Journal of Materials and Environmental Sciences
ISSN : 2028-2508

JMES, 2017 Volume 8, Issue 11, Page 4040-4051

http://www.jmaterenvironsci.com/

Drugs as environmentally benign corrosion inhibitors for ferrous and nonferrous materials in acid environment: An overview

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Received 13 Feb 2017,
Revised 26 Apr 2017,
Accepted 28 Apr 2017

Keywords

- ✓ Green chemistry;
- ✓ Corrosion inhibitors;
- ✓ Drugs;
- ✓ Mild steel;
- ✓ Acid corrosion

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Abstract

Due to the increasing ecological awareness and environmental regulations, recent advancements in the field of corrosion science and technology is directed towards "green chemistry". One of the major factors that restrict the utilization of synthetic corrosion inhibitors is their toxic nature. The preparation of organic corrosion inhibitors is associated with the huge discharge of environmentally malignant chemicals into the surrounding environment. Commercially drugs present ideal candidature to replace these traditional toxic corrosion inhibitors. The article overviews the results of previous works describing the influence of chemical medicines on the corrosion inhibition of industrially important metals in acid solution.

1. Introduction

In recent years, there is a growing concern about the toxicity, biodegradability, and accumulation of corrosion inhibitors discharged into the environment. Major issues such as safety, environmental pollution, and economics require that the corrosion inhibitors be non-polluting, safe, and cost-effective. Environmentally toxic inhibitors are sometimes referred to as gray inhibitors, and environmentally friendly inhibitors are termed as green inhibitors. Some non-toxic "green," corrosion inhibitors have been reported for different metals [1-5]. These consist of organic compounds, amino acids, plant extracts, and rare earth metal compounds [6].

Organic compounds containing N, O, S heteroatoms and π electrons in their molecules are extensively used in the protection of metals and alloys [7, 8] and are considered as effective corrosion inhibitors [9, 10]. It is noteworthy that a vast majority of these compounds e.g. pyridines, furans, imidazoles, thiophenes, isoxazoles, etc. have considerable similarity with the substructures of many of the commonly used drugs. This feature has prompted scientists across the globe to investigate the applicability of drugs as corrosion inhibitors. Bearing non-toxic characteristics and negligible negative environmental impact, drugs (chemical medicines) have emerged as suitable candidates to replace the conventionally used toxic corrosion inhibitors [11].

Gece [11] has substantially covered the work done on drugs as corrosion inhibitors. Still there are so many recent reports and developments in the area, that there is a need for a comprehensive review to obtain an understanding of the current state of research in this area. There are a large number of research articles available describing the use of drugs as corrosion inhibitors for a variety of metal surfaces in a diverse range of corrosive media. Therefore, we have focused on the use of drugs as corrosion inhibitors for iron, aluminum, zinc and copper metals in acidic solutions. Accordingly, we herein present an overview on the use of drugs as corrosion inhibitors.

1. Drugs as corrosion inhibitors for mild steel in acidic solution

Due to corrosion, the metallic surface often requires removal of rust and scales through strong acids such as hydrochloric acid, sulphuric acid, nitric acid and phosphoric acid [12,13]. The process of acid cleaning is generally known as acid pickling [12-14]. Although hydrochloric acid is more expensive and reactive than sulphuric acid, however it is more commonly used as a pickling agent compared to sulphuric acid because waste liquor can be recovered more economically in the case of hydrochloric acid. Moreover, since hydrochloric acid is more reactive than sulphuric acid, in hydrochloric acid, the pickling is generally carried out at the lower temperature, while pickling with sulphuric acid requires boiling of the pickling solution. Apart from that, the residual chloride (ferrous or ferric) produced from hydrochloric acid pickling can be rinsed off more readily than the residual sulfates (ferrous or ferric) produced due to sulphuric acid pickling. Several drugs have been investigated as efficient corrosion inhibitors for mild steel in hydrochloric acid solution.

