_{corr}$ value, although was decreased with the addition of the inhibitor, it reached its lowest value when 400 ppm of inhibitor were added, and it increased once again with a further increase in the *Erythrina americana* concentration. Thus, the inhibitor efficiency reached its



**Figure 4.** Effect of *Bromelia hemisphaerica* concentration on the polarization curves for 1018 carbon steel in 0.5 M $H_2SO_4$.

**Table 2.** Electrochemical parameters obtained from polarization curves in *Bromelia hemisphaerica*.

| $C_{inh}$ (ppm) | $E_{corr}$ (mV) | $i_{corr}$ (mA/cm$^2$) | $\beta_a$ (mV/dec) | $\beta_c$ (mV/dec) | I.E. (%) | $E_{pas}$ (mV) | $i_{pas}$ (mA/cm$^2$) |
|---|---|---|---|---|---|---|---|
| 0 | −426 | $1.94 \times 10^{-4}$ | 36 | 177 | --- | 680 | $7.8 \times 10^{-4}$ |
| 200 | −414 | $7.1 \times 10^{-5}$ | 34 | 155 | 64 | 530 | $5.94 \times 10^{-4}$ |
| 400 | −394 | $7.4 \times 10^{-5}$ | 32 | 146 | 62 | 635 | $4 \times 10^{-4}$ |
| 600 | −416 | $6.7 \times 10^{-5}$ | 30 | 134 | 65 | 615 | $2.94 \times 10^{-4}$ |
| 800 | −431 | $5.0 \times 10^{-5}$ | 29 | 128 | 74 | 570 | $1 \times 10^{-4}$ |
| 1000 | −407 | $6.8 \times 10^{-5}$ | 20 | 123 | 65 | 570 | $2.54 \times 10^{-4}$ |

**Figure 5.** Effect of *Erythrina americana* concentration on the polarization curves for 1018 carbon steel in 0.5 M H$_2$SO$_4$.
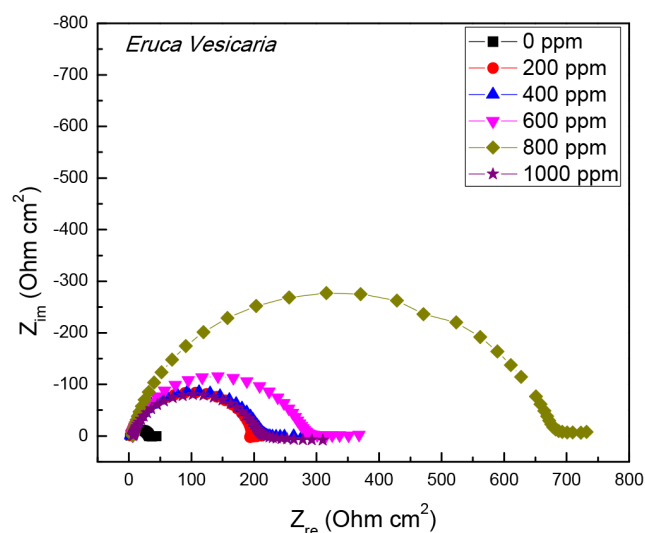
**Table 3.** Electrochemical parameters obtained from polarization curves in *Erythrina americana*.

| C$_{inh}$ (ppm) | E$_{corr}$ (mV) | i$_{corr}$ (mA/cm$^2$) | $\beta_a$ (mV/dec) | $\beta_c$ (mV/dec) | I.E. (%) | E$_{pas}$ (mV) | i$_{pas}$ (mA/cm$^2$) |
|---|---|---|---|---|---|---|---|
| 0 | −426 | 1.94 × 10$^{-4}$ | 36 | 177 | --- | 680 | 7.8 × 10$^{-4}$ |
| 200 | −403 | 3.5 × 10$^{-5}$ | 32 | 136 | 82 | 530 | 3.7 × 10$^{-4}$ |
| 400 | −400 | 3.0 × 10$^{-5}$ | 24 | 138 | 84 | 735 | 4.6 × 10$^{-5}$ |
| 600 | −384 | 6.3 × 10$^{-5}$ | 58 | 131 | 67 | 678 | 6.54 × 10$^{-5}$ |
| 800 | −403 | 3.9 × 10$^{-5}$ | 24 | 172 | 79 | 640 | 4.94 × 10$^{-5}$ |
| 1000 | −385 | 7.1 × 10$^{-5}$ | 36 | 170 | 63 | 670 | 8.34 × 10$^{-5}$ |

highest value, 84%, at 400 ppm of *Erythrina americana*, value slightly lower than the highest efficiency obtained with *Eruca vesicaria*, 90%. Both anodic and cathodic Tafel slopes were lowered by the addition of *Erythrina americana*, indicating that it acts as a mixed type of inhibitor, decreasing both the anodic iron dissolution and cathodic hydrogen evolution reactions. The E$_{pas}$ value was lowered only with the addition of 200 ppm of *Erythrina americana*, whereas the passive current density value, i$_{pas}$, was lowered by the addition of 200, 800 and 1000 ppm of *Erythrina americana*, forming, at these concentrations, a better passive film on top of the steel, improving, thus, the film passive properties.

## 3.3. EIS Measurements

The effect of *Eruca vesicaria* concentration in the Nyquist diagrams for 1018 carbon steel in 0.5 M H$_2$SO$_4$ is given in **Figure 6**, where it can be seen that data display a single, capacitive-like, depressed semicircle at all frequency values, with its centre at the real axis, indicating that the corrosion process is under charge transfer control from the metal to the solution through the double electrochemical layer. The semicircle diameter, equivalent to the charge transfer resistance, which is inversely proportional to the i$_{corr}$ value, increases with increasing the *Eruca vesicaria* concentration up to 800 ppm, decreasing with a further increase in the inhibitor concentration, **Table 4**, as explained above. This way, the lowest corrosion rate is obtained with the addition of 800 ppm of *Eruca vesicaria*. The double layer capacitance, C$_{dl}$, decreases with increasing the *Eruca vesicaria* concentration reaching its lowest value at 800 ppm, increasing once again with a further increase in the *Eruca vesicaria* concentration. This decrease in the C$_{dl}$ value is due to the adsorption of *Eruca vesicaria* on to the steel

**Figure 6.** Effect of *Eruca vesicaria* concentration on the Nyquist diagrams for 1018 carbon steel in 0.5 M $H_2SO_4$.

**Table 4.** Electrochemical parameters obtained from Nyquist plots in *Eruca vesicaria*.

| $C_{inh}$ (ppm) | $R_s$ (Ohm cm$^2$) | $R_{ct}$ (Ohm cm$^2$) | $C_{dl}$ (F/cm$^2$) | I.E. (%) |
|---|---|---|---|---|
| 0 | 1.7 | 46 | $8.5 \times 10^{-5}$ | --- |
| 200 | 1.8 | 214 | $3.7 \times 10^{-5}$ | 78 |
| 400 | 3.6 | 298 | $3.3 \times 10^{-5}$ | 84 |
| 600 | 2.4 | 386 | $2.6 \times 10^{-5}$ | 88 |
| 800 | 2.4 | 731 | $2.4 \times 10^{-5}$ | 93 |
| 1000 | 1.8 | 314 | $3.5 \times 10^{-5}$ | 85 |

surface, displacing the water molecules from the steel surface.

Nyquist diagrams for 1018 carbon steel at different concentrations of *Bromelia hemisphaerica* is shown in **Figure 7**, where it can be seen that data describe a single depressed, capacitive-like semicircle at all frequency values regardless of the presence of the inhibitor, indicating a corrosion process under charge transfer control. The semicircle diameter increases with increasing the *Bromelia hemisphaerica* concentration up to 800 ppm, decreasing its value with a further increase in the inhibitor concentration. Thus, the lowest corrosion rate is obtained at 800 ppm of *Bromelia hemisphaerica*. Finally, the Nyquist diagrams for 1018 carbon steel in 0.5 M $H_2SO_4$ at different concentrations of *Erythrina americana* is given in **Figure 8**, where the presence of a single capacitive-like semicircle at all frequency values is clear, indicating a charge transfer control. The semicircle diameter increase with increasing the inhibitor concentration up to 400 ppm, decreasing with a further increase in the inhibitor concentration. Thus, the lowest corrosion rate of carbon steel in 0.5 M $H_2SO_4$ is obtained with the addition of 400 ppm of *Erythrina americana*.

The effect of the three extracts concentration on the $R_{ct}$ values for 1018 carbon steel in 0.5 M $H_2SO_4$ is shown in **Figure 9**, where it can be seen that the highest $R_{ct}$ values, and thus, the lowest corrosion rates, were obtained with the addition of *Eruca vesicaria*, whereas the lowest $R_{ct}$ values, and thus, the highest corrosion rates, were obtained with the addition of *Bromelia hemisphaerica*. It can be seen, however, that each extract has an optimum concentration where the highest $R_{ct}$ value is obtained. Thus, this optimum inhibitor concentration was 800 ppm for *Eruca vesicaria* and *Bromelia hemisphaerica*, whereas for *Erythrina americana* was 400 ppm. The addition of an inhibitor concentration higher than this optimum value increases the corrosion rate.
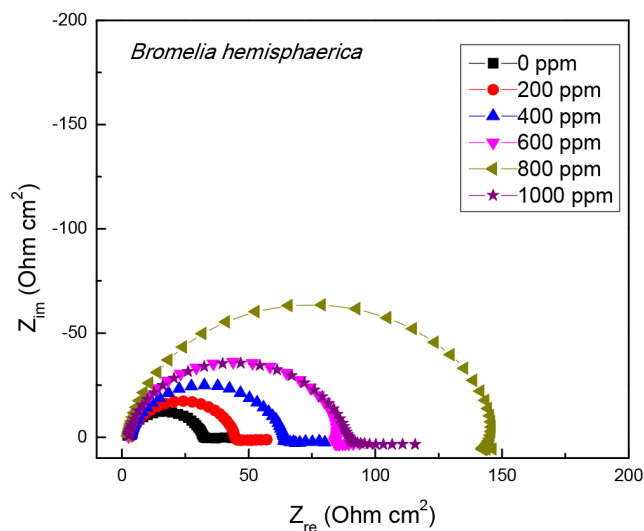
**Figure 7.** Effect of *Bromelia hemisphaerica* concentration on the Nyquist diagrams for 1018 carbon steel in 0.5 M $H_2SO_4$.
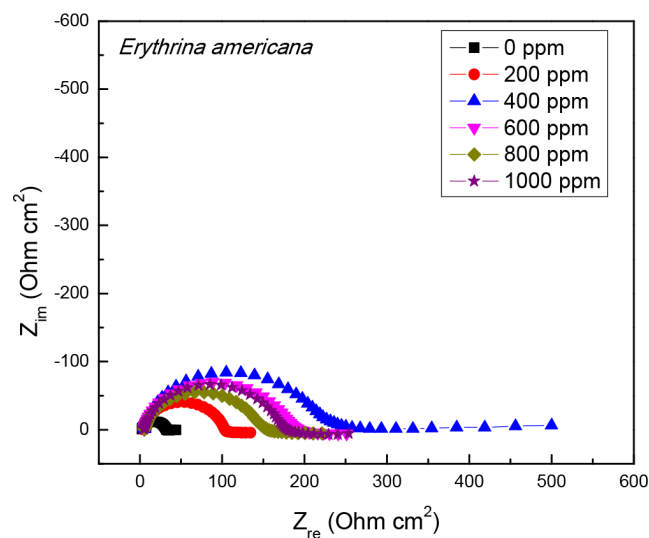


**Figure 8.** Effect of *Erythrina americana* concentration on the Nyquist diagrams for 1018 carbon steel in 0.5 M $H_2SO_4$.

It is generally accepted that the first step during the adsorption of an organic inhibitor on a metal surface usually involves replacement of water molecules absorbed on the metal surface:

$$Inh_{sol} + xH_2O_{ads} \rightarrow Inh_{ads} + xH_2O_{sol} \tag{3}$$
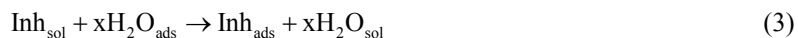
The inhibitor may then combine with freshly generated $Fe^{2+}$ ions on steel surface, forming metal inhibitor complexes [30] [31]:

$$Fe \rightarrow Fe^{2+} + 2e \tag{4}$$

$$Fe^{2+} + Inh_{ads} \rightarrow [Fe - Inh]_{ads}^{2+} \tag{5}$$

The resulting complex, depending on its relative solubility, can either inhibit or catalyze further metal dissolution. At low concentrations the amount of inhibitor is not enough to form a compact complex with the metal

ions, so that the resulting adsorbed intermediate will be readily soluble in the acidic environment. But at relatively higher inhibitor concentrations, more inhibitor molecules become available for the complex formation, which subsequently diminishes the solubility of the surface layer, leading to improve the inhibition of metal corrosion. Thus, it has been shown that the decrease in $i_{corr}$ and the increase in the $R_{ct}$ values is due to the protective character of the inhibitors. Micrographs of corroded surfaces after being corroded in $H_2SO_4$ shown in **Figure 10** are an evidence of this. For steel corroded in the uninhibited solution, **Figure 10(a)**, micrograph shows a
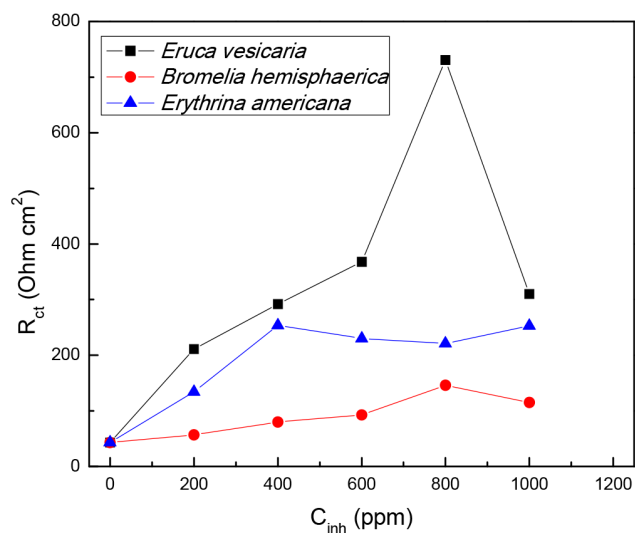


**Figure 9.** Effect of *Eruca vesicaria*, *Bromelia hemisphaerica* and *Erythrina americana* concentration on the $R_{ct}$ values for 1018 carbon steel in 0.5 M $H_2SO_4$.
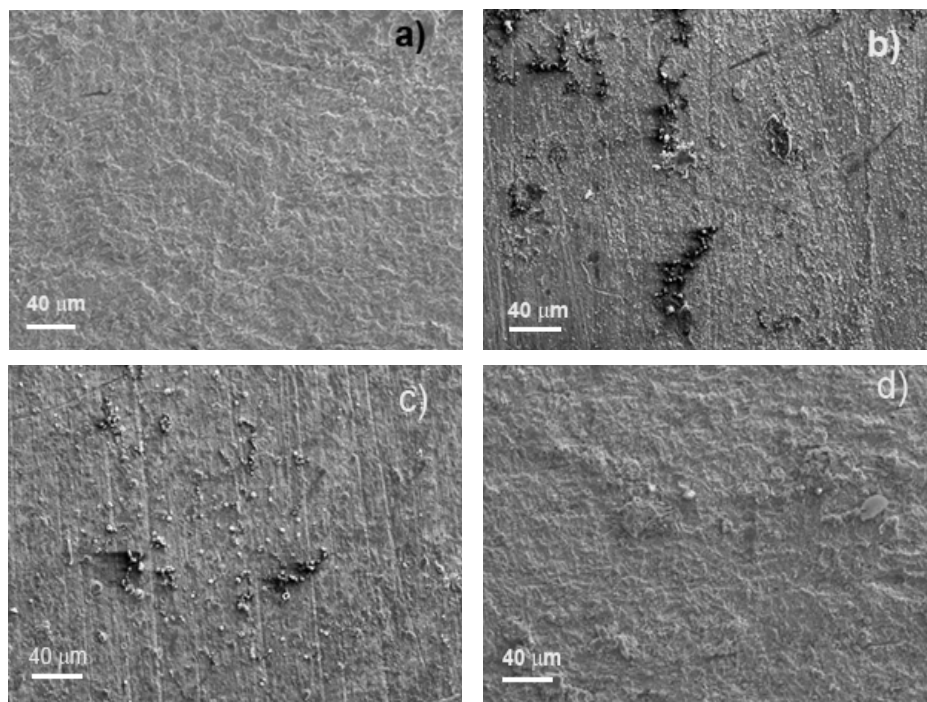


