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Tribulus terrestris Extracts: An Eco-Friendly Corrosion Inhibitor for Mild Steel in H_2SO_4 Medium

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The easily available plant *Tribulus terrestris* can be used as low-cost, eco-friendly corrosion inhibitor for mild steel in aggressive industrial environment. The inhibition efficiencies of different extracts (fruit, leaf and stem) in relation to the concentration of inhibitor and temperature were determined by mass loss method. Further electrochemical measurements (EIS and potentiodynamic polarization) were also done. Surface analysis was examined by scanning electron microscope. The adsorption process obeys Langmuir adsorption isotherm. All these analysis confirm that plant *Tribulus terrestris* has good properties to prevent the corrosion of mild steel in acidic medium.

Keywords: Corrosion inhibitors, *Tribulus terrestris*, Mass loss, Electrochemical measurement, Langmuir adsorption isotherm.

INTRODUCTION

The use of mild steel in industries is due to its availability, good strength and comparatively low cost. The overall cost of metal is the total cost of itself plus its maintenance cost and it can be reduced by reducing the maintenance cost. The maintenance cost can be controlled and minimized. But presently in all countries, most of the industries are facing the problem of corrosion of mild steel in acidic medium [1]. It involves a significant cost expense for prevent or non-prevent of the metals. On the one hand if protection methods are not used, the maintenance and renovation cost will be increased due to many premature, unexpected and expensive failure in system. On the other hand, if protection methods are used, it involves the cost of corrosion prevention but protection of metal is a powerful tool to reduce the overall cost and liabilities of the system. The cost also increases due to high temperature and corrosive sulphur gases, surrounding chemical and petroleum industries in industrial areas. Cost of corrosion will escalate substantially during the next decade because of worldwide shortages of construction materials, higher energy costs, aggressive corrosion environment in coal conversion processes and other factors. In fact our economy would be drastically changed if there is no corrosion and appliances would not require coatings. However, corrosion rate can be controlled and minimized. Most of the methods reported in literature are not only expensive but also toxic in nature. Therefore, a great need to investigate a non-toxic replacement that is compatible with current industrial technologies with their availability and relatively low cost, naturally substances. The use of plant extracts as corrosion inhibitors are economic, environmentally safe and readily available and it can be replaced the synthetic and toxic inhibitors. Extract of plants contain various organic compounds having hetero-atoms such as O [2], S [3] and N [3,4]. These hetero-atoms coordinate with the metal atom though their π electrons and form a protective film on metal surface, therefore corrosion is prevented. A lot of technological efforts have been studied to workout the natural corrosion inhibitors for iron or steel in acidic media, such as *Amaranthus* by Nigam and Srivastava [5], *Prosopis juliflora* by Chowdhary *et al.* [6], *Azardirachta indica* (Neem) by Oguzie [7], *Emblica officinal* (Indian Gooseberry) by Sartha and Vasudha [8], *Facourita jangomas* by Khalid Hasan and Sisodia [9], *Andrographis paniculata* (Kalmegh) by Singh *et al.* [10], Aloes by Cang *et al.* [11]. *Tagetes erecta* by Mourya *et al.* [12], *Retema monosperma* by Hamdani *et al.* [13] and *Canna indica* by Mathina and Rajlakshmi [14].

In the present work, an attempt has been made to study the influence of various concentrations of alcoholic extracts of fruit, leaf and stem constituents of plant *Tribulus terrestris* on mild steel in sulphuric acid as a powerful tool to reduce the cost of maintenance and increase the plant life. The *Tribulus terrestris* plant belongs to the Zygophyllaceae family. It is an annual creeping herb widespread in large area of India, China, eastern Asia and extends into western Asia and southern Europe. The preliminary phytochemical study of *Tribulus terrestris* revealed the presence of saponins, flavonoids, glycosides, alkaloids and tannins [15]. In India its usage in Ayurvedic medicine was for the purpose of impotency, poor appetite, jaundice, urogenital disorders and cardiovascular diseases [16].

Its common name is *Gokshura* or *Chhota Gokshura* or puncture vine.

EXPERIMENTAL

To find out the suitability of plant *Tribulus terrestris* for corrosion preventive properties, initially the study of corrosion inhibition efficiency of *Tribulus terrestris* was analyzed by mass loss measurement. For further study, electrochemical measurement [potentiodynamic polarization measurement and electrochemical impedance spectroscopy (EIS)] were employed.

Mass loss measurement

Preparation of plant extract: The extracts of *Tribulus terrestris* were prepared by the different parts of plant which were dried in air and grained then formed them as dried powder. It was subjected to the Soxhlet extraction using 80 % methanol, the solvent can be removed by boiling at constant temperature at 328 K in vacuum evaporator.

Specimen and test solution: The rectangular specimens of mild steel of size 1.5 cm × 2.5 cm × 0.025 cm were used. The weighed coupons were suspended with the help of glass hooks in borosil beakers containing 50 mL of 1.0 N H_2SO_4 solution with different plant extracts at the desired concentrations range for predefined time and temperature. The desired temperature was maintained by bacteriological incubator. At the end of the test, the coupons were taken out, washed with double distilled water, degreased with acetone, washed again with double distilled water, dried and then weighed using a weighing machine of precision ± 0.1 mg to calculate the mass loss.

Composition of mild steel: Elemental composition of mild steel was analyzed by Optical Emission Spectroscopy at MNIT Jaipur.

Element	Fe	Ni	Mo	Cr	S
Composition (%)	99.7	0.00	0.00	0.0194	0.0128
Element	P	Si	Mn	C	
Composition (%)	0.0162	0.00	0.162	0.0889	

The inhibition efficiency (IE %), degree of surface coverage (θ) and corrosion rate (CR) were calculated from the eqns. 1 and 2:

$$\text{IE}(\%) = \text{Surface coverage}(\theta)\times 100 = \left(\frac{\Delta W_0 - \Delta W}{\Delta W_0}\right)100 \quad (1)$$

$$\text{Corrosion rate (CR)} = \frac{\text{Mass loss} \times 8.76 \times 10^4}{\text{Area} \times \text{Time} \times \text{Density}} \quad (2)$$

where, ΔW_0 and ΔW are the mass loss of metal in absence and presence of inhibitor respectively. Mass loss is in gram; corrosion rate is in millimeter per year (mmpy); Area is in cm^2 of metal surface; exposed time is expressed in hours and metal density is expressed in g/cm^3.

Adsorption isotherm: According to Langmuir adsorption isotherm equation:

$$\log\left(C/\theta\right) = \log C - \log K_{ads} \quad (3)$$

where, C is concentration of inhibitor, K_{ads} is adsorption equilibrium constant and θ is degree of surface coverage area. A straight line graph should be obtained between log (C/θ) *versus* log C with gradient equal to one.

Electrochemical measurement: The electrochemical studies were made using a Gamry Potentiostat/Galvanostat (Model Reference 600) with EIS software Gamry Instruments Inc., USA of three electrode cell assembly (Euro Cell™) at room temperature. These electrodes are as (1) working electrode-mild steel strip of 7.5 cm^2 (2) graphite/auxiliary/counter electrode and (3) standard calomel electrode (SCE) as reference electrode. All the measurements for Tafel polarization curves were done by changing the electrode potential automatically from -0.10 to 0.10 V *vs.* SCE to workout the corrosion current (i_{corr}) and Nyquist diagram the charge transfer resistance R_{ct} (diameter of high-frequency loop) and the double layer capacity C_{dl} were done in solutions open to atmosphere under unstirred conditions and stabilization period of 30 min to the electrochemical measurement. Then

$$\text{Inhibition efficiency (IE, \%)} = \left(\frac{i^0_{corr} - i_{corr}}{i^0_{corr}}\right)\times 100 \quad (4)$$

where, i^0_{corr} and i_{corr} are the corrosion current in absence and presence of inhibitor, respectively.

$$\text{Inhibition efficiency (\%)} = \left(\frac{R_{ct} - R^0_{ct}}{R_{ct}}\right)\times 100 \quad (5)$$

where, R^0_{ct} and R_{ct} are the charge transfer resistance in absence and presence of inhibitor, respectively.

RESULTS AND DISCUSSION

Mass loss measurements

Inhibitor concentration: The surrounding atmosphere in industries involves the corrosive sulphur gases and temperature differences. The experimental results and their calculations for inhibition efficiency, surface coverage and corrosion rate were obtained from mass loss method at different concentration of different inhibitors in 1.0 N H_2SO_4 at 303 ± 1 K are shown in Table-1. The results indicate that all three inhibitors *i.e.* fruit, leaf and stem effectively protect the mild steel from corrosion in H_2SO_4 solution at various concentrations from 0.12 to 0.60 % and inhibition efficiency is function of the concentration of the inhibitor. It increases with increase of concentration of the inhibitor suggesting that increase of adsorption of inhibitors molecules on the metal surface provides wider surface coverage [17,18] and the increased coverage will defend the metal from the corrosion process by creating a separation of the metal surface from the acid medium. The results of IE % *v/s* inhibitor concentration are shown graphically in Fig. 1 for all the three extracts. The highest IE % obtained for fruit, leaf and stem extracts were 94.38, 92.25 and 88.76 % at their highest concentration, respectively.