Quartarone et al. [15] investigated inhibition performance of gramine or donaxine (Table 1) on mild steel corrosion in 1 M hydrochloric acid solution using weight loss and electrochemical techniques in the temperature range from 25 °C to 55 °C. Gramine exhibited maximum inhibition efficiency of 98% at 7.5 mM concentration. Adsorption of the drug on metallic surface obeyed the Langmuir isotherm. Polarization study revealed that gramine acted as mixed type inhibitor. Kumar and coworkers [16] studied the inhibition performance of an eco-friendly racemic mixture of amisulpride using electrochemical techniques. Results showed that inhibition performance of the drug increases with increasing concentration. The qualitative structure-activity relationship (QSAR) approach was also applied to correlate the results of quantum chemical calculations with results obtained experimentally. Polarization results showed that amisulpride acted as a mixed type inhibitor with cathodic predominance. Adsorption of the amisulpride on metallic surface obeyed the Langmuir adsorption isotherm. Amisulpride exhibited maximum inhibition efficiency of 91.3% at 600 ppm concentration. The inhibition effect of three antibacterial drugs namely, penicillin G, ampicillin and amoxicillin on carbon steel corrosion using electrochemical techniques was studied by Golestani and coworkers [17]. Adsorption of these drugs on the metallic surface followed the Langmuir isotherm. Polarization measurements suggested that the studied drugs act as mixed type inhibitors. Karthik and Sundaravadivelu [18] investigated the inhibition performance of atenolol drug using weight loss and electrochemical experiments. The drug showed a maximum inhibition efficiency of 93.8% at 300 ppm concentration. Adsorption of the drug on mild steel surface obeyed the Langmuir isotherm. Tafel polarization study suggested that atenolol acts as mixed type inhibitor. The inhibition performance of atenolol was also studied by Fourier-transform infrared (FT-IR) spectroscopy and scanning electron microscopy (SEM) methods. The experimental results were supported by quantum chemical calculations. Aldana-Gonzalezand coworkers [19] studied the inhibition property of cephalothin on API 5L X52 steel corrosion in 1M hydrochloric acid solution by electrochemical impedance spectroscopy and SEM analysis. The studied drug exhibited a maximum efficiency of 92% at 600 ppm concentration. Adsorption of the drug on the metallic surface followed Langmuir isotherm. The inhibition effect of Telmisartan on mild steel corrosion was investigated by Verma et al. [20] in 1M hydrochloric acid solution using several techniques such as weight loss, electrochemical measurements and surface analysis. The Telmisartan acted as a mixed type inhibitor and exhibited a maximum efficiency of 97.39% at 125 mgL^{-1} concentration. Adsorption of Telmisartan on metallic surface obeyed the Temkin isotherm. The adsorption of Telmisartan on the metallic surface was supported by SEM, EDX and AFM analyses.

Obot and coworkers [21] investigated the inhibition effect of Metronidazoleas an environmental friendly inhibitor for mild steel corrosion in 0.5M hydrochloric acid solution using gravimetric and potentiodynamic polarization techniques. The donor-acceptor interaction between the metal and the inhibitor was also investigated using quantum chemical calculations and molecular dynamics simulations. Adsorption of metronidazole on mild steel surface followed the Temkin isotherm. The metronidazole acted as anodic type inhibitor and showed a maximum efficiency of 80.01% at ten µM concentration. Mohammed et al. [22] studied the inhibition characteristics of an antibacterial drug belonging to cephalosporin's group. Adsorption of the studied drug followed the Langmuir isotherm. It exhibited a maximum efficiency of 97% at 6×10^{-5} M concentration at 303 K temperature. Reza and coworkers [23] studied the inhibition effect of Tinidazole on mild steel corrosion in 1M hydrochloric acid solution using weight loss and electrochemical techniques. Tinidazole showed a maximum efficiency of 90% at 400 ppm concentration. Adsorption of the drug on metallic surface

obeyed the Langmuir isotherm and showed a mixed type inhibition behavior. The inhibition effect of cimetidine on mild steel corrosion in 1M hydrochloric acid using weight loss and electrochemical methods has been investigated by Singh et al. [24]. The cimetidine showed a maximum inhibition efficiency of 95.6% at 600 ppm concentration. Adsorption of the drug on metallic surface obeyed the Langmuir isotherm. Polarization study revealed that the drug acted as a mixed type inhibitor. The inhibition effect of expired Phenytoin sodium drug on carbon steel corrosion in 1M hydrochloric acid was studied by Al-Shafeyand coworkers [25] using several experimental techniques. The phenytoin sodium exhibited a maximum efficiency of 79% at 500 ppm concentration and behaved as a mixed type inhibitor. Adsorption of the phenytoin on the metallic surface followed Langmuir adsorption isotherm.

Table 1: Chemical structures, names, nature of metals and electrolytes, biological nature, techniques used and maximum inhibition efficiencies of the drugs used as corrosion inhibitors for mild steel in acid solution.

Drug name and Structure	**Nature of metal/ electrolyte**	**Biological nature of drug**	**Mode of adsorption**	**Salient features / Techniques**	**Maximum efficiency/Conc**	**Ref. (s)**
Donaxine	Mild steel/ 1M HCl	agonist of the adiponectin receptor 1 (AdipoR1)	Mixed type/ Langmuir adsorption isotherm	Inhibition efficiency increases with temperature	98% at 7.5 mM	[15]
Penicillin G (X, Y=H); ampicillin (X=H, Y=-NH2); amoxicillin (X=-OH, Y=-NH2)	Carbon/ 1M HCl	Antibacterial	Mixed type/ Langmuir adsorption isotherm	The investigated drugs were highly soluble in the test medium	98.4%, 95.5% and 93% at 10 mM for Pen, Amp and Amo, respectively	[17]
Atenolol	Mild steel/ 1M HCl	β1 receptor antagonist	Mixed type/ Langmuir adsorption isotherm	Experimental results were supported by theoretical studies	93.8% at 300 ppm	[18]
Cephalothin	API 5L X52/ 1M HCl	Broad spectrum antibiotics	Langmuir adsorption isotherm	Efficiency decreases with temperature	92% at 600 ppm	[19]
Telmisartan	Mild steel / 1M HCl	Angiotensin II receptor, Anti-hypertension	Mixed type/ Temkinadsorption isotherm	Mechanism of inhibition was explained with suitable modal	97.39% at 125 mgL^{-1}	[20]
Metronidazole	Mild steel / 0.5M HCl	antimicrobial, antigiardial, anti-trichomonas	Anodic type/ Temkin adsorption isotherm	Theoretical studies were carried for protonated form of drug	80.01% at 10 µM	[21]

Tinidazole	Mild steel / 1M HCl	Antibacterial, anticancer, antitubercular, antifungal	Mixed type/ Langmuir adsorption isotherm	Exhibited maximum efficiency at 30 °C	90% at 400 ppm	[23]
Cimetidine	Mild steel / 1M HCl	histamine H2 receptor antagonist	Mixed type/ Langmuir adsorption isotherm	Experimental results were supported by theoretical results	95.6% at 500 ppm	[24]
Phenytoin	Carbon steel/ 1M HCl	anti-seizure medication	Mixed type/ Langmuir adsorption isotherm		79% at 500 ppm	[25]
Amodiaquine	Mild steel / 1M HCl	Antimalarial, Anti-bacterial	Langmuir adsorption isotherm	LD50 value is 550 mg/Kg	44.33% at 0.006M	[27]
Sparfloxacin	Mild steel / 2.5M HCl	Fluoroquinolone antibiotic	Langmuir adsorption isotherm	gravimetric, gasometric and thermometric	97.47% at 12 × 10^{-4} M	[29]
Fluconazole	Mild steel / 2.5M HCl	Cytochrome P450 2C19 Inhibitor	Anodic type/ Langmuir adsorption isotherm	Electrochemical, AFM/ Chemically adsorbs and forms protective film	96% at 0.30 mM	[30]
Piperacillin Sodium	Mild steel / 1M HCl	β-lactam antibiotic	Mixed type/ Langmuir adsorption isotherm	Weight loss, electrochemical	93% at 7.2 × 10^{-4}M	[31]
Ciprofloxacin	Mild steel / 1M HCl	Broad-spectrum antibiotic of the fluoroquinolone class	Langmuir adsorption isotherm	weight loss technique	86% at 2.570 × 10^{-3} M	[32, 33]

Gliclazide	Mild steel / 1M HCl	hypoglycemic (anti-diabetic)	Mixed type/ Langmuir adsorption isotherm	Weight loss, electrochemical;	91% at 400 ppm	[34]
Acyclovir	Mild steel / 1M HCl	Antiviral	Mixed type/ Langmuir adsorption isotherm	Weight loss, electrochemical; LD50 is 20000 mg/kg rat	92% at 500 ppm	[35]
Cefixime	Mild steel / 1M HCl	Anti-bacterial	Mixed type/ Langmuir adsorption isotherm	Weight loss, electrochemical; LD50 is 10000 mg/kg for rat	90% at 8.8×10^{-4}M	[36]
Meclizine hydrochloride	Mild steel / 1M HCl	Antihistamine	Mixed type/ Langmuir adsorption isotherm	Weight loss, electrochemical, SEM; LD50 is 1600 mg/kg for rat	92.29% at 200 ppm	[37]
Metformin	Mild steel / 1M HCl	Hypoglycemic drug	Mixed type/ Langmuir adsorption isotherm	Weight loss, electrochemical, quantum chemical calculations	96% at 400 ppm	[38]
Cetirizine	Mild steel / 1M HCl	second-generation antihistamine	Mixed type/ Langmuir adsorption isotherm	Weight loss, electrochemical, quantum chemical calculations;	95.2% at 100 ppm	[39]
Ketosulfone	Mild steel / 1M HCl	anti-inflammatory	Mixed type/ Langmuir adsorption isotherm	Weight loss, electrochemical, SEM, QC calculations;	96.61% at 200 ppm	[41]
Fexofenadine	Mild steel / 1M HCl	Antihistamine drug	Mixed type/ Langmuir adsorption isotherm	Weight loss, electrochemical, SEM, QC calculations; FT-IR	97% at 3.0×10^{-4}M	[42]
Ceftriaxone	Mild steel / 1M HCl	Broad spectrum anti-bacterial	Mixed type/ Langmuir adsorption isotherm	Weight loss, electrochemical	90% at 400 ppm	[43]

diethylcarbamazine	Mild steel / 1M HCl	Anthelmintic drug	Cathodic type/ Langmuir adsorption isotherm	Weight loss, electrochemical, AFM	>90% at 5.0 x 10-4 M	[44]
Aminophylline	Carbon steel / 1M HCl	Phosphodiesterase inhibitor, reduces inflammation,innate immunity	Mixed type	electrochemical, UV–Vis spectrophotometry ,optical microscopy	87.3% at 0.6 mM	[46]
Ampicillin	Mildsteel / 0.1M H_2SO_4	Broad range antibacterial	Langmuir adsorption isotherm	gravimetric, gasometric, thermometric and infrared (IR), DFT methods	Effect of halide ions investigated (Synergism)	[58]
Doxycycline	Mild steel / 1M HCl	Broad range antibacterial	Mixed type/ Langmuir adsorption isotherm	gravimetric, gasometric, thermometric and infrared (IR), AFM methods	95% at $9.02x10^{-4}$ M	[59]
Streptomycin	Mild steel / 1M HCl	Broad range antibacterial	Mixed type/ Langmuir adsorption isotherm	gravimetric, gasometric, thermometric and infrared (IR), AFM methods	88.5% at 500 ppm	[60]
Ketoconazole	Mild steel / 0.1M H_2SO_4	Antifungal drug	Langmuir adsorption isotherm	gravimetric, DFT calculations AFM methods	46.40% at 1 x 10^{-4} M	[61]
Cefazolin	Mild steel / 1M HCl	Antibiotics	Mixed type/ Langmuir adsorption isotherm	gravimetric, gaso-metric, thermo-metric and infrared (IR), AFM methods	93.9% at 1 x 10^{-5} M	[62]

Fouda et al. [26] investigated the inhibition performance of three drugs namely Actonel, Fosamax, and Etidron on carbon steel corrosion in 1M hydrochloric acid solution using weight loss, electrochemical and surface (SEM, EDX) analyses. Results showed that all the studied drugs acted as mixed type inhibitors and their adsorption on the metallic surface obeyed the Langmuir isotherm. The inhibition efficacies of these drugs at the optimum concentration (21×10^{-6}M) were 91.4%, 87.3% and 85.5 for Actonel, Fosamax, and Etidron, respectively. Ebenso and coworkers [28] studied the inhibition effect of four rhodanineazo sulpha drugs on mild steel corrosion in hydrochloric acid solution using DFT based quantum chemical calculations. These drugs were 5-sulfadiazineazo-3-phenyl-2-thioxo-4-thiazolidinone, 5-sulfamethazineazo-3-phenyl-2-thioxo-4-thiazolidinone, 5-sulfadimethoxineazo-3-phenyl-2-thioxo-4-thiazolidinone, and 5-sulfamethoxazoleazo-3-phenyl-2-thioxo-4-

thiazolidinone. Several parameters were calculated and correlated with experimentally observed inhibition efficiencies of these drugs. Results of the theoretical calculations were in good agreement with the results obtained by experimental methods. The authors reported that the presence of several active centers is responsible for effective adsorption of these sulpha drugs on the metal surface. Kumar and Karthikeyan [40] studied the inhibition performance of Torsemide and Furosemide on mild steel corrosion in 1M HCl using various experimental and quantum chemical calculation methods. Adsorption of both the inhibitors on mild steel surface obeyed the Langmuir isotherm. Both the drugs acted as mixed type inhibitors. Good agreement was observed between experimental and theoretical studies. Furosemide and Torsemideexhibited maximum efficiencies of 84.73% and 88.75% at 14 $\times 10^{-4}$ M concentration. Fouda et al. [45] used three antibacterial drugs namely (3-thiazinonyl-bicyclo [4.2.0] octene-carboxylate derivatives as corrosion inhibitors for 304 type steel in 1M HCl solution using weight loss and electrochemical experiments. The adsorption of these drugs on the metallic surface followed the Langmuir isotherm and showed a mixed type inhibition behavior. The synergism by iodine ions is also reported by these authors in their study.

Obot et al. [47] further studied the inhibition effect of itraconazole drug on mild steel corrosion in 0.5M hydrochloric acid using gravimetric and quantum calculation methods. Adsorption of the itraconazole on mild steel surface obeyed the Langmuir isotherm. The studied drug exhibited a maximum inhibition efficiency of 80% at 1.0 µM concentration. The inhibition effect of cefazolin (CZ) and cefotaxime (CT) antibacterial drugs have been investigated by Nazeer and coworkers [48], on steel corrosion in sulphuric acid solution using several experimental techniques. Both the studied drugs acted as mixed type inhibitors and their adsorption on mild steel surface obeyed the Langmuir isotherm. Inhibition efficiencies of 99.6% and 90.9% were obtained at 5.9 × 10^{-4}M and 7.9 × 10^{-4} M concentrations for CZ and CT, respectively. The inhibition effect of Cefotaxime sodium was studied by Shukla and Quraishi [49] on mild steel corrosion in 1M hydrochloric acid solution. The studied drug showed a maximum inhibition efficiency of 95.8% at 300 ppm concentration. The drug behaved as a mixed type inhibitor and its adsorption followed the Langmuir isotherm. Amlodipinebesