Plant Extracts as Corrosion Inhibitors for Mild Steel in HCl Media – Review I

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Abstract

Due to fact that most of the chemical compounds, are called inhibitors, that prevent the corrosion of metals and alloys are toxic and harmful for human health and environment. Therefore, scientists have focused on a new class of inhibitors such as plant extracts, fruit and vegetable extracts, essential oils in recent years. In addition to being environmentally friendly in preventing corrosion, plant extracts are getting more and more important because they are cheap, less toxic and easy to obtain. Therefore, the usage of plant extracts as corrosion inhibitors is the subject of many researches in recent years. Plant extracts contain many organic compounds, having polar atoms such as O, P, S and N. These are adsorbed on the metal surface by these polar atoms, and protective films are formed, and various adsorption isotherms are obeyed. Mild steel has been the mostly widely used alloy due to the importance of industrial applications such as mining, cleaning of boilers, oil well tubes and metal processing equipment. Some acids such as hydrochloric acid and sulphuric acid are used for pickling mild steel and industrial cleaning and acid descaling. Therefore, the corrosion of mild steel in these acids is objectionable. In this review as the recent studies regarding as plant extracts as eco-friendly corrosion inhibitors for mild steel in hydrochloric acid media have been summarized.

Keywords: *corrosion, hydrochloric acid, mild steel, inhibitors, plant extracts.*

Received: September 21, 2020. Published: February 4, 2021 doi: 10.17675/2305-6894-2021-10-1-9

I. Introduction

As is known the use of inhibitors is one of the best effective methods to prevent metals and alloy against corrosion. Corrosion inhibitors such as inorganic substances like phosphates, chromates, dichromates, silicates, borates, tungstates, molybdates and arsenates are used to reduce the corrosion rates. Many of inhibitors are organic compounds [1–8]. These compounds show high protection effect against metal corrosion. However, most of them are toxic and using them is harmful for human health and environments [9–15]. Therefore their usage is limited in practice. For example chromium; especially hexagonal chromium compounds used as inhibitor are forbidden by European Union due to their carcinogenic effects [16, 17]. Therefore responsible agencies like U.S. Department of Transportation (DOT), U.S. Environmental Protection Agency (EPA), and the Occupational Safety and Health Administration (OSHA) limited the usage of toxic inhibitors [18–20].

Among the alternative corrosion inhibitors, organic substances containing polar function groups with nitrogen, oxygen, sulphur as π electrons in the conjugated properties. These compounds prevent corrosion either by being adsorbed on metals and alloys, or by forming a protective layer, or by causing the formation of insoluble complex. However, the toxicity of these compounds affect either during the synthesis of them or during their applications. Plant extracts have become important because of their non-toxic, inexpensive, available and renewable sources of materials and eco-friendly benign nature. Therefore, looking at the literature, it is seen that they are many studies done with plant extract against the corrosion of various metals and alloys [21–41].

Mild steel is one of the most important metals in several industrial applications due to low cost, ease of fabrication and good tensile strength. However, mild steel corrosion has been a serious problem in its application in various fields such as automobiles, aviation, agriculture, building construction, power plants, oil and gas industry. The mild steel corrosion has gained importance in the recent past due to increased industrial applications of mild steel especially in acidic solutions such as pickling, acid descaling, industrial cleaning and oil well acidizing [42]. In the present review, many plant extracts and their inhibition efficiencies on the corrosion of mild steel in hydrochloric acid media have been summarized.

There are many studies showing the effect of various plant extracts against the corrosion of mild steel in HCl media [43–64] such as *Justicia gendarussa* [43], *Uncaria gambir* extract [44], *Chrysophylium albidum* [45], *Psidum guazava* [46], *Lavandula mairei* [47], *Nypa fruticans Wurmb* [48], *Phyllanthus amarus* [49], *Lemon balm extract* [50], *Opuntia ficus-indica* [51], *Fig Leaves* [52], *Lavandula dentate* [53], *Aniba rosaeodora* [54], *Anacardium occidentale* (cashew) [55], *Embilica officianalis*, *Terminalia bellirica* and *Terminalia chebula* [56], *Nigella sativa* L. [57], *Alstonia angustifolia latifolia* [58], *Spirogyra algae* [59], *Zingiber officinal roscoe* [60], *Caulerpa prolifera* [61], *Tithonia diversifolia* [62], *Ocimum sanctum*, *Aegle marmelos* and *Solanum trilobatum* [63], *Dennettia tripetala* [64].

The inhibition action of *Aloes* extract has been shown by H. Cang *et al.* [65]. The inhibition properties of *Aloes* extract have been determined using weight loss method, potentiodynamic polarization and electrochemical impedance spectroscopy techniques. The results show that the inhibition efficiency increases with the increase of the extract concentration. The effect of temperature on the corrosion behavior of mild steel in 1 M HCl with addition of *Aloes* extract has been shown. The adsorption of the extract molecules on the steel surface obeys Langmuir isotherm. In the study, thermodynamic parameters confirm the presence strong interaction between extract and mild steel surface [65]. Mathina and Rajalashmi [66] used *Canna indica* as green corrosion inhibitor. *Argan hulls* extract has been used by L. Afia *et al*. [67]. The protection effect of *Cassia senna* extract on mild steel corrosion in HCl medium was researched R. Karthik *et al.* [68]. Mathina and Rajalakshmi [69] studied with *Heliconia rostate* [69] as flower extract to determine the inhibition efficiency against mild steel corrosion in HCl medium. *Luffa aegyptiaca* leaves extract was tested as corrosion inhibitor for mild steel in hydrochloric acid medium by Jyothi and Ravichandran [70].

In the study both potentiodynamic polarization and electrochemical impedance spectroscopy techniques were used. According to polarization measurements this extract indicated mixed type inhibitor behavior. It was found that percentage inhibition efficiency increased with extract concentration and decreased with temperature. Thermodynamic parameters show the spontaneous adsorption of *Luffa aegyptiaca* leaves extract on mild steel surface. In addition, it has been proven that the adsorption process obeys the Langmuir isotherm [70].

A. Singh *et al*. [71] investigated the inhibition property of *Cuminum cyminum* extract by gravimetric, potentiodynamic polarization and electrochemical impedance spectroscopy. Polarization results showed that the extract behaved as mixed type inhibitor. It supplied 93% inhibition efficiency at 300 ppm concentration. R_p and i_{corr} values of Tafel polarization method were in good agreement with weight loss findings. *Cuminum cyminum* extract was attributed to the adherent adsorption of the inhibitor on the steel surface UV–Visible spectroscopy experiments also showed the complex formation between the inhibitor and mild steel surface.

The inhibition effects of *Allium cepa* and *Allium sativum* [72], *Aquilaria crassna* leaves [73], *Ficus hispida* [74], Rubber leaf extract [75], *Bryophyllum pinnatum* leaves [76], *Boerhavia diffusa* (Punarvana) [77] have been published [72–77].

F. Zucchi and H. Omar [78] determined the effects of *Papaia*, *Ponciana pulcherrima*, *Cassia occidentails* and *Datura stramonium* seeds and *Papaia*, *Calotropis procera* B, *Azydracta indica* and *Auforpio turkiale* sap. on the corrosion of steel in HCl media. The researchers used weight-loss experiments and electrochemical measurements for determining the inhibition efficiencies. The found that all extracts except those of *Auforpio turkiale* and *Azydracta indica* decreased the corrosion of steel with an efficiency of 88%–96% in 1 N HCl and with a slightly lower efficiency in 2 N HCl. According to the researchers the inhibition property is mostly due to the products of the hydrolysis of the protein content of these plants.

Raja *et al*. [79] investigated the inhibitive effect of *Xylopia ferruginea* [79] leaves from different extract and partitions. In this study researchers investigated anti corrosion potential on mild steel corrosion in a hydrochloric acid medium by using electrochemical impedance spectroscopy and potentiodynamic polarization measurement. Electrochemical findings were confirmed by scanning electron microscopy (SEM) and Fourier transform infrared (FTIR) analysis. In the study, it was determined that *Xylopia ferruginea* extract acts both anodic and cathodic inhibitor. In other words it is a mixed type inhibitor. Another study with *Xylopia ferruginea* was done by Elyn Amira *et al*. [80]. The authors used mass loss, potentiodynamic polarization, EIS and SEM techniques. The results showed that *Xylopia ferruginea* is an excellent green inhibitor. According to the Nyquist plots as increasing the inhibitor concentration the charge transfer resistance increased and double layer capacitance decreased. The adsorption isotherm obeys the Langmuir isotherm. SEM studies confirmed that the corrosion protection of mild steel by the adsorption of *Xylopia ferruginea* [80].

Yun Sin *et al*. [81] investigated *Aquilaria subintegra* leaves extracts on mild steel in HCl medium. The leaves extracts from non and inoculated *Aquilaria subintegra* were tested and were shown to have high corrosion inhibition of up 93% at 1500 ppm concentration. The authors studied using weight loss, electrochemical impedance spectroscopy and potentiodynamic polarization measurements. The electrochemical results indicated that the leaf extract from the chemically inoculated tree was the best inhibitor. The extracts were shown to adsorb on the mild steel surface by physisorption process from the Langmuir adsorption isotherm model and the potential zero charge analysis.

R. Karthik *et al*. [82] used *Tiliacora accuminata* leaves extract for mild steel corrosion in 1 M hydrochloric acid solution. A. Ostowari *et al*. [83] investigated *Henna* extract for corrosion inhibition of mild steel in 1 M HCl solution. They made a comparative study of the inhibition by *henna* and its constituents (Lawsone, Gallic acid, α-d-Glucose and Tannic acid). In the study, authors used electrochemical techniques and surface analysis (SEM/EDS). Polarization curves show that all the examined compounds behave as a mixed inhibitor and inhibition efficiency increases with inhibitor concentration. Maximum inhibition efficiency (92.06%) was found at 1.2 $g\cdot dm^{-3}$ henna extract. Inhibition efficiency increases in the order:

lawsone > henna extract > gallic acid > α-d-Glucose > tannic acid [83].

The inhibition efficiency of *UAE Rhazya Stricta Decne* extract studied on the corrosion of mild steel in HCl solution by A. Nahie *et al*. [84]. Weight loss measurements were carried out on the mild steel samples in 1.0 M HCl and in 1.0 M HCl containing various concentrations (from 2.0 to 0.002 $g\cdot dm^{-3}$) of the *UAE Rhazya Stricta Decne* extract was found to be very effective inhibitor for mild steel in 1.0 M HCl solution. The authors determined maximum efficient of the inhibitor about 90% at 2.0 $g\cdot dm^{-3}$ at 303 K. However, one-tenth of that concentration 0.2 $g\cdot dm^{-3}$, an inhibition efficiency is about 82% at 303 K. The researchers investigated the concentration effect of the extract. Corrosion rate increases as the concentration of extract is increased. The percentage of inhibition in the presence of this inhibitor was decreased with temperature which indicates that physical adsorption was the predominant inhibition mechanism because the quantity of adsorbed inhibitor decreases with increasing temperature. According to these results it can be said that this inhibitor could have application in industries, where HCl solutions at elevated temperatures are used to remove scale and salts from steel surfaces, such as acid cleaning of tankage and pipeline and may render dismantling unnecessary. This extract as green corrosion inhibitor shows high protection against corrosion of mild steel [84].

T. Ibrahim *et al*. [85] researched the effect of *Thyme* leaves extract on the corrosion of mild steel. K. Anupama *et al*. [86] investigated the adsorption and electrochemical properties of *Pimenta diocia leaf* extract. The inhibition property of *Pancratium foetidum pom* extracts on the corrosion of mild steel was investigated by Bendaif *et al*. [87]. The researchers studied by polarization curve, electrochemical impedance spectroscopy and weight loss methods. The experimental results showed that the efficiency of inhibition is proportional of the inhibitor concentration and can reach 93% at 308 K. J.R. Vimala *et al*. [88] studied with *Basella alba L.* extract as a corrosion inhibitor of mild steel in 1 N HCl using weight loss, electrochemical polarization, electrochemical impedance spectroscopy methods and scanning electron microscope findings. According to weight loss results *Basella alba L.* leaves extract is an excellent corrosion inhibitor. Inhibition efficiency increases with inhibitor concentration and maximum inhibition efficiency was 81.28% at the 95 ppm inhibitor concentration. Polarization studies show the inhibitor to be a mixed type inhibiting both cathodic and anodic reactions.

An investigation in hydrochloric acid medium by environment friendly green inhibitor has been published by Hamdani *et al*. [89]. Krishnan *et al*. [90] researched *Sesbania grandiflora* leaf extract on the efficient, economic and ecofriendly inhibitor properties. The authors used weight loss method, open-circuit voltage analysis, Tafel polarization, AC impedance analysis, *etc*. for the evaluation of inhibition efficiency. Infrared (IR) spectroscopy and energy dispersive X-ray spectroscopy analysis were used to characterise the passive film. In the study maximum inhibitor efficiency has been found as 98.01% at room temperature for 10.000 ppm extract solution. This value has been determined about 96.16%. Efficiency of inhibitor was shown to increase with an increase in extract concentration. This extract behaves as an anodic inhibitor.

M. Eshaghi *et al*. [91] investigated efficiency of *plantain* extract as corrosion inhibitor on the mild steel in 1 M HCl solution. To find the inhibition effect of *plantain* extract, Tafel polarization, electrochemical impedance spectroscopy and weight loss methods were applied on mild steel in 1 M HCl solution. In addition the sample surface morphology was verified by scanning electron microscopy. Experimental findings show the inhibition effect of this extract was increased with the increase in the inhibitor concentration due to its adsorption on the steel surface. The adsorption mechanism of the plantain extract on mild steel is physical adsorption and obeys Langmuir isotherm [91].

O. Joseph *et al*. [92] researched heating effect of extract in corrosion inhibition of normalized and annealed mild steels in 0.5 M HCl. A.A. Ganash [93] made experimental studies with *marjoram* leaves extract. Inhibition properties of *Musa paradisiaca* peels [94], *Moringa oleifera* leaves and *Carica papaya* peels [94], *Spandias mombin* L. [95], *Alpinia galanga* [96] have been investigated. *Acalypha torta* leaf extract as green corrosion inhibitor for mild steel in hydrochloric acid solution has been investigated by Krishnegowda *et al*. [97]. Loto *et al*. [98] determined the inhibition properties of eco-friendly green corrosion inhibitor formild steel in hydrochloric acid. Nnanna *et al*. [99] researched the inhibition effect of *Pentaclethra macrophylla bentham* extract. In the study, weight loss, electrochemical techniques (open circuit potential, linear sweep voltammetry and potentiodynamic polarization were used to determine the effectiveness of *Pentaclethra macrophylla bentham* (PMB) extracts as corrosion inhibitor for mild steel in 1.0 M HCl solution at 30–45°C. It was shown that these extracts retarded the dissolution of mild steel in 1.0 M HCl solution. The inhibition efficiency increased with increase in extract concentration. According to potentiodynamic results PMB extracts acts as mixed type inhibitor. The adsorption of PMB extracts on mild steel surface followed Langumir and Temkin adsorption isotherm models. The mechanism of physisorption of the extracts onto the steel surface is proposed from the trend of inhibition efficiency with temperature which is corroborated by the values of activation parameters obtained from the experimental data. The weight loss in grams was taken as the difference in weight of the mild steel coupons before and after immersion in different test solutions. Tests were performed for the blanch solution (1 M HCl), *Pentaclethra macrophylla bentham* root extracts concentration of 0.1–0.5 g·dm^{-3} at different temperatures. In the study, corrosion rates were calculated using the classic following equation

$$\rho = \frac{K\Delta W}{DAt}$$

where ρ is corrosion rate, ΔW is the weight loss (mg), D is metal density (g·cm^{-3}), A is the area of coupon as cm^2, t shows the exposure time as hour and K represents constant. From this equation inhibition efficiency (IE%) can be found from the following equation

$$IE(\%) = \frac{i_{\text{blank}} - i_{\text{inh}}}{i_{\text{blank}}} \cdot 100$$

where i_{blank} and i_{inh} are the corrosion rates in the absence and presence of the inhibitor. The following graph [Figure 1] shows the corrosion rate of mild steel in 1.0 M HCl absence and presence inhibitor at 30°C and 45°C [taken from Ref. 99]. The variation of surface coverage with extract concentration (as ln concentration) for two different temperatures in Figure 2. In this study obtained potantiodynamic polarization curves for blank and different extract concentrations is given in Figure 3.

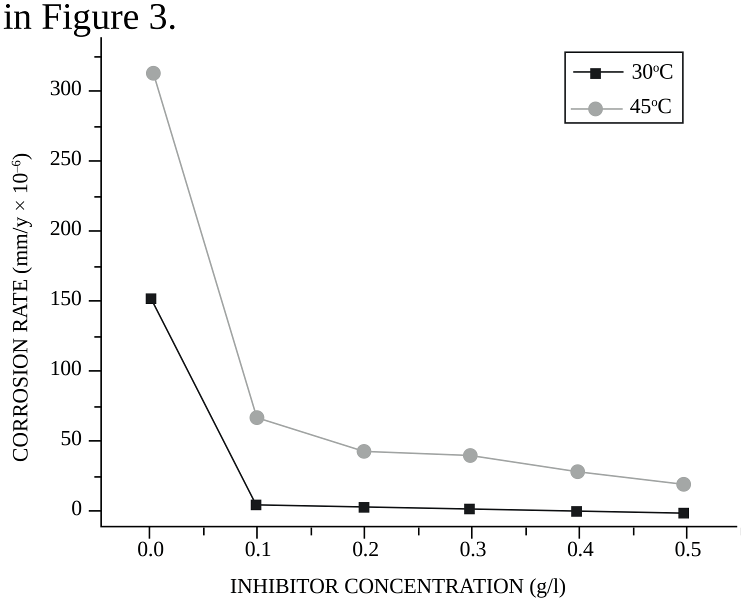

Figure 1. Corrosion rate of the mild steel in 1.0 M HCl with and without the inhibitor. [taken from Ref. 99].

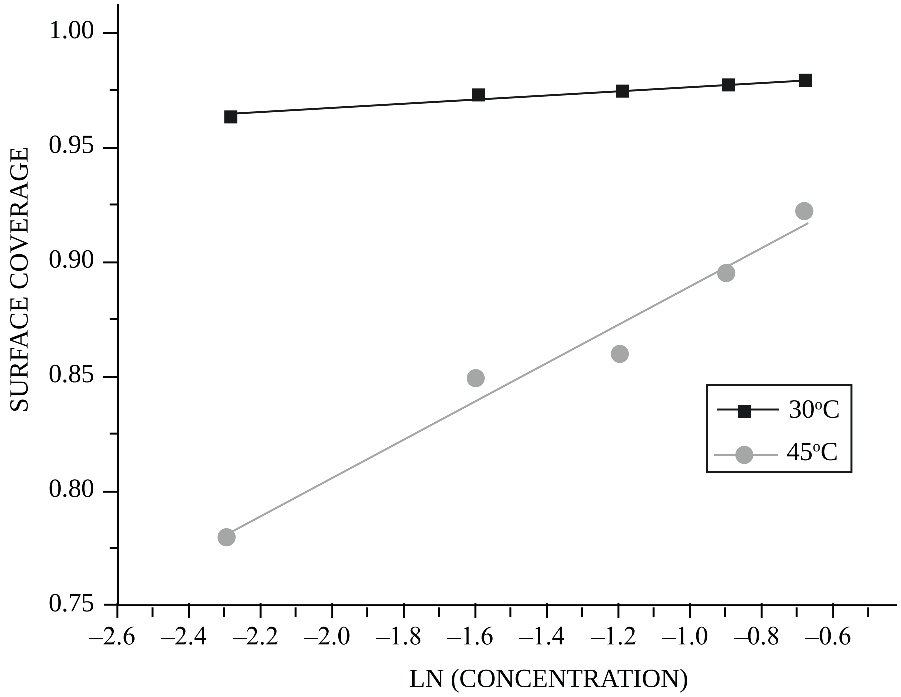

Figure 2. Temkin Isotherm Plots of the Corrosion of Mild Steel in 1.0 M HCl in the presence of *Pentaclethra macrophylla* Bentham Root Extract. [taken from Ref. 99].

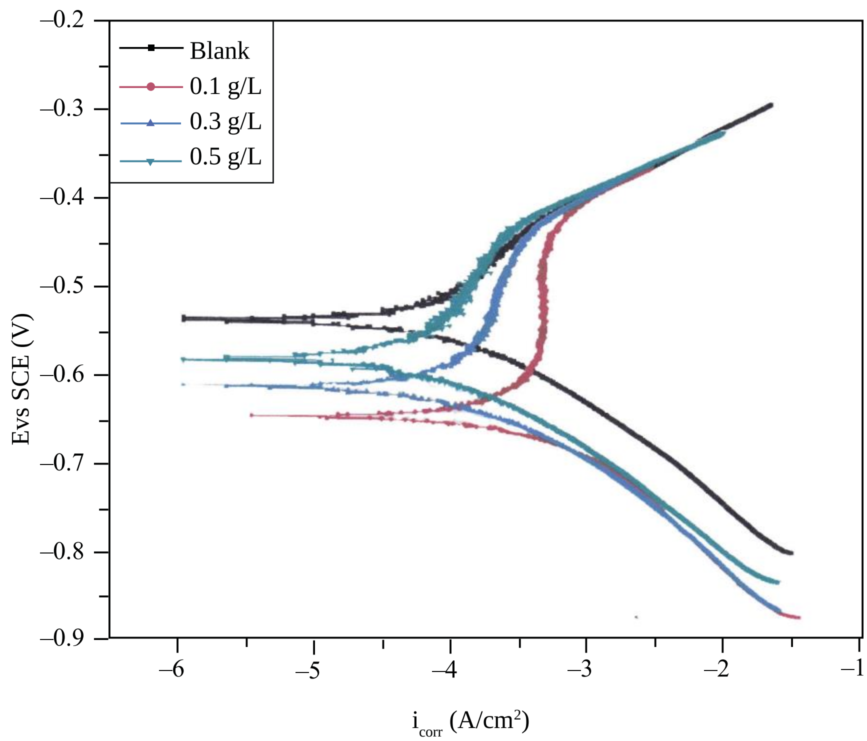

Figure 3. Potentiodynamic polarization curves of mild steel in 1.0 M HCl without and with different concentrations of *Pentaclethra macrophylla* Bentham Roots Extract. [taken from Ref. 99].

In the study, the polarization kinetic parameters obtained from current–potential curves such as corrosion potential (E_{corr}), corrosion current density (corrosion rate), anodic and cathodic Tafel slopes and inhibition efficiency *IE* (%) are given in Table 1.

Table 1. Potentiodynamic polarization kinetic parameters and inhibition efficiency for mild steel in 1.0 M HCl without and with different concentrations of *Pentaclethra macrophylla Bentham* root Extract [taken from Ref. 99].

System	E_{corr} (mV)	I_{corr} (mA/cm^2)	β_a	β_c	*IE* (%)
Blank	–607.8	841	5838.9	356.2	–
0.1 g/L	–638.1	117.5	497.7	140	86
0.3 g/L	–602.5	79.4	290.1	105.6	90.6
0.5 g/L	–574	36.7	172	93	95.6

As can be seen from this table inhibitor significantly inhibited the corrosion of mild steel in 1 M HCl solution with the optimum value of 95.6% obtained for the highest concentration of extract.

A. Singh *et al*. [100] studied *Kalmegh* (*Andrographis panicula*) leaves extract. Ajeigbe *et al*. [101] used *Alpinia galanga* to find the inhibition efficiencies on the mild steel corrosion in HCl. Baran *et al*. [102] made electrochemical and phytochemical evaluation using *Gentiana olivieri* extracts. K. Abiola [103] studied the fruit juice of *Citrus paradisi*. M. Omotioma and D. Onukwali [104] showed the inhibitor property of Pawpaw leaves extract. Samuel *et al*. [105] investigated the inhibitory action of *Brachystegia eurycoma* (Achi) seed extracts on the corrosion of mild steel in 2 M HCl solution. The researchers used weight loss method to show the inhibition effect of extracts. C. Chaunan and G. Gunasekaran [106] researched the inhibition effect of *Zenthoxylum alatum* plant extract on the corrosion of mild steel in 5% and 15% aqueous hydrochloric acid solution. The researchers studied by weight loss and electrochemical impedance spectroscopy (EIS) methods. It has been found that increased inhibition efficiencies depending on plant extract concentration till 2400 ppm. To determine the effect of temperature on the mild steel corrosion in both 5% and 15% HCl with addition of *Zenthoxylum alatum* extract was studied in the temperature range 50–80°C. A. Boujakhrout *et al*. [107] investigated *Kimbiolongo* extract as corrosion inhibitor for mild steel in 1.0 M HCl.

The corrosion inhibition property of *Plectranthus amboinicus* leaves extract for mild steel in HCl has been studying using EIS and potentiodynamic techniques by Anupama *et al*. [108]. Potentiodynamic polarization studies revealed the mixed type inhibitor behaviour of the extracts. It was found adsorption obeys Langmuir isotherm. Ameer and Amany [109] investigated the inhibition effects of *Hibiscus sabdariffa* plant extracts. R. Ragul *et al*. [110] studied with *Mitracarpus hirtus* extract to show the protection effects against corrosion of mild steel in 1 M HCl. Annatto extract was used to indicate its inhibition efficiency by Ituer and Umoren [111].

The inhibition efficiencies of *Tamarindus indica* [112], *Lagerstroemia speciosa* [113], *Artemisia pallens* [114], *Matricaria aurea* [115], *Passiflora foetida* [116] have been published [112–116]. Akalezi *et al*. [117] used *Gongronema latifollium* extract as corrosion inhibitor. They studied with weight loss and electrochemical techniques. An important decrease in the corrosion rate of mild steel was observed in the presence of the investigated additive and inhibition efficiency was found to depend on the concentration of *Gongronema latifollium* extract. According to experimental findings *Gongronema latifollium* extract acts an efficient corrosion inhibitor and its inhibition efficiency increases with the extract concentration. It can be seen the variation of inhibition efficiency (%) with inhibitor concentration can be seen in Table 2. Polarization parameters obtained is given in Table 3. Table 4 shows the impedance parameters for mild steel in 1 M HCl at 303 K without and with extract.

Table 2. Corrosion rate of mild in 1 M HCl solution without and with different concentrations of GL extract for 24 h at 303 K [taken from Ref. 117].

Inhibitor mg/L	Average weight-loss Δg	Corrosion rate $mg/cm^2 \cdot h$	Inhibition efficiency %
Blank	0.1285	0.280	
50	0.0339	0.074	73.62
200	0.0194	0.042	84.90
400	0.0149	0.033	88.40
600	0.0147	0.032	88.56
800	0.0138	0.030	89.46
1000	0.0120	0.026	90.66

Table 3. Polarization parameters for mild steel corrosion in 1 M HCl solution without and with GL extract at 303 K [taken from Ref. 117].

System	β_c (mV)	β_a (mV)	E_{corr} (mV)	I_{corr} ($mA \cdot cm^{-2}$)	IE_p%
1.0 M HCl	110.574	49.423	–475.702	204.783	
50 mg/L	111.414	40.126	–480.831	113.839	44.40
200 mg/L	103.252	38.902	–480.519	40.502	80.22
400 mg/L	141.955	91.092	–479.918	38.666	81.12
1000 mg/L	133.858	72.261	–472.777	25.837	87.38

Table 4. Impedance parameters for mild steel corrosion in 1 M HCl solution at 303 K without and with GL extract. [taken from Ref. 117]

System	R_s (Ω·cm²)	R_{et} (Ω·cm²)	*n*	*C* (μF·cm⁻²)	IE_E%
1.0 M HCl	1.285	49.13	0.7143	72.72	
50 mg/L	1.771	87.53	0.8151	50.70	43.87
200 mg/L	1.228	262.7	0.8852	33.33	81.29
400 mg/L	5.057	357.12	0.9273	22.12	86.21
1000 mg/L	9.661	581.7	0.9381	19.11	91.58

Effect of temperature is shown in Figure 4.

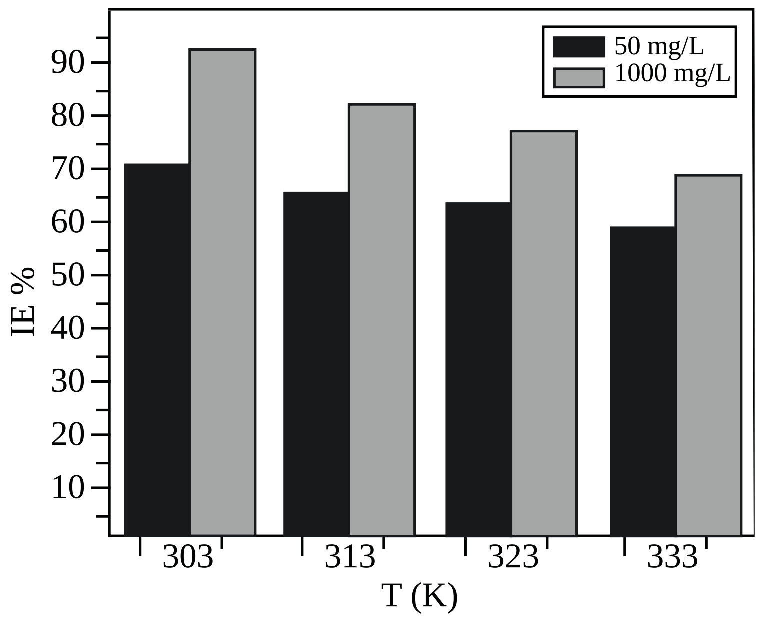

Figure 4. Effect of temperature on inhibition efficiency of GL extract in 1 M HCl solution [taken from Ref. 117].

The inhibition efficiencies from ac impedance study, show the same trend as those obtained from polarization curves measurements. The adsorption of the extract on the mild steel in 1 M HCl solution obeys Langmuir isotherm. The thermodynamic parameters obtained reveal a physical adsorption between the extract and metal surface [117].

Dehghani *et al*. [118] showed *Myrobalan* extract retarded mild steel corrosion in acidic media. They used integrated modeling and electrochemical studies for experimental findings. *Arcatium lappa* [119], *Galinsoga parviflora* [120], *Theobroma cacao* peels [121], *Stevia rebaudiana* [122], *Anthemis pseudocotula* [123], Essential Oil of *Thymus capitatus* [124], *Pogasteman quadrifolius* (Benth) [125], *Spathodea campanulata* [126], *Tecoma capensis* [127], *Chamaerops humilis L* [128], *Alaysia citdora* [129], *Carum carvi* [130], *Cryptocarya nigra* [131], *Luffa cylindrica* [132], *Dillenia pentagyna* [133] have been proven as corrosion inhibitors for mild steel in HCl media. Dharmara *et al*. [134], M.S. Al-Otaibi *et al*. [135] proved that some plant extracts acted as corrosion inhibitors for mild steel. *Ephedra alata* [136] behaves as efficiently corrosion inhibitor for mild steel in HCl medium. This result gave by Chebouat *et al*. [136]. The researchers experimental measurements including potentiodynamic polarization and impedance studies were performed. The corrosion rates and inhibition efficiencies of extract were calculated. The results show that the extract can be used as an effective inhibitor for the corrosion of mild steel in HCl media. The results reveal that acid extract of *Ephedra alata* leaves acts mixed type with cathodic predominance inhibitor. The maximum efficiency of this extract is 86.90% at a concentration of 1.65% v/v of the inhibitor. Corrosion inhibitive properties of *Epimedium grandiflorum* extract have been submitted by A. Olanrewaju *et al*. [137] in 13th Conference on Chemistry. In the study, the gasometric, weight loss and the linear polarization methods were used. The Tafel plot for the extract shows good inhibitive properties with inhibition efficiency increasing with extract concentration. In all the methods studied, the maximum inhibition efficiency was obtained in the 50% extract concentration. The extract fits best into the Freundlich adsorption isotherm indicating pyhysisorption. A. Seddik *et al*. [138] investigated the inhibition property of *Dardagan fruit* extract for mild steel in 1 M HCl. The authors made electrochemical and surface morphological studies. The protection of *Ircinia strobilina* crude extract as corrosion inhibitor has been investigated by Fernandes *et al*. [139]. The corrosion behavior was evaluated using weight loss method, potentiodynamic polarization, linear polarization resistance and electrochemical impedance spectroscopy. The results show an increase in anticorrosive efficiency as extract concentrations increase (from ±55% at 0.5 g·dm^{-3} to ±82% at 2.0 g·dm^{-3}). The protection properties of pineapple leaves (*Ananas comosus L*) extract have been determined by F. Ekanem *et al*. [140]. The researchers studied using weight loss and hydrogen evolution methods at 30–60°C. It was found that the pineapple leaves extract inhibited the acid induced corrosion of mild steel. According to experimental findings the inhibition efficiency increases with increase in the extract concentration and with rise in temperature. Adsorption of the extract was found to obey Langmuir adsorption isotherm at all the concentrations and temperatures studied. The mechanism of chemical adsorption is proposed from the trend of inhibition efficiency with temperature. P.S. Desai [141] investigated the efficiency of Hibiscus–Rosa–Sinensis (Jasud) extract as corrosion inhibitor. He researched the variation of extract efficiency with concentration and temperature. He used gravimetric (weight loss) and electrochemical techniques. Results obtained showed that inhibition efficiency (*IE*%) increased with the in concentration of extracts and with the increase in temperature. Polarization study reveals that the inhibitor behaves as a mixed inhibitor. *Parthenium hysterophous* extract has been investigated by J. Gopal *et al*. [142]. The protection efficiencies of Parsley (*Petroselium sativum*) [143], *Eugenia jambolana* [144], *Azadirachta excelsa* [145], some natural products [146], *inulin* and *aloe vera* [147], *Cnidoscolus aconitifolius* [148], *Genetum africana* [149], *Thymus zygis* subs. *gracilis* [150], *Glycyrrhiza glabra* leaves extract [151], *Tridax* *procumbers* leaves extract [152], *Datura metel* [153] have been reported as corrosion inhibitors for mild steel in HCl media [142–153].

H.A. Alkhathlan *et al*. [154] showed the inhibitive effect of *Launaea nodicaulis* [154] and aqueous extracts on the corrosion of mild steel in 1.0 M HCl solution by using weight loss, Tafel plots, linear polarization, electrochemical impedance spectroscopy, SEM and EDS techniques. It was found that extract inhibits the corrosion of mild steel and inhibition efficiencies increased with the increase of extract concentration. For determining the effect of temperature on the corrosion behavior of mild steel was studied in the range of 298–328±1 K. Adsorption behavior obeyed the Langmuir adsorption isotherm. Adsorption process was exotermic and spontaneous. The results showed that the inhibitor acts as efficient corrosion inhibitor for mild steel in 1.0 M HCl environment.

E. El-Katori *et al*. [155] studied with *Chicorium intybus* extract. They investigated synergistic corrosion inhibition activity of this extract and iodide ions for mild steel in HCl media. N. Fathima *et al*. [156] researched the inhibition efficiency of *Podranea ricasoliana* leaves extract [156]. They used 1 M HCl solution as corrosive medium. This extract has been investigated by mass loss and potentiodynamic polarization. The results indicated that the inhibition efficiency increase with increase in concentration of plant extract and corrosion rate increased with increase in temperature. Electrochemical impedance results confirmed the inhibitive nature and Tafel polarization studies. The studies indicated mixed type of inhibitor of the extract. In the study, surface analytical techniques were carried out using FT-IR and scanning electron microscope (SEM). The overall result suggested that *Podranea ricasoliana* extract could serve as an effective inhibitor for mild steel corrosion in 1 M HCl solution [156] *Staminate flower* of *Cocos nucifera* was investigated R. Rajalakshi and S. Safina [157]. The researchers applied classical weight loss measurements and electrochemical polarization methods. The acid extract could bring out a maximum of 97.3% inhibition of mild steel corrosion in 1 M HCl. Termodynamic parameters were calculated from different temperature studies. The adsorption behaviour of the extract in acid solution may be approximated both Langmuir and Temkin type isotherms. Evaluation of Tafel constant confirmed the exact acts like mixed type inhibitor. From this study was determined that *Staminate flower* extract efficiently inhibited the corrosion of mild steel [157].

Verma *et al*. [158] made on an overview on plant extracts as environmental sustainable and green corrosion inhibitors [158].

Abiola *et al*. [159] revealed the anti-corrosive properties of *Delonix regia* extract [121]. Efficiency of *Liqularia fischeri* green extract on the corrosion of mild steel has been reported by Parabakaran *et al*. [160].

Al-Moghrabi *et al*. [161] researched the anti-corrosion effects of *Crataegus oxyacantha* and *Prunus avium* plant leaved extracts on the corrosion of mild steel in hydrochloric acid solution. They made comparision of two plants.

K. Alaneme *et al*. [162], Anadebe *et al*. [163] published the corrosion inhibition performance of *Elephant grass* (*Penniseteum purperum*) [162] extract and *Pigeon pea* [163] leaf extract.

J. Lazrak *et al*. [164] determined that *Mentha viridis* oil is a green effective corrosion inhibitor for mild steel in 1 M HCl medium. S. Peumal *et al*. [165] indicated that *Bauhinia tomentosa* [165] leaves extract behaved as an effective corrosion inhibitor in 1 M HCl. S. Kathiraran *et al*. [166] made both theoretical and experimental studies for inhibitive action of *Ruellia tuberosa L* [166] on mild steel in HCl medium. The inhibition efficiencies of *Cleodendron calebrookianum walp* [167], *Bidens pilosa* [168] were researched P. Rajan *et al*. [167] and J. Olesegun *et al*. [168] respectively.

Anupama *et al*. [169] reported the inhibitive interaction of *Plactranthus amboinicus* leaf extract with mild steel in HCl. The authors studied with both electrochemical measurements and theoretical calculations. Anupama *et al*. [169] studied using EIS and potentiodynamic polarization techniques. EIS studies revealed that the dried and fresh leaf extracts of *Plectranthus amboinicus* (PADE and PAFE) showed good inhibition efficiencies up to 98% for PADE and 93% for (PAFE) in the studied system. According to the potentiodynamic polarization studies inhibition behaviour of the extract showed the property of mixed type inhibitor. The mode adsorption of the extracts was found obeying Langmuir isotherm [169].

An investigation on mitigation of corrosion of mild steel by *Origanum vulgare* in acidic medium have been done by Dhaundiyal *et al*. [170]. The result of the study showed *Origanum vulgare* (oregano) extract could be used as environment friendly corrosion inhibitor. Methods include weight loss, quantum chemical calculations and scanning electron microscopy (SEM). The outcomes revealed that the efficiency of the extract increased with increasing its concentration reaching maximum of 91.2% at 1 $g\cdot dm^{-3}$ at 30°C. Results showed that adsorption followed Langmuir adsorption isotherm. The adsorption attributed of chosen extract were hypothetically assessed by quantum chemical and morphology of metal was studied by using SEM analysis [170]. L. Nnanna *et al*. [171] investigated the inhibitive effects of *Costus afer* extracts [171]. The authors observed the high value of inhibition concentration increased in rationalized in terms of the tannins which are present in the extract. *Emilia sonchifolia* and *Vitex doniana* extract has been investigated as corrosion inhibitors of mild steel in 2.5 M HCl medium by I.I. Iloamaeke [172]. Iloamaeke *et al*. [173] showed the corrosion inhibition behavior of *Emilia sonchifolia* leaves extract as green corrosion inhibitor for mild steel in hydrochloric acid medium.

The inhibition effect of *Tephrosia purpurea* was published by T.K. Bhuvaneswari *et al*. [174]. R.A. Prabhu *et al*. [175] researched *Carmine* and Fast Green as corrosion inhibitors for mild steel in 0.5 M HCl solution. Researchers used mass loss, polarization and electrochemical impedance (EIS) methods at 300 K. The inhibition efficiency was found to increase with increasing concentration of the inhibitors. The inhibition efficiency of Fast Green (98%) is higher than that of *Carmine* (92%) and found to be maximum in $1\cdot 10^{-3}$ M solution. The inhibitors act as mixed type with predominant cathodic effect. The inhibitors were adsorbed on the mild steel surface according to the Temkin adsorption isotherm. The surface morphology of the mild steel speciments was determined using SEM images [175]. The adsorptive and inhibitive effects of *Maranthes polyandra* stem bark extract against the corrosion of mild steel in 1.0 M HCl was researched by Chahu *et al*. [176]. The researchers studied using weight loss measurement at 303, 313, 323 and 333 K. The researches determined the inhibition efficiency increased with an increase in inhibitor concentration but decreased with rise in temperature and exposure time. The adsorption of the inhibitor on the mild steel surface was spontaneous and found to follow to Langmuir adsorption isotherm model. In the study thermodynamic parameters have been calculated as such activation energies (E_a), free energy of adsorption (ΔG_{ads}). It was found that adsorption energy values in the presence of the inhibitor was between –52.70 kJ·mol^{-1} – 56.28 kJ·mol^{-1}. These values were less than that which was found in the absence of the inhibitor (69.46 kJ·mol^{-1}) and the there should values of 80 kJ·mol^{-1}, signifying physisorption. Negative values of free energy of adsorption ΔG_{ads} was found from –15.45 kJ·mol^{-1} to –16.85 kJ·mol^{-1}. This values shows spontaneity of the adsorption process. A. Bader *et al*. [177] showed the inhibitory effect of *Acacia hamulosa* methanolic extract on the corrosion of mild steel in 1 M hydrochloric acid. Morrocan flax seed oil as an eco-friendly inhibitor on mild steel 1 M HCl has been investigated by I. Najjari *et al*. [178], *Tragia plukenetii* extract has been researched by Prabakaran *et al*. [179]. A. Zaher *et al*. [180] determined anti-corrosion performance of *Ammi visnaga* L. Lam Seeds for mild steel corrosion in 1 M Hydrochloric Acid Medium. *Bitter kola* leaf extract as corrosion inhibitor was reported by Anadebe *et al*. [181] N.E. Ibisi *et al*. [182] reported the comparative study of mild steel corrosion inhibition of *Piper guineense* leaves extract and *Vernonia amygdalina* leaves extract in concentrated corrosive medium. M.T.G. de Sampaino *et al*. [183] investigated the inhibitory properties of *Mandevilla fragrans* leaves on mild steel corrosion in hydrochloric acid. M. Khan *et al*. [184] evaluated of *Matricaria aurea* extracts as effective anti-corrosive agent for mild steel in 1.0 M HCl and they made isolation of their active ingredients. Therefore, the researchers prepared several *Matricaria aurea* extracts and assessed for their anticorrosive actions for mild steel in 1.0 M HCl. The researchers measured its properties using gravimetric, linear polarization, Tafel plots, EIS and techniques like SEM and EDS. These findings showed that extract performs like a mixed-type inhibitor and conforms the Langmuir adsorption model. The outcome of results through electrochemical analysis and weight loss methods were in good consonance, which depicts remarkable inhibition properties of the *Matricaria aurea* extracts [184]. Jisha *et al*. [185] investigated the inhibitor properties of *Pogostemon quadrifolius* methanolic stem extract. Same researchers studied with *Pogostemon quadrifolius* extract for mild steel corrosion in HCl medium [186].

The inhibition performance of Millet Starch (*Panicum miliaceum*) was shown by C. Nwanonenyi *et al*. [154]. The researchers showed the protection performance of millet starch in 0.5 M HCl solution in the range of 30–60°C using potentiodynamic polarization, gravimetric, thermometric and mathematical simulation technique. Data obtained from gravimetric and thermometric results revealed that millet starch inhibited corrosion of mild steel in 0.5 M HCl solution. It was determined that increase in inhibition efficiency depends on the for all concentrations of the extract. It was shown that the mode of adsorption of extract on the mild steel surface obeyed Langmuir adsorption isotherm. The potentiodynamic polarization result indicates that this extract behaves a mixed type inhibitor with absolute control on the cathodic partial reactions. The thermodynamic parameters calculated for the inhibition process and mathematical simulation technique was used to evaluate the correlation between in inhibition efficiency of the extract and in electronic molecular structure. The results show that there is a agreement between mathematical simulation technique and experimental data.

A.O. Yüce [188] published the inhibition behaviour on mild steel of *Robinia pseudoacacia* [188] leaves extract in different concentrations in 0.5 M HCl. The author investigated the inhibition behaviour of the extract by using electrochemical techniques and surface analysis. Electrochemical spectroscopy findings showed that extract augments the charge transfer resistance and then reduces the double layer capacitance. Polarization measurements have shown that *Robinia pseudoacacia* reduced both anodic and cathodic current densities, but is more effective in cathodic regions. In the study, the corrosion performance of the extract was also tested at diverse temperatures. The inhibition efficiencies have decreased with increasing temperature. According to the experimental results the adsorption of extract on mild steel surface obeys to Langmuir adsorption isotherm with mono layer. The adsorption of the extract is chemical with the predominant physical adsorption process.

Results

As can be seen from this review, studies with plant extracts used as corrosion inhibitors are important and provide a lot of data to scientific literature.

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