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Research Article

Experimental investigation of anti-corrosive behaviour of *Beta vulgaris*: A green approach

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Abstract
The loss of metals due to corrosion can be prevented using green inhibitors. Using natural and eco-friendly plant products is futuristic, preventing the environment from toxic and harmful chemicals. The present study aimed to investigate whole beetroot (BR, *Beta vulgaris*) for its anti-corrosion behaviour by galvanostatic polarization and electrochemical impedance techniques at a temperature between 298 K- 328 K. The temperature study would help in proposing BR's adsorption mechanism on metal surfaces. The maximum inhibition efficiency of 94% at 298 K for 5% BR was observed, whereas a minimum of 75% was obtained for 1% BR at 328 K. It was found to be a mixed-type inhibitor that followed Langmuir isotherm. From thermodynamic studies, ΔG^{o}_{ads} was found to be -13.64 kJ/mol, which revealed that BR adsorbed physically on the surface of mild steel. R_{ct} values increased while C_{dl} values decreased on exposure of metal surface with BR extract. The scanning electron micrographs (SEM) and atomic force micrographs (AFM) witnessed the formation of a protective layer on the mild steel surface, which served as a barrier between the metal and corrosive medium. The present study provides a remedy for the financial and structural losses due to metal corrosion in an acidic medium.

Keywords: Corrosion, Electrochemical Impedance Spectroscopy, Mild Steel, Langmuir isotherm, Physical adsorption

INTRODUCTION

Mild steel deterioration is one of the major concerns as it is widely used in various industries including processing, water pipes, cooling water systems, boilers, refining and mining of gas, oil industries, and skyscrapers (Habeeb *et al.*, 2018; Alibakhshi *et al.*, 2019; Badr *et al.*, 2018 and Medupin et al., 2013). It is low cost, affordability, high mechanical power, and ease of processing encouraged its widespread usage as an industrial input (Punitha *et al.*, 2022 and Muthamma *et al.*, 2021). The main problem associated with using mild steel (MS) in industry is its resistance against corrosion, especially in acidic solutions (Habeeb *et al.*, 2018). Corrosion is described as the physicochemical reaction between a metal and its environment that significantly changes the properties of the metal, environment and its technical system. (Umeozokwere *et al*., 2016; Chaouiki *et al*., 2020 and Chugh *et al*., 2020). Corrosion results in the formation of many useless products, which reduces the structural stability and durability of metal system. It is a major concern in sectors where acids are being used for many purposes. Many inorganic and organic corrosion inhibitors are being investigated and used as inhibitors to prevent various metals from being eaten away due to corrosion (Abdallah et al*.,* 2006; Yohai *et al*., 2013; Durowaye *et al*., 2014; Zou *et al*., 2014; Goyal *et al*., 2018 and Caldona *et al*., 2021). Numerous researchers have studied the suitability of various organic compounds as inhibitors, particularly those containing chromate, other heavy metals, and heterocyclic compounds, which are gradually being restricted as they have toxic effects on the environment. In the present time, awareness of the toxic effects of these chemicals has resulted in shifting towards the green revolution in industries too. Therefore, using natural and eco-friendly plant products is futuristic, and they have several advantages such as availability, biodegradability, efficiency, and they are environmentally friendly and renewable. *Origanum vulgare* has been investigated as a corrosion inhibitor on aluminium and mild steel in an acidic medium, resulting in 97.7% and 91.4% efficiency, respectively (Bashir *et al.*, 2018; Dhaundiyal *et al.,* 2019). The extract of *Asparagus racemosus* proved to be a good corrosion inhibitor, and it follows Langmuir adsorption isotherm (Bashir *et al*., 2017). In a study by Rodríguez et al. (2018), inhibition efficiency of 97% was reported for Prunus persica leaves extract in the presence of sulphuric acid. *Prunus persica* extract retards both cathodic and anodic reactions but with cathodic predominance. The same trend of inhibition efficiency was reported for rhizome extracts of *Acorus calamus* on mild steel corrosion (Kumar et al., 2013). Numerous plant extracts from plant leaves, barks, seeds, fruits, and roots have shown promising behaviour to inhibit the corrosion of metals in different aggressive media (Ambrish *et al*., 2012; Sangeetha *et al*., 2012; Prabakaran *et al*., 2017; Al Otaibi *et al*., 2021 and Sajadi *et al*., 2022). The plant extracts are rich in nitrogen, sulphur and oxygen-containing functional groups, which have free electrons that can bind to partially dissolved metal ions, retarding further dissolution and exhibiting good corrosion inhibition (Victoria *et al*., 2015; Aribo *et al*., 2017 and Verma *et al*., 2018).

Beetroot is an edible plant of the *Amaranthaceae* family (Nikan *et al*., 2019) and is distributed throughout Asia Minor, the Mediterranean, and Europe. BR benefits the human body's ionic balance, which is associated with low sodium concentrations and significant potassium and magnesium content. The high content of red colour content (betacyanins), high vitamins (B and C), minerals, and fibre present in BR are responsible for its beneficial dietary and medicinal effects.

Betacyanins reduce oxidative stress and the harmful effects of free radicals as well as exhibit antibacterial and antiviral properties, which inhibit the proliferation of cancer cells and are involved in the prevention of cardiovascular diseases (Nikan *et al*., 2019 and Chhikara *et al*., 2019). The processing of beets and the consumption of products made from them has increased rapidly since it was recognized as an extremely rich source of antioxidants (Balázs, 1994; Székely & Máté, 2022). A significant amount of essential and non-essential amino acids is also present in BR (Nemzer *et al.*, 2011). The present study aims to investigate the extract of whole beetroot (BR) in sulphuric acid medium as an inhibitor of corrosion of mild steel.

The corrosion inhibition of mild steel in well water (Selvi *et al*., 2009), in simulated oil well water (Joycee *et al*., 2022) and in HCl medium (Nagiub *et al*., 2016) by the extract of beetroot has been studied and reported. The corrosion inhibition by beet extract has also been reported on aluminium metal in aqueous medium (Nithya *et al*., 2015) and all these studies have shown promising results. The present study aimed to investigate the corrosion inhibition of mild steel in 0.5 M H_2SO_4 using the extract of *Beta vulgaris* (BR) by electrochemical studies, temperature kinetics, electrochemical impedance studies (EIS) and surface morphology using Scanning electron microscopy (SEM) and Atomic force microscopy (AFM).

MATERIALS AND METHODS

Preparation of beetroot extract

Beta vulgaris, commonly known as beetroot, subfamily Betoideae of the family Amaranthaceae, was purchased from the local market of North Delhi, India. It was then washed and cleaned. 150 g of the whole root was taken in a round bottom flask and was refluxed with 250 ml of 0.5 M H_2SO_4 for 8 hours. It was kept overnight to extract the basic components. After extraction, the resultant acidic solution of BR was filtered off and used as a stock solution for all the studies. Various concentrations (v/v %) 1%, 3%, 4% and 5% of the extract were prepared by dissolving the desired volume in 0.5 M H_2SO_4 solution.

Mild steel specimen

The present study used a mild steel specimen with a chemical composition of 0.15% carbon, 1.02% manganese, 0.8% silicon, 0.025% sulphur, 0.025% phosphorous, and the rest iron. The specimens of dimensions 3.0 cm×1.0 cm×1.0 cm soldered on one end with an insulated Cu (copper) wire embedded in epoxy resin, leaving a working area of 1 cm^2, were used for electrochemical studies. Coupons of 1 cm×1 cm×0.4 cm were used for SEM and AFM studies. The surface preparation of the mechanically abraded specimens was carried out using different grades of emery paper (up to 1200 grit), followed by cleaning with acetone and rinsing with double-distilled water to obtain polished coupons for all the studies (Kanojia *et al*., 2005).

Electrochemical techniques

A conventional three electrodes cell assembly was used for Galvanostatic Polarization Studies (GPS) and Electrochemical Impedance Studies (EIS), having mild steel (MS) as the working electrode, platinum as the counter electrode, and Saturated calomel electrode (SCE) fixed in luggin capillary as the reference electrode. A constant distance of approximately 1-2 mm was maintained throughout the experiment between the tip of luggin capillary and working electrode surface. The measurements were carried out in aerated non-stirred 0.5 M H_2SO_4 solutions without and with various concentrations of 1%, 3%, 4% and 5% of the BR extract at temperatures 298 K, 308 K, 318 K and 328 K. The cell assembly was kept for 4 hours to achieve open circuit potential (OCP) before each run. The potential of the metal electrode vs. SCE was measured with the help of an electrochemical workstation CHI760C (CH Instruments, Inc, USA). Tafel plots were performed at a scan rate of 0.010 V/s. Kinetic and activation parameters for adsorption and dissolution processes were then calculated. Impedance measurements were carried out using AC signals of amplitude 5 mV peak to peak at the open circuit potential in the frequency range 100 kHz to 10 mHz.

Surface characterization

Polished and pit-free mild steel coupons were subjected to corrosion exposure using 0.5 M H_2SO_4, the highest 5% and lowest 1% concentration of BR extract to observe the extent of inhibition for 24 hours. They were removed from the solutions without touching the surface, dried in desiccators for 24 hours and then (LEO 435 VP) SEM was used to study 2-D surface morphology. A Scanning probe microscope VEECO CP II AFM was used to study 3D surface morphology (Verma *et al*., 2018).

RESULTS AND DISCUSSION

Galvanostatic polarization studies

The cathodic and anodic polarization curves for different concentrations 5%, 4%, 3%, 1% of BR extract at four different temperatures 208 K-328 K are displayed in Fig. 1 (a-d), on which acid plots were overlaid.

The corrosion kinetic parameters such as corrosion potential (E_{corr}), corrosion current density (I_{corr}), anodic and cathodic Tafel slopes (β_a and β_c) and Inhibition efficiency (IE%) were derived from tafel plots and tabulated in Table 1. The polarization curves were extrapolated back to OCP to get the corrosion current (Kanojia *et al*., 2005). The Inhibition efficiency (IE) is then calculated using equation (1)

$$IE\ (\%)\ =\ \left[\frac{Icorr_{Acid} - Icorr_{BR}}{Icorr_{Acid}}\right] \times 100 \qquad (1)$$

No remarkable change in the OCP values was observed in the absence and presence of BR at all temperatures, indicating that BR behaved as a mixed-type inhibitor. Recent studies have shown that if the E_{corr} displacement is greater than 85 mV, an inhibitor may be classified as cathodic or anodic; otherwise, it may be classified as mixed type (Gao *et al*., 2014; Vu *et al*., 2020 and Badreah *et al*., 2023). The present study indicated that the examined inhibitor was a mixed-type inhibitor because the maximum displacement in E_{corr} varied from 5 to 30 mV. β_a and β_c varied with the addition of different concentrations of BR, implying controlled reactions (Sharma *et al*., 2023). The BR extract not only hindered cathodic hydrogen evolution reaction, but also retarded MS anodic dissolution. The values of anodic slopes were influenced significantly by the inhibitor, which showed that BR inhibits the corrosion process mainly by inhibiting the anodic metal dissolution reaction. A prominent decreasing trend in I_{corr} values was observed with BR in H_2SO_4. It was observed that I_{corr} values decreased with higher concentration of BR and increased with a temperature rise. This indicates that BR extract shows promising results at 5% concentration for MS corrosion in H_2SO_4, at lower temperatures. Interestingly, IE of BR at highest c (5%) was 94% and at lowest c (1%) was 84%. This could be due to the better θ accomplished by BR molecules on the MS surface (Shukla *et al*., 2011). The corrosion rate in the presence of BR increased with an increase in the solution temperature from 298 K to 328 K. From Table 1, it is obvious that the highest IE was observed at 298 K while the lowest was at 328 K. The IE % in BR showed a decreasing trend as reported earlier (Sharma *et al*., 2023; Shukla *et al*., 2011; Al-Baghdadi *et al.,* 2021), with an increase in temperature from 298 K to 328 K. This can be explained based on Le-Chatelier's principle; the adsorption exothermic reaction started to move in the backward direction, leading to the desorption of extract molecules from the MS surface, as the system temperature increased. These results suggested that BR retarded the dissolution of MS, by adhering to the MS surface, which hindered the contact of corrosive medium, even at high temperatures.

Temperature kinetics

The nature of the adsorption of the protective layer on

Table 1. Parameters of MS in 0.5 M H_2SO_4 in the presence of BR extract

Temp. (K)	Concentration of BR in 0.5 M H_2SO_4 (v/v) %	$-E_{corr}$ (mV)	I_{corr} (mA/cm^2)	β_c (V/dec)	β_a (V/dec)	IE (%)	θ
298	5	474	0.0842	9.158	21.944	94.09	0.9409
	4	481	0.1216	9.036	13.368	91.46	0.9146
	3	514	0.1911	8.045	10.113	86.59	0.8659
	1	487	0.2256	9.085	25.921	84.17	0.8417
	0	509	1.425	7.203	8.721	-	-
308	5	487	0.1512	9.298	12.694	90.59	0.9059
	4	474	0.1473	9.121	24.309	90.85	0.9085
	3	473	0.1864	8.956	20.865	88.46	0.8846
	1	474	0.3685	8.728	21.558	77.11	0.7711
	0	500	1.616	7.361	9.880	-	-
318	5	482	0.2824	8.725	24.230	89.58	0.8958
	4	483	0.3035	8.579	21.683	88.83	0.8883
	3	481	0.4743	8.229	26.583	82.47	0.8247
	1	490	0.6371	8.032	24.043	76.49	0.7649
	0	473	2.706	7.184	13.384	-	-
328	5	501	0.6820	7.934	9.578	89.03	0.8903
	4	490	0.8973	7.589	20.986	85.57	0.8557
	3	480	1.207	7.536	19.204	80.59	0.8059
	1	503	1.533	8.878	2.610	75.35	0.7535
	0	475	6.219	6.033	9.199	-	-

MS: Mild steel, BR: Beetroot

the MS surface can be determined by studying the temperature kinetics. In chemisorption, adsorbed molecules are bonded to the surface through valence bonds, which may be endothermic or exothermic. In physisorption, adsorbed molecules are held to the MS surface through physical attraction, which does not involve a significant change in the electronic orbital patterns. The type of adsorption involved between MS surface and inhibitor molecules depends on adsorption isotherms. In this study, different adsorption isotherms like Langmuir, Temkin, Frumkin, Freundlich, El-Awady and Flory- Huggins were tried and the best-fitted adsorption isotherm (where $R^2 \approx 1$) for adsorption of BR on mild steel was obtained. Corrosion and surface coverage, θ of mild steel in 0.5 M H_2SO_4 in the presence of various concentrations of BR at different temperatures are tabulated in Table 1. c/θ vs c produces a straight line with R ≈ 0.99 at all temperatures as shown in Fig. 2 and Table 2. This elucidates that the adsorption of the BR obeys the Langmuir adsorption isotherm (Al-Baghdadi *et al.,* 2021), which follows equation (2):

$$\frac{c}{\theta} = \frac{1}{K_{ads}} + c \qquad (2)$$

where K_{ads} is the equilibrium constant for the process of adsorption.

The intercept of the plot (Table 2) was used to calculate the adsorption equilibrium constant (K_{ads}) which in turn was used to calculate the Gibb's free energy change (Mobin *et al*., 2019) for the adsorption process using equation (3).

$$\Delta G^{\circ}_{ads} = -2.303\, RTlog\, (55.5\, K_{ads}) \qquad (3)$$

The determined thermodynamic parameters are summarized in Table 3. According to the literature, $\Delta G^{\circ}_{ads} > -20\, kJ/mol$ is considered as physisorption, $\Delta G^{\circ}_{ads} < -40\, kJ/mol$ is chemisorption while $-20\, kJ/mol < \Delta G^{\circ}_{ads} < -40\, kJ/mol$ is considered as comprehensive adsorption (Sin *et al*., 2017; Loto and Tobilola, 2018 and Chen *et al.,* 2022). The negative values of ΔG°_{ads} reveal the spontaneity of the adsorption process and the calculated values of $\Delta G^{\circ}_{ads} > -20\, kJ/mol$ indicating that the adsorption mechanism of BR on mild steel surface in 0.5 M H_2SO_4 solutions was typical of physisorption.

Fig. 3 depicts the graph log K vs. 1/T, used to calculate ΔH°_{ads} and ΔS°_{ads} and parameters (Akinbulumo *et al*., 2020) which are given in Table 3. The negative value of ΔH°_{ads} (-11.68 kJ/mol) indicated the exothermic and spontaneous nature of adsorption of BR on MS surface, which concurs with the decrease in IE % with a rise in temperature. The positive ΔS°_{ads} (6.81 × 10^{-3}

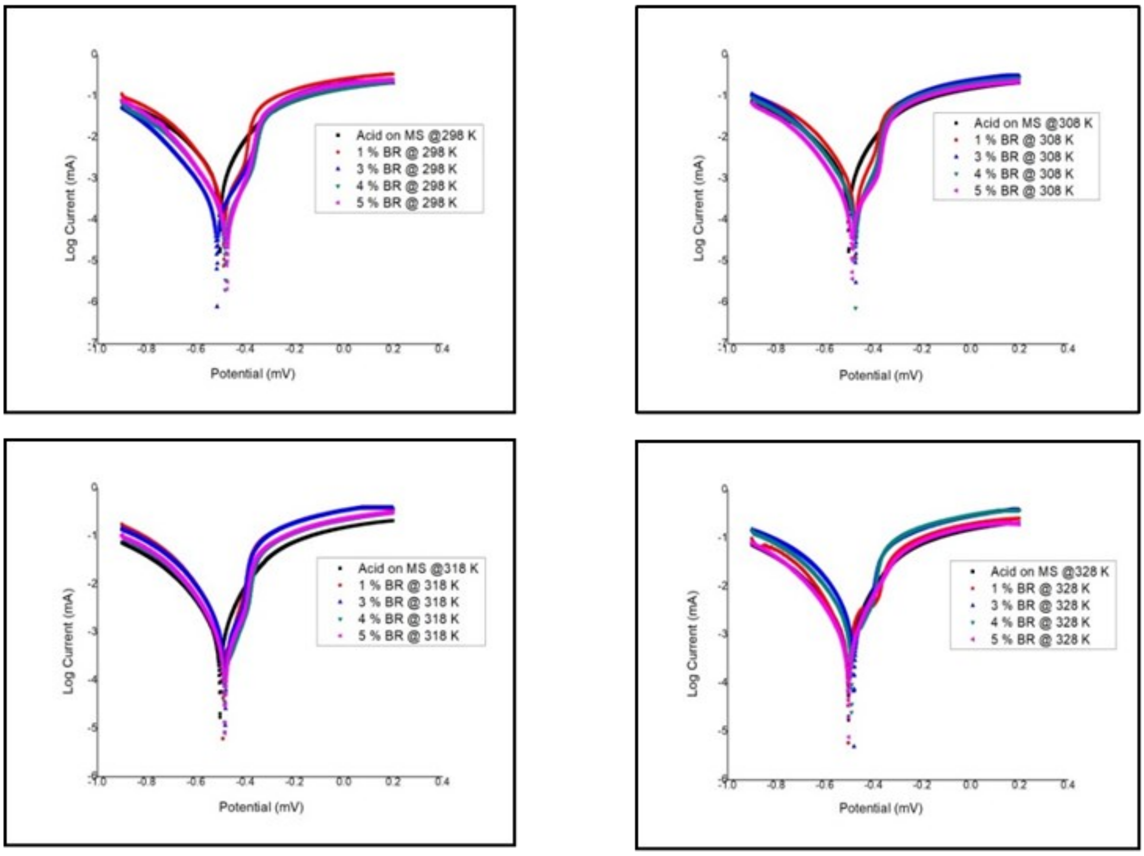

Fig. 1. *Galvanostatic polarization curves for mild steel in the presence of various concentrations of BR at (a) 298K, (b) 308K, (c) 318K and (d) 328K.*

kJ K^{-1} mol^{-1}) also supplements the spontaneity of physisorption BR extract on MS surface.

The plot of log I_{corr} against 1/T in equation (4) gives a slope from which the activation energy, E_a was calculated. The Arrhenius equation described the relationship (Akinbulumo *et al*., 2020) between the corrosion rate (I_{corr}) and temperature (T) as

$$log\, I_{corr} = log\, A - \frac{E_a}{2.303\, RT} \qquad (4)$$

where A is the Arrhenius factor and R is the universal gas constant.

The increased E_a in the presence of BR than that of free acid indicates that the extract considerably increased the activation energy of the metal dissolution process, which can be explained based on the adsorption of BR on the metal surface, thereby creating a barrier between the metal surface and the corrosive media. Literature has revealed that the higher activation energy value in the presence of the inhibitor is attributed to its physisorption, while the lower value is associated with its chemisorption (Larabi *et al.,* 2005; Negm *et al*., 2008; Rahiman *et al*., 2017). As shown in Table 4, the E_a decreased with the decrease in BR concentration; however, it was still greater than that of the uninhibited solution.

Electrochemical impedance studies

Electrochemical impedance studies (EIS) are an additional tool to study the effect of BR on the MS surface immersed in acidic corrosive medium. Charge transfer resistance (R_{ct}) and double layer capacitance (C_{dl}) of the system were determined in order to understand the adsorption behaviour and are represented in the form of Nyquist plot in Fig. 5, in the presence and absence of BR at 298 K at different concentrations. The experimentally determined parameters, such as R_{ct}, C_{dl}, phase angle *(α°)* are presented in Table 5. It could be seen from the table that with the increase in BR concentration, R_{ct} values increased while C_{dl} values decreased. R_{ct} value was reported as maximum for 5% BR and the value of C_{dl} is minimum for it. The decrease

Table 2. Linear regression parameters for Langmuir isotherm of BR

Temp. (K)	Slope	Intercept(1/K)	R^2
298	1.0330	0.2269	0.9967
308	1.0506	0.2372	0.9998
318	1.0622	0.3050	0.9971
328	1.0767	0.3354	0.9957

R^2: Regression coefficient

Table 3. Thermodynamic parameters for BR calculated from Langmuir isotherm

Temp. (K)	K	ΔG^o_{ads}(kJ/mol)	ΔH^o_{ads}(kJ/mol)	ΔS^o_{ads}(kJ/K/ mol)
298	4.4072	-13.64		
308	4.2158	-13.78		
318	3.2786	-13.57	-11.68	6.8077×10^{-3}
328	2.9815	-13.74		

in C_{dl} values is related to the decline in local dielectric constant and/or an increase in the thickness of the protective layer (Mathew *et al.,* 2020).

This decline in dielectric constant was due to the replacement of water molecules by BR extract, which is responsible for the thickening of double electric layer (Fu *et al*., 2023) and in turn, decreases the extent of metal dissolution. A single capacitive loop was observed in all Nyquist curves (Fig. 5(a)). The arc radius increased with increased BR concentration, indicating that adding BR strengthens the corrosion-inhibitive film on MS surface. The smallest arc was observed in the presence of acid. The low−frequency impedance value (*f*) and the maximum phase angle *(α°)* both increased with the addition of BR, suggesting the formation of a more stable protective layer on MS surface to prevent corrosive ions from eroding carbon steel (Fu *et al*., 2023).

Fig. 5 (b) shows the Bode plot; there was an increase in the absolute impedance value |Z|, at low frequencies, after MS treatment with BR. As the concentration of BR increased from 1% to 5%, the inhibitive layer strengthened as adsorption became more effective Fig. 5(c) shows a continuous well-pronounced phase angle shift at higher frequencies. Addition of BR to the acid, changes the phase angle to more negative values, indicating the adsorption of the inhibitor (Mathew *et al*., 2020). IE% was calculated using equation 5 (Sharma *et al*., 2023)

$$IE\ \% = \frac{R_{ct(BR)} - R_{ct(acid)}}{R_{ct(BR)}} \times 100 \qquad (5)$$

Table 4. E_a for the corrosion of mild steel in absence and presence of BR

c (v/v %)	E_a(kJ/mol)
5	56.59
4	55.11
3	53.01
1	51.64
0	40.51

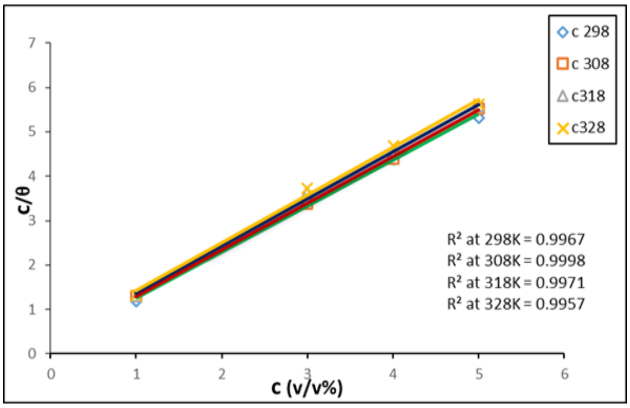

Fig. 2. *Langmuir adsorption isotherm of beet root*

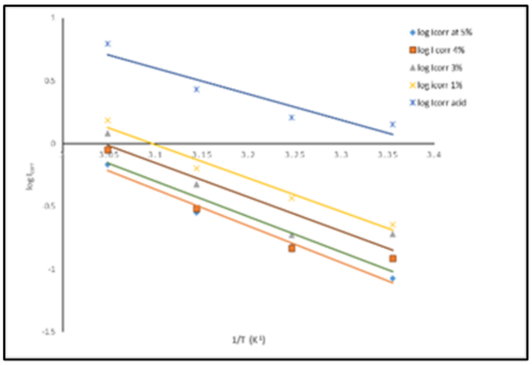

Fig. 3. *Plot of variation of log K vs 1/T*

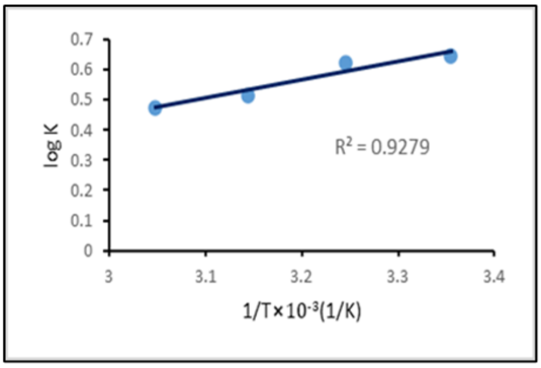

Fig. 4. *Plot of log I_{corr} vs 1/T*

Morphological studies

Surface morphology of MS surface with and without inhibitor has been examined using SEM images which complimented the results obtained from electrochemical techniques. Fig. 6 (a) shows the polished MS surface without any treatment at ×1000 magnification, while Fig. 6 (b) and (c) show the MS surface after immersion in 0.5 M H_2SO_4 for 24 hours at two different magnifications viz. ×1000 and ×3000, respectively. The effect of the corrosive medium is seen in these figures. SEM images of MS surface after dipping in 5% and 1% BR extract solution for 24 hours are shown in Fig. 6 (d)

Table 5. Impedance parameters for the corrosion of MS in absence and presence of BR

Inhibitor c (v/v %)	R_{ct} (Ωcm^2)	F (Hz)	α°	C_{dl} ($\mu F/cm^2$)	IE (%)	θ
5	303.164	9.766	66.4	53.78	91.18	0.9118
4	231.649	9.766	65.5	70.38	88.45	0.8845
3	170.422	17.44	66.5	53.57	84.30	0.8430
1	145.862	5.486	60.1	198.99	81.66	0.8166
0	26.750	25.70	52.2	231.62	-	

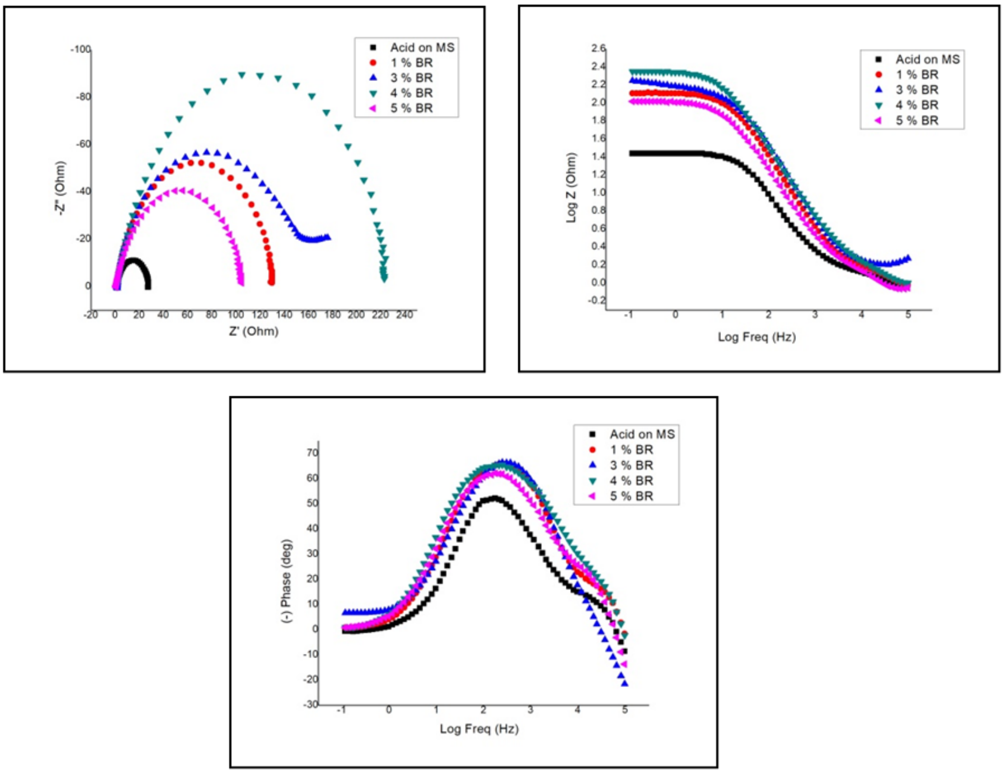

Fig. 5. *(a) Nyquist plot, (b) Bode Plot and (c) Phase angle of MS in absence and presence of BR at 5%, 4%, 3%, 1% at 298 K.*

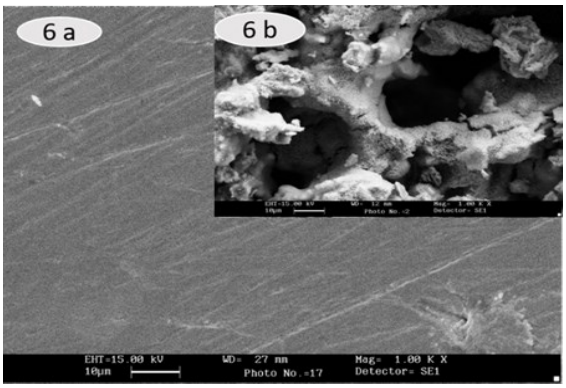

Fig. 6 (a). *Polished Mild steel* (***b***) *Mild Steel in 0.5 M H_2SO_4 at 1000 magnification*

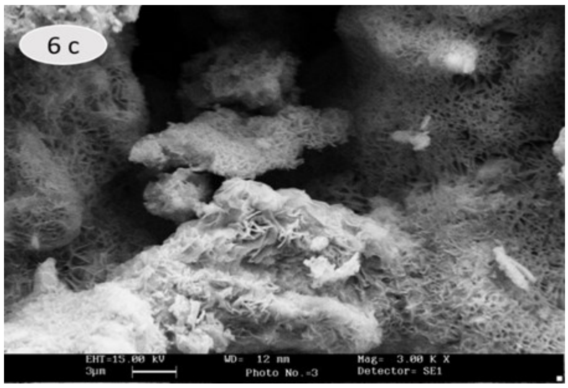

Fig. 6 (c). *Mild steel in 0.5 M H_2SO_4 at 3000 magnification*

– 6 (g) at magnifications ×1000 and ×3000. The metal surface was fully covered with the inhibitor molecules, giving it a high degree of protection against corrosion in the presence of 5% solution of BR. The extent of corrosion as visible from micrographs was much less at higher concentrations (5%) than specimens exposed to lower (1%) concentration of BR. This is in direct agreement with the results obtained from other techniques, i.e. the extent of corrosion inhibition increases with an increase in BR concentration.

AFM is a powerful technique to investigate the surface morphology at nano- to micro-scale. The three-dimensional (3D) AFM morphologies in the presence of corrosive H_2SO_4, 5% and 1% BR are shown in Fig. 7

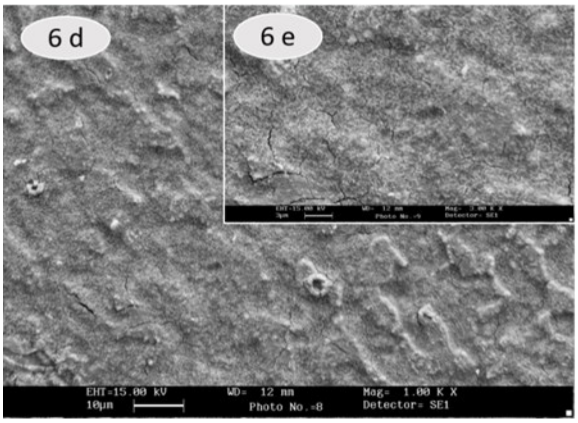

Fig. 6 (d). *Mild steel in the presence of 5% BR at 1000 magnification* **(e)** *Mild steel in 0.5 M H_2SO_4 in the presence of 5% BR at 3000 magnification*

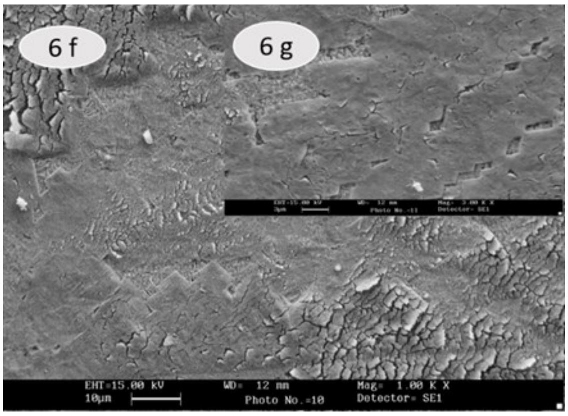

Fig. 6 (f). *Mild steel in the presence of 1% BR at 1000 magnification* **(g)** *Mild steel in 0.5 M H_2SO_4 in the presence of 1% BR at 3000 magnification*

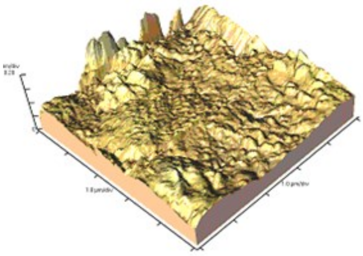

Fig. 7. (a). *Mild steel in the presence*

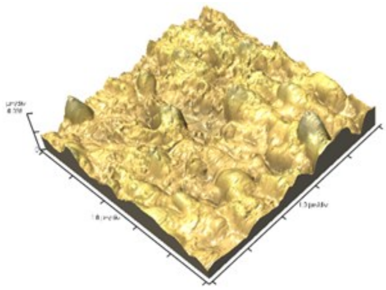

Fig. 7 (b). *Mild steel in presence of 5%*

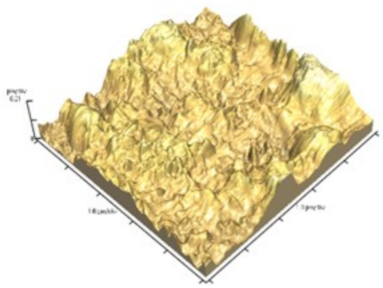

Fig. 7 (c). *Mild steel in presence of*

Table 6. AFM roughness data for the MS surface in 0.5 M H_2SO_4 without and with BR

Extracts	Average area RMS (nm)
Acid	141.3
5% BR	32.7
1% BR	73.9

MS: Mild steel, BR: Beetroot

(a) – (c). AFM images qualitatively characterized topographical changes. The metal surface could be quantitatively evaluated by measuring the difference in the surface roughness and is given in Table 6. The average area analysis method is employed to calculate the roughness of the metal surface. In this, the whole area of one side of the metal surface was considered.

Fig. 7(a) clearly shows the extent of corrosion in the presence of sulphuric acid. Deep pits and cracks were seen clearly, which shows the degree of surface damage. The roughness of metal surface (RMS) value of MS in acid was 141.3 nm, signifying the extent of corrosion as the higher the RMS, the greater the corrosion extent as reported by Peimani *et al.* (2018). MS exposed in the presence of 5% BR formed a coherent layer on the surface of carbon steel, and after that, small, spherical particles deposited on the top of the film. In this case, the RMS value was 32.7 nm, which showed the inhibiting nature of the film formed. The surface topography of MS in the presence of 1% BR showed that the BR molecules formed a barrier film, which protect the mild steel surface from corrosion but to a lesser extent. This can be seen by its RMS value (73.9 nm).

Conclusion

Electrochemical measurements in the present study showed that the inhibition efficiency decreases slightly with the decrease in *B. vulgaris* (BR) extract concentration from 5% to 1%. IE % decreased as the temperature increased. BR is a mixed type of inhibitor as indicated by E_{corr} but predominantly anodic as the anodic Tafel slope (β_a) was found to be higher than cathodic Tafel slope (β_c), therefore retarded corrosion mainly by anodic metal dissolution reaction. The adsorption of BR followed Langmuir's isotherm. The calculated value of Gibb's free energy values signified the physical adsorption of BR on MS surface. EIS measurements were in good agreement with results obtained from galvanostatic studies. SEM and AFM micrographs witnessed the formation of a protective layer on MS. Thus, it was concluded that *B. vulgaris* could be an effective, eco-friendly, and economic inhibitor to retard the corrosion of mild steel in corrosive acidic media.

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Conflict of interest

The authors declare that they have no conflict of interest.

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