Temperature effects: The change in temperature plays an important role to change of physical and chemical properties of metal and materials. Therefore, by using the bacteriological incubator for temperature control, an attempt for experimental analysis was done for workout of corrosion rate, degree of surface coverage and the inhibition efficiency for various concentrations of fruit, leaf and stem extracts. The computed values of mass loss method at the various temperature of 303 ± 1 K to

TABLE-1
CORROSION PARAMETERS FOR MILD STEEL IN SOLUTION OF 1 N H_2SO_4 IN ABSENCE AND PRESENCE OF DIFFERENT EXTRACTS OF *Tribulus terrestris* at 303 ± 1 K
Effective area of specimen – 7.50 cm^2; Immersion Time – 24 h

Concentration of inhibitor (% w/v)	CR	θ	IE (%)
Blank	31.949	–	–
Fruit extract			
0.12	9.659	0.6977	69.77
0.24	6.254	0.8043	80.43
0.36	4.148	0.8702	87.02
0.48	2.415	0.9244	92.44
0.60	1.796	0.9438	94.38
Leaf extract			
0.12	10.712	0.6647	66.47
0.24	6.687	0.7907	79.07
0.36	5.015	0.8430	84.30
0.48	2.91	0.9089	90.89
0.60	2.477	0.9225	92.25
Stem extract			
0.12	12.755	0.6008	60.08
0.24	8.173	0.7442	74.42
0.36	6.439	0.7985	79.85
0.48	5.139	0.8391	83.91
0.60	3.591	0.8876	88.76

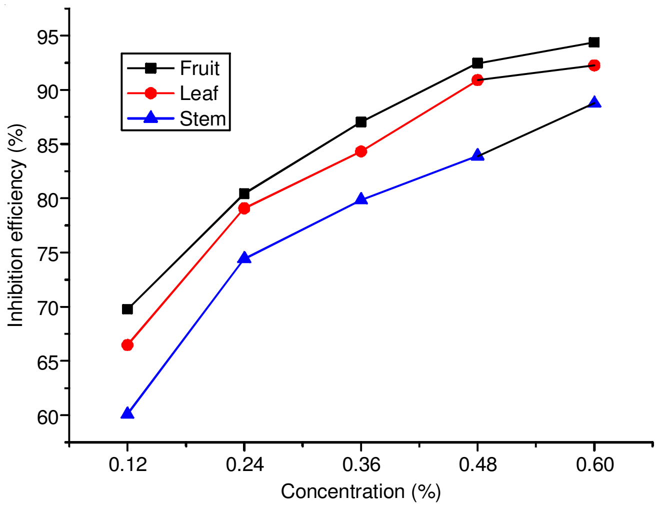

Fig. 1. Relation between percentages of inhibition efficiency with concentration of different extracts of *Tribulus terrestris*

333 ± 1 K after 6 h of immersion in 1 N H_2SO_4 solution are presented in the Table-2. The results indicate that the inhibition efficiency decreases with increase in temperature from 303 to 333 K and there was a minor decline at the highest concentration but rapidly decline at lowest concentration in the value of IE % which may be attributed to the insignificant removal of loosely adsorbed additive molecules by mechanical vibration of thermal energy. The inhibitor extracts have predictable that the mild steel was effectively protected from corrosive environment of high temperature with presence of sulphuric acid medium due to presence of active and adsorbed molecules [19-23].

Adsorption isotherm and thermodynamic study: To find out the adsorption behaviour of inhibitor on mild steel surface different adsorption isotherm were applied and it was found that Langmuir adsorption isotherm was most fitted

TABLE-2
CORROSION PARAMETERS FOR MILD STEEL IN SOLUTION OF 1.0 N H_2SO_4 IN ABSENCE AND PRESENCE OF FRUIT EXTRACTS OF *Tribulus terrestris* AT DIFFERENT TEMPERATURE;
Effective area of specimen – 7.50 cm^2; Immersion Time – 06 h

Temperature (K)	Concentration of inhibitor (% w/v)	CR	θ	IE (%)
303 ± 1	Blank	25.01	–	–
	0.12	5.20	0.7921	79.21
	0.24	3.47	0.8614	86.14
	0.36	2.23	0.9109	91.09
	0.48	1.49	0.9406	94.06
	0.60	1.24	0.9505	95.05
313 ± 1	Blank	48.79	–	–
	0.12	11.89	0.7563	75.63
	0.24	8.42	0.8274	82.74
	0.36	5.45	0.8883	88.83
	0.48	4.46	0.9086	90.86
	0.60	3.72	0.9239	92.39
323 ± 1	Blank	78.51	–	–
	0.12	26.01	0.6688	66.88
	0.24	20.06	0.7445	74.45
	0.36	13.62	0.8265	82.65
	0.48	10.15	0.8707	87.07
	0.60	9.41	0.8801	88.01
333 ± 1	Blank	144.64	–	–
	0.12	67.37	0.5342	53.42
	0.24	48.79	0.6627	66.27
	0.36	35.66	0.7534	75.34
	0.48	26.50	0.8168	81.68
	0.60	21.55	0.8510	85.10

isotherm. According to Langmuir adsorption isotherm a graph was plotted between log (C/θ) and log C, where C is concentration of inhibitor. This graph is almost straight line with approximate unity slop. This straight line can be represented by eqn. 6.

$$Y = mX + C \qquad (6)$$

May be represented as eqn. 3.

$$\log\left(C/\theta\right) = \log C - \log K_{ads}$$

where, Y is equal to log(C/θ); X is equal to log C; slop m is unity and constant value C is equal to $-\log K_{ads}$ constant and the value of K_{ads} is the equilibrium constant and computed from the intercept of the Y-axis. This equation is known as Langmuir adsorption isotherm. In graphical analysis, it was assumed that inhibition effect is mainly due to the adsorption at metal/solution interface and belongs to the monolayer adsorption. The mechanism of the adsorption was further analyzed by fitting the weight loss measurements into adsorption isotherm models. The results for different temperatures and concentration of the *Tribulus terrestris* fruit extract are shown in Table-2 and graphically presented in Fig. 2, which confirms the assumptions.

Further, the computed results of K_{ads} and free-energy of adsorption (ΔG^0_{ads}) are shown in Table-3 and is determine by eqn. 7:

$$\Delta G^0_{ads} = -RT \ln (K_{ads} \times 55.5) \qquad (7)$$

where, ΔG^0_{ads} is change in Gibbs free energy, K_{ads} is adsorption equilibrium constant, R is universal gas constant (8.314 J K^{-1} mol^{-1}), T is absolute temperature in K and concentration of water is 55.5 mol/L.

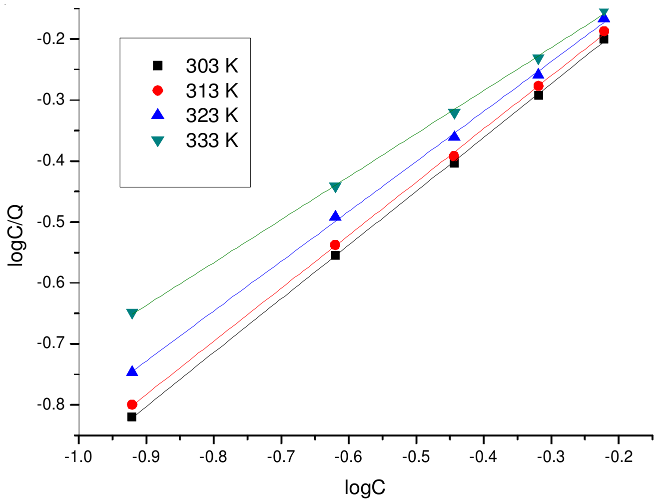

Fig. 2. Langmuir adsorption plots for mild steel in 1 N H_2SO_4 at different temperatures in presence of various concentration of *Tribulus terrestris* fruit extract

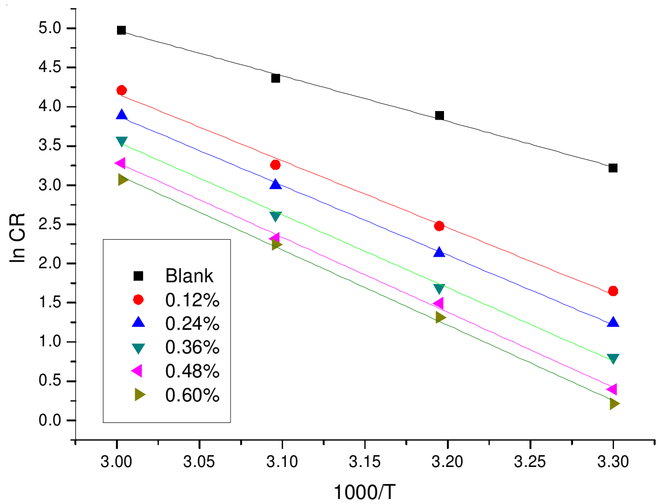

Fig. 3. Arrhenius plots for mild steel in 1 N H_2SO_4 in the presence and absence of fruit extract of *Tribulus terrestris*

TABLE-3
CHANGES IN ADSORPTION EQUILIBRIUM CONSTANT (K_{ads}) AND GIBBS FREE ENERGY AT DIFFERENT TEMPERATURES

Temperature (K)	K_{ads}	ΔG^0_{ads} (kJ/mol)
303	1.0195	-10.17
313	0.9974	-10.44
323	0.9807	-10.73
333	1.0065	-11.14

TABLE-4
THERMODYNAMIC PARAMETERS FOR MILD STEEL CORROSION IN 1 N H_2SO_4 WITH FRUIT EXTRACT OF *Tribulus terrestris*

Extract concentration	E_a (kJ/mol)	Enthalpy (kJ/mol)	Entropy (kJ/mol/k)
Blank	48.22	45.56	-0.225
0.12 %	71.00	68.34	-0.163
0.24 %	73.91	71.17	-0.157
0.36 %	77.49	74.83	-0.149
0.48 %	79.48	76.90	-0.145
0.60 %	79.90	77.24	-0.145

The negative values (around -10.75 kJ/mol) of ΔG^0_{ads} reflect the spontaneous nature of adsorption of inhibitor on metal surface and the adsorption supports physisorption and it is accredited to electrostatic interactions between the charged metal and charged molecules [24].

The thermodynamic adsorption parameters such as activation energy, heat of adsorption and entropy of adsorption, were also calculated for further analysis with the help of Arrhenius equation (eqn. 8) and transition state equation (eqn. 9) shown as below [25]:

$$\ln k = -\frac{E_a}{RT} + \ln A \quad (8)$$

$$\ln \frac{k}{T} = -\frac{\Delta H^0_{ads}}{RT} + \left(\ln\left\{\frac{R}{NH}\right\} + \frac{\Delta S^0_{ads}}{R} \right) \quad (9)$$

where, k is the rate constant which is directly proportional to corrosion rate; A is the Arrhenius constant; E_a is the activation energy; R is the gas constant and T is the absolute temperature.

For graphical analysis, from eqn. 8, graph was plotted between ln CR and 1/T (or 1000/T), which gives straight line with slop $-E_a/R$ is shown in Fig. 3 and computed values of E_a are shown in Table-4. It is observed that the activation energy E_a rises in the presence of inhibitor, it means the energy barrier increases for the corrosion reaction results in decrease of corrosion rate. Similarly from eqn. 9, graph was plotted between ln(k/T) or ln(CR/T) and 1/T which gives straight line with slop ($-\Delta H^0_{ads}/R$) and intercept [ln(R/Nh)+ ($\Delta S^0_{ads}/R$)] as shown in Fig. 4 and computed value of enthalpies ΔH^0_{ads} and entropies ΔS^0_{ads} for mild steel dissolution in 1 N H_2SO_4 solution are shown in Table-4. The positive values of the enthalpies and negative

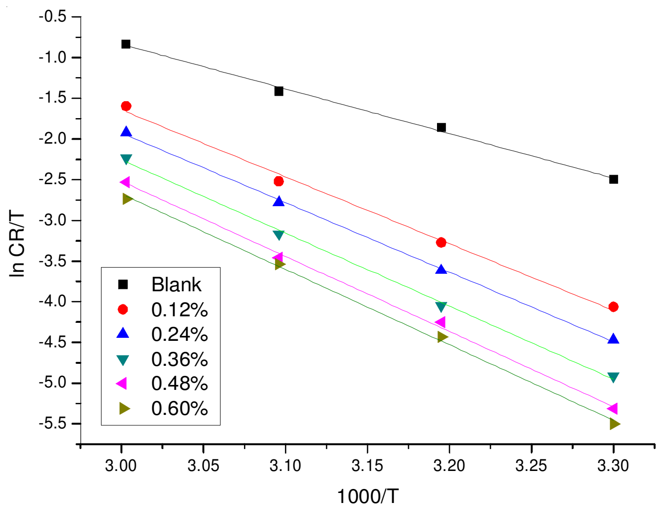

Fig. 4. Transition state plots (lnCR/T *vs.* 1/T) for mild steel in 1 N H_2SO_4 in the presence and absence of fruit extract of *Tribulus terrestris*

value of entropy reflect the endothermic nature of the mild steel dissolution process in H_2SO_4 solution. This implies that the activated complex in the rate determining step represents association rather than dissociation, this reflects the formation of an ordered stable layer of inhibitor on the steel surface [26] *i.e.*, increasing inhibitor concentration causes an increase in ordering on going from reactants to the activated complex.

Electrochemical measurement

EIS measurements: The corrosion or electrochemical impedance of a material is the most important property for the study of the nature of corrosion in metals. In present work, the electrochemical impedance was measured using a Gamry Potentiostat/Galvanostat for the frequency range from 100 kHz to 100 mHz at open circuit potential by fitting a circuit consisting the combination of resistance and reactance as shown in Fig. 5. This circuit constituted of series solution resistance R_s with the parallel combination of resistance R_{ct} and capacitor C_{dl} which represent the protective film/metal interface. The impedance behaviour of mild steel in 1 N H_2SO_4 with and without addition of extracts of different parts of plant *Tribulus terrestris* is presented as complex impedance (real and imaginary) plot also known as Nyquist plot is shown in Fig. 6.

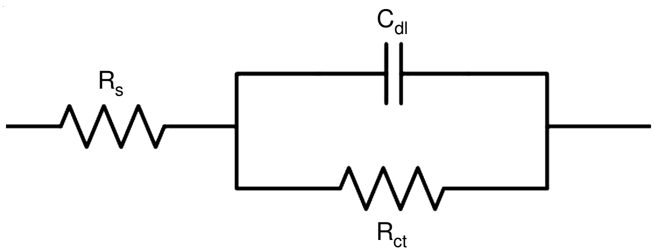

Fig. 5. Randle equivalent circuit corresponding to analyzed system

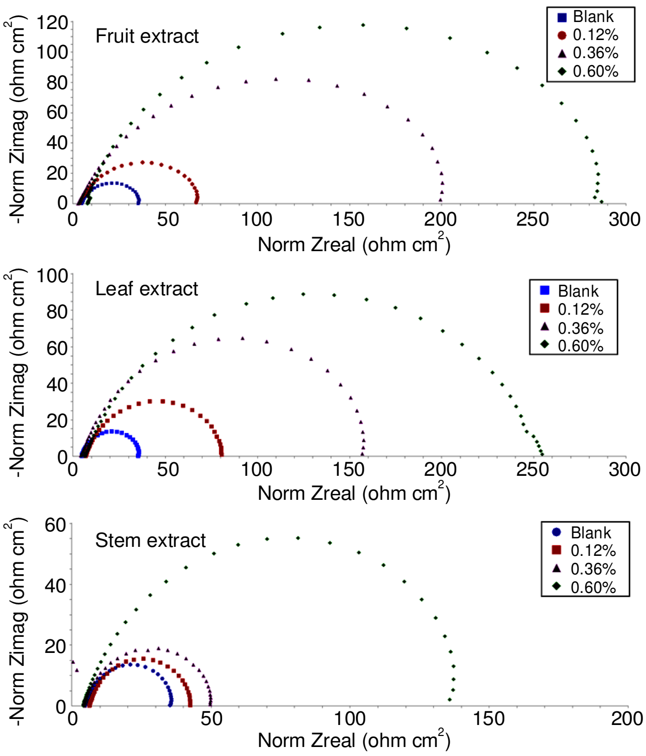

Fig. 6. Nyquist plots in absence and presence of different concentrations of *Tribulus terrestris* in 1 N H_2SO_4

The single semi-circle of Nyquist plots for without and with inhibitors indicates that the single charge transfer process during dissolution is unaffected by the presence of inhibitor molecules. The increase of radius of plot indicates the increase of impedance due to increase in number of inhibitive molecules present in the extract concentrations and also indicate that the corrosion rate of mild steel is decrease with increase of extract in H_2SO_4 solution. By addition of inhibitor, it increases the value of charge transfer resistance due to creation of protective film on mild steel or solution interface and reduces the double layer capacitance and increases in thickness of electronic double layer [27-29]. The charge transfer resistance R_{ct} and double layer capacitance C_{dl} are computed from the semi-circles are shown in Table-5. These semi-circles also indicated that IE % increases with increases their concentrations. It is also observed that these are not perfect due to the in homogeneity of the mild steel surface arising from surface roughness or interfacial phenomena [30,31]. The result of the above study shows that fruit extract of plant has better inhibition than stem extract or leaf extract.

TABLE-5
IMPEDANCE PARAMETERS OBTAINED USING EQUIVALENT CIRCUIT IN FIG. 5 FOR MILD STEEL IN 1 N H_2SO_4 SOLUTIONS WITHOUT AND WITH VARIOUS CONCENTRATIONS OF THE PLANT EXTRACT AT 303 ± 1K

Conc. of inhibitor (% w/v)	R_{sol} (Ω cm^2)	R_{ct} (Ω cm^2)	C_{dl} (µF cm^{-2})	θ	IE (%)
Blank	5.20	27.00	54.21	–	–
Fruit extract					
0.12	4.03	58.35	46.84	0.5373	53.73
0.36	3.99	173.00	31.95	0.8439	84.39
0.60	8.63	253.30	15.89	0.8934	89.34
Leaf extract					
0.12	7.68	67.27	39.54	0.5986	59.86
0.36	5.18	135.00	32.97	0.8000	80.00
0.60	8.62	209.40	19.19	0.8711	87.11
Stem extract					
0.12	6.81	36.00	74.28	0.2500	25.00
0.36	4.79	45.00	61.49	0.4000	40.00
0.60	4.81	118.70	35.92	0.7725	77.25

Potentiodynamic polarization: One another method by using Gamry Potentiostat/Galvanostat is also a powerful tool for study of anticorrosion behaviour *via* anodic and cathodic polarization by plotting a curve between corrosion potential E_{corr} and corrosion current density i_{corr}. This polarization curve is known as Tafel plot and β_a and β_c (mV/decade) are the slop of anodic and cathodic Tafel curve respectively. Various corrosion parameters such as corrosion potential (E_{corr}), corrosion current density (i_{corr}), anodic and cathodic slopes (β_a and β_c) and inhibition efficiency (IE %) are given in Table-6 and experimental Tafel plots are shown in Fig. 7. It can be seen from the experimental values that the corrosion current density decreases with increase in concentration of inhibitor suggest the retardation of the corrosion process. The shift in E_{corr} values is lesser than +33 mV. During literature survey, it was found [32] that if shift in corrosion potential is less than ± 85 mV with respect to corrosion potential of uninhibited solution the inhibitor act as mixed type inhibition. In present case the shift in E_{corr} value is +33 mV, indicating that these inhibitors are mixed type of inhibition. The value of β_a and β_c for fruit, leaf and stem inhibitors remains almost constant as compare to uninhibited solution indicates that inhibition process occurs without changing mechanism of corrosion reaction [33]. Thus inhibition process takes place only due to blocking of active

TABLE-6
POTENTIODYNAMIC POLARIZATION PARAMETERS FOR THE CORROSION OF MILD STEEL IN 1 N H_2SO_4 SOLUTIONS WITHOUT AND WITH VARIOUS CONCENTRATIONS OF PLANT EXTRACT AT 303 ± 1 K

Concentration of inhibitor (% w/v)	$-E_{corr}$ (mV)	i_{corr} ($\mu A/cm^2$)	β_a (mV/dec)	$-\beta_c$ (mV/dec)	Corrosion rate (mmpy)	θ	IE (%)
Blank	496	774	143.8	104.3	9.018	–	–
Fruit extract							
0.12	484	310	56.2	200.9	3.611	0.5995	59.95
0.36	478	153	45.4	197.9	1.78	0.8023	80.23
0.60	467	39.2	48.1	129.5	0.457	0.9494	94.94
Leaf extract							
0.12	480	325	54.9	182.1	3.793	0.5801	58.01
0.36	475	162	47.1	184.6	1.892	0.7907	79.07
0.60	463	103	42.8	175.5	1.199	0.8669	86.69
Stem extract							
0.12	476	418	64	107.7	4.88	0.4599	45.99
0.36	485	381	55.6	158.9	4.439	0.5078	50.78
0.60	472	139	42.3	211.7	1.625	0.8204	82.04

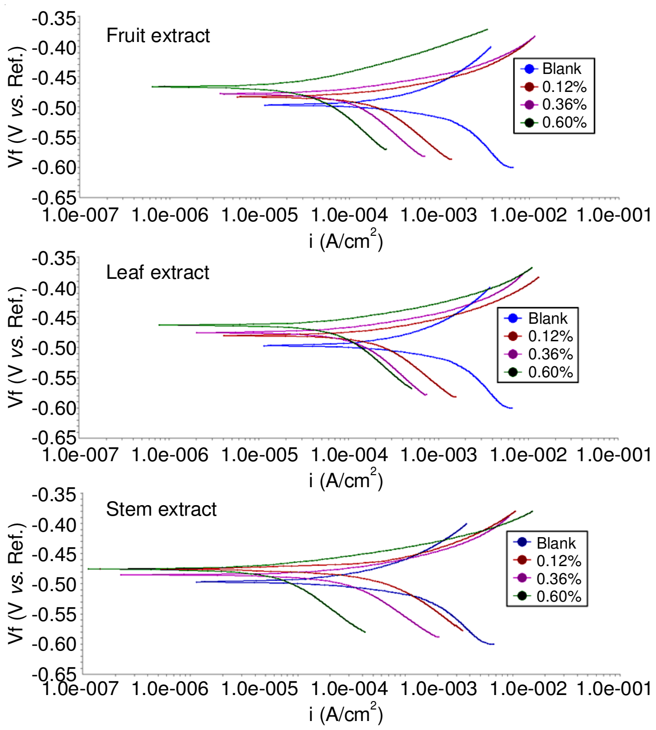

Fig. 7. Tafel curve in absence and presence of different concentrations of *Tribulus terrestris* in 1 N H_2SO_4

sites by inhibitor molecule. The result of the above study shows that fruit extract of plant has better inhibition than stem extract and leaf extract. These factors and the analysis, it is observed that these inhibitor extract have anticorrosion properties.

SEM analysis of mild steel surface: Three SEM images of magnification (x 10000) of mild steel were used for analysis purpose. These are namely (a) polished mild steel *i.e.* uncorroded surface, (b) mild steel in 1.0 N H_2SO_4 without extract and (c) mild steel in 1.0 N H_2SO_4 with 60 % of *Tribulus terrestris* leaf extract as shown in Fig. 8. By comparing these SEM micrographs, it is clear that the mild steel coupon 1.0 N H_2SO_4 without extract was awfully damaged and scratched which indicates the corrosion of mild steel in H_2SO_4. In another coupon in 1 N H_2SO_4 with extract, there is a formation of adsorbed layer of inhibitor on metal surface which effectively control the dissolution of mild steel.

Conclusions

The experimental data and their analysis can be concluded as under:

• The analysis of the experiments of *Tribulus terrestris* extracts (fruit, leaf and stem) show that it can be used as an effective inhibitor to prevent the corrosion of mild steel in aggressive circumstances and is compatible with current industrial technologies with their availability and relatively low cost naturally substances. It is also concluded that fruit of this plant is the most effective corrosion inhibitor amongst all the three parts.

• Mass loss study has shown that the inhibition efficiency increases with increases of inhibitor concentration. However,

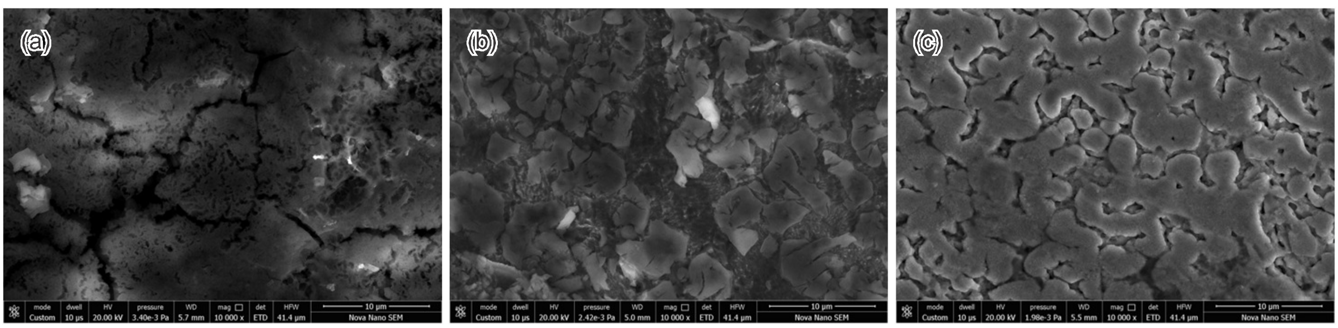

Fig. 8. SEM images of mild steel (a) polished mild steel (b) mild steel in 1 N H_2SO_4 (blank) (c) mild steel in 1 N H_2SO_4 with 0.60 % of *Tribulus terrestris* leaf extract

IE % decreases with increases of temperature but in both cases it effectively protects the mild steel from corrosion.

• The adsorption of plant *Tribulus terrestris* extracts on mild steel surface follow Langmuir adsorption isotherm model.

• The thermodynamic parameters indicate that the adsorption process is spontaneous and suggest that these inhibitors are strongly adsorbed on mild steel surface by physical adsorption mechanism.

• The EIS analysis indicates that the corrosion resistance or impedance increases with increasing plant extract concentration due to formation of a protective layer on metal.

• Tafel analysis indicates that *Tribulus terrestris* extracts are a mixed-type inhibitor.

• The SEM images also confirm the formation of a protective layer on metal.

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