**Figure 10.** SEM micrographs of corroded 1018 carbon steel in a) 0.5 M $H_2SO_4$; b) 0.5 M $H_2SO_4$ + 800 ppm of *Eruca vesicaria*; c) 0.5 M $H_2SO_4$ +800 ppm of *Bromelia hemisphaerica* and d) 0.5 M $H_2SO_4$ + 800 ppm of *Erythrina americana*.

film formed on top of steel, which gives some protection to the steel as evidenced by polarization curves in **Figure 3** for the blank, uninhibited solution. This film, however, contains micro cracks and porous, sites where the aggressive solution can penetrate and corrode the underlying metal. When the three inhibitors were added, however, these porous and micro cracks disappeared, improving the film protectiveness, as evidenced by polarization curves, **Figures 3-5**, and evidencing that the addition of either *Eruca vesicaria*, *Bromelia hemisphaerica* or *Erythrina americana* are the responsible for the steel improved corrosion resistance.

## 3.4. FTIR Results

The good corrosion inhibition properties shown by *Eruca vesicaria*, *Bromelia hemisphaerica* and *Erythrina americana* is due to the presence of antioxidants present in their molecular structure containing heteroatoms such as N, C and O. For instance, *Eruca vesicaria* and *Erythrina americana* contain amino acids, and phenols. Infrared diagram for the pure *Eruca vesicaria*, 0.5 M $H_2SO_4$ + 800 ppm of *Eruca vesicaria* before and after the polarization curve are shown in **Figure 11**. For the pure extract, four peaks can be distinguished: the one at 3340 $cm^{-1}$, which corresponds to the hydroxyl group, O-H, whereas the peak at 2900 $cm^{-1}$ has been assigned to the amine, $NH_2$, group. The peak found at 1740 $cm^{-1}$ corresponds to the carboxile, C=O, group, **Table 5**, whereas the one at 1050 $cm^{-1}$ has been assigned to the C-O group. It is well known that $OH^{-1}$ can passivate the steel protecting it against corrosion, reacting with $Fe^{2+}$ ions to form $Fe(OH)_2$ responsible for the steel passivation. Amine is also well known to form a good passive film on metals to protect steel from corrosion, and it can be protonatedto give $NH^{3+}$ to react with $Fe(OH)_2$ to give $FeONH^{2+}$ + $H^+$, and probably the $FeONH^{2+}$ complex, equations [3] and [5] is the one which remains on the steel surface to protect it.
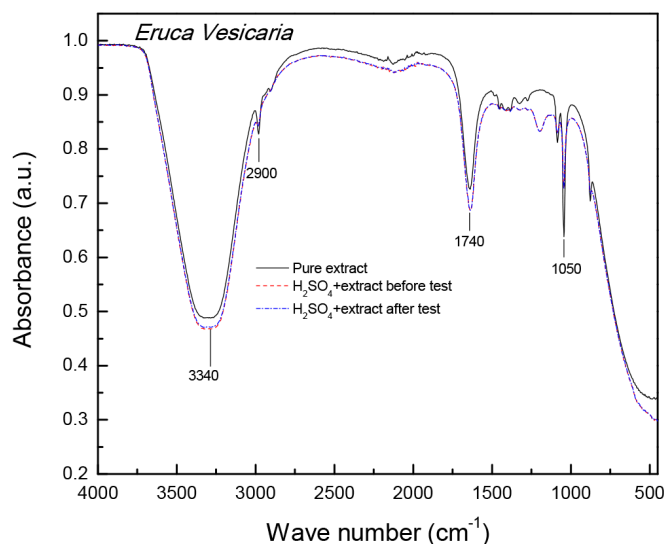


**Figure 11.** FTIR for pure *Eruca vesicaria* and 0.5 M $H_2SO_4$ + 800 ppm *Eruca vesicaria* before and after the corrosion test.

**Table 5.** Assigned functional groups to the FTIR spectrum corresponding to *Eruca vesicaria*.

| Wave number ($cm^{-1}$) | Assigned functional group |
|---|---|
| 3340 | O-H |
| 2900 | $NH_2$ |
| 1740 | C=O |
| 1050 | C-O |

## 4. Conclusion

It has been shown that *Eruca vesicaria*, *Bromelia hemisphaerica* and *Erythrina americana* acted as good corrosion inhibitors for 1018 carbon steel in 0.5 M $H_2SO_4$, with the best efficiency exhibited by *Eruca vesicaria*, 80%, whereas the worst efficiency, 40%, was exhibited by *Bromelia hemisphaerica*. The three inhibitors improved the protective properties of the formed passive film on top of the steel by reducing both the passivation potential and current density values. The protection given by the different extracts is due to the presence of antioxidants like phenols and amino acids, which contain heteroatoms in their structure such as C, N, or O, which react with metal and environment to form a complex which adsorbs on to the steel and protect it from the environment.

## References

[1] Qiu, L.G., Wu, Y., Wang, Y.M. and Jiang, X. (2008) Synergistic Effect between Cationic Gemini Surfactant and Chloride Ion for the Corrosion Inhibition of Steel in Sulphuric Acid. *Corrosion Science*, **50**, 576-582. http://dx.doi.org/10.1016/j.corsci.2007.07.010

[2] Abiola, O.K. and James, A.O. (2010) The Effects of Aloe Vera Extract on Corrosion and Kinetics of Corrosion Process of Zinc in HCl Solution. *Corrosion Science*, **52**, 661-664. http://dx.doi.org/10.1016/j.corsci.2009.10.026

[3] Cao, P.G., Yao, J.L., Zheng, J.W., Gu, R.A. and Tian, Z.Q. (2002) Comparative Study of Inhibition Effects of Benzotriazole for Metals in Neutral Solutions as Observed with Surface-Enhanced Raman Spectroscopy. *Langmuir*, **18**, 100-104. http://dx.doi.org/10.1021/la010575p

[4] Seeland, A., Oetken, M., Kiss, A. and Fries, E.J. (2012) Oehlmann. *Environmental Science and Pollution Research*, **19**, 1781-1790. http://dx.doi.org/10.1007/s11356-011-0705-z

[5] Osman, M.M. and Shalaby, M.N. (2003) Some Ethoxylated Fatty Acids as Corrosion Inhibitors for Low Carbon Steel in Formation Water. *MaterialsChemistry and Physics*, **77**, 261-269. http://dx.doi.org/10.1016/S0254-0584(01)00580-6

[6] Nešić, S. and Sun, W. (2010) Corrosion in Acid Gas Solutions. In: Tony, J.A.R., Ed., *Shreir's Corrosion*, Elsevier, Oxford, 1270-1298. http://dx.doi.org/10.1016/B978-044452787-5.00055-X

[7] Murthy, Z.V.P. and Vijayaragavan, K. (2014) Mild Steel Corrosion Inhibition by Acid Extract of Leaves of *Hibiscus sabdariffa* as a Green Corrosion Inhibitor and Sorption Behavior. *Green Chemistry Letters and Reviews*, **7**, 209-219. http://dx.doi.org/10.1080/17518253.2014.924592

[8] Chowdhary, R., Jain, T., Rathoria, M.K. and Mathur, S.P.B. (2004) Corrosion Inhibition of Aluminum in Hydrochloric Acid Solutions by Peepal (*Ficus religeosa*) Extracts. *Bulletin of Electrochemistry*, **20**, 67-75.

[9] Torres, A.R., Cisneros, M.G.V. and Rodríguez, J.G. (2015) Use of *Salvia officinalis* as Green Corrosion Inhibitor for Carbon Steel in Acidic Media. *International Journal of Electrochemical Science*, **10**, 4053-4067.

[10] Ji, G., Anjum, S., Sundaram, S. and Prakash, R. (2015) *Musa paradisica* Peel Extract as Green Corrosion Inhibitor for Mild Steel in HCl Solution. *Corrosion Scince*, **90**, 107-117. http://dx.doi.org/10.1016/j.corsci.2014.10.002

[11] Ji, G., Shukla, S.K., Dwivedi, P., Sundaram, S., Ebenso, E.E. and Prakash, R. (2012) Inhibitive Effect of Azorubine Dye on the Corrosion of Mild Steel in Hydrochloric Acid Medium and Synergistic Iodide Additive. *International Journal of Electrochemical Science*, **7**, 12146-12158.

[12] Singh, M.R. (2913) A Green Approach: A Corrosion Inhibition of Mild Steel by *Adhatoda vasica* Plant Extract in 0.5 M $H_2SO_4$. *Journal of Materials and Environmental Science*, **4**, 117-126.

[13] Petek, A. and Kovačič, S. (2014) The Influence of $Ce^{3+}$ Ions on the Corrosion Rate of Stainless Steel in Acidic Solutions of Different pH-Values. *Green Chemistry Letters and Reviews*, **7**, 337-341.

[14] Fouda, A.S., Shalabi, K. and Idress, A.A. (2015) *Ceratonia siliqua* Extract as a Green Corrosion Inhibitor for Copper and Brass in Nitric Acid Solutions. *Green Chemistry Letters and Reviews*, **8**, 17-29.

[15] Rahman, H.H.A., Seleim, S.M., Hafez, A.M. and Helmy, A.A. (2015) Study of Electropolishing Inhibition of Steel Using Natural Products as a Green Inhibitorin Ortho-Phosphoric Acid. *Green Chemistry Letters and Reviews*, **8**, 88-94.

[16] Arias-Montoya, M.I., Dominguez-Patiño, G.F., Gonzalez-Rodriguez, J.G., Dominguez-Patiño, J.A. and Dominguez-Patiño, M.L. (2015) Corrosion Inhibition of Carbon Steel in Acidic Mediaby Using *Actinidia deliciosa*(Kiwifruit) Extract. *Advances in Materials Physics and Chemistry*, **5**, 447-457. http://dx.doi.org/10.4236/ampc.2015.511045

[17] Anupama, K.K., Ramya, K., Shainy, K.M. and Joseph, A. (2015) Adsorption and Electrochemical Studies of *Pimenta dioica* Leaf Extracts as Corrosion Inhibitor for Mild Steel in Hydrochloric Acid. *Materials Chemistry and Physics*, **167**, 28-41. http://dx.doi.org/10.1016/j.matchemphys.2015.09.013

[18] 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. *Materials Chemistry and Physics*, **141**, 240-247. http://dx.doi.org/10.1016/j.matchemphys.2013.05.006

[19] Fuchs-Godec, R. and Zerjav, G. (2015) Corrosion Resistance of High-Level-Hydrophobic Layers in Combination with Vitamin E—(α-Tocopherol) as Green Inhibitor. *Corrosion Science*, **97**, 7-16. http://dx.doi.org/10.1016/j.corsci.2015.03.016

[20] El-Hamdani, N., Fdil, R., Tourabi, M., Jama, C. and Bentiss, F. (2015) Alkaloids Extract of *Retama monosperma* (*L.*) *Boiss.* Seeds Used as Novel Eco-Friendly Inhibitor for Carbon Steel Corrosion in 1 M HCl Solution: Electrochemical and Surface Studies. *Applied Surface Science*, **357**, 1294-1305. http://dx.doi.org/10.1016/j.apsusc.2015.09.159

[21] Rajeswari, V., Kesavan, D., Gopiraman, M., Viswanathamurthi, P., Poonkuzhali, K. and Palvannan, T. (2014) Corrosion Inhibition of *Eleusine aegyptiaca* and *Croton rottleri* Leaf Extracts on Cast Iron Surface in 1 M HCl medium. *Applied Surface Science*, **314**, 537-545. http://dx.doi.org/10.1016/j.apsusc.2014.07.017

[22] Heuer, B., Yaniv, Z. and Ravina, I. (2002) Effect of Late Salinization of Chia (*Salia hispanica*), Stock (*Matthiola tricuspidata*) and Evening Primrose (*Oenothera biennis*) on Their Oil Content and Quality. *Industrial Crops and Products*, **15**, 163-167. http://dx.doi.org/10.1016/S0926-6690(01)00107-8

[23] Sharma, K.S., Ackmez, M., Gargi, J. and Jyoti, S. (2009) Inhibitory Effects of *Ocimum tenuiflorum*(*thulasi*) Corrosion of Zinc in Sulphuric Acid: A Green Approach. *Rasayan Journal of Chemistry*, **2**, 332-339.

[24] Chen, S. and Andreasson, E. (2001) Update on Glucosinolate Metabolism and Transport. *Plant Physiology and Biochemistry*, **39**, 743-758. http://dx.doi.org/10.1016/S0981-9428(01)01301-8

[25] Doran, P.M. (2002) Properties and Applications of Hairy-Root Cultures. In: Oksman-Caldenty, K.-M. and Barz,W.H., Eds., *Plant Biotechnology and Transgenic Plants*, Marcel Dekker Inc., New York, 143-162. http://dx.doi.org/10.1201/9780203910849.ch7

[26] Schaller, A. (2004) A Cut above the Rest: The Regulatory Function of Plant Proteases. *Planta*, **220**, 183-197. http://dx.doi.org/10.1007/s00425-004-1407-2

[27] Lehman, A.J. (1936) Curare-actions of *Erythrina americana*. *Proceedings of the Society for Experimental Biology and Medicine*, **33**, 501-503. http://dx.doi.org/10.3181/00379727-33-8426P

[28] Ghosal, S., Dutta, S. and Bhattacharya, S.K. (1972) *Erythrina*—Chemical and Pharmacological Evaluation. II: Alkaloids of *Erythrina ariegata*. *International Journal of Pharmacy Science*, **61**, 1274-1277. http://dx.doi.org/10.1002/jps.2600610821

[29] Garcia-Mateos, M.E. and Garcia-Aguilar, A. (2000) Effect of B-Erythroidine and B-Dihydroerythroidine from *Erythrina americana* on Rats Aggressive Behaviour. *Pharmaceutical Letters*, **10**, 34-37.

[30] Jiang, X., Zheng, Y.G. and Ke, W. (2005) Effect of Flow Velocity and Entrained Sand on Inhibition Performances of Two Inhibitors for $CO_2$ Corrosion of N80 Steel in 3% NaCl Solution. *Corrosion Science*, **47**, 2636-2658. http://dx.doi.org/10.1016/j.corsci.2004.11.012

[31] Oguzie, E.E., Li, Y. and Wang, F.H. (2007) Corrosion Inhibition and Adsorption Behaviour of Methionine on Mild Steel in Sulfuric Acid and Synergistic Effect of Iodide Ion. *Journal of Colloid Interface Science*, **310**, 90-98. http://dx.doi.org/10.1016/j.corsci.2004.11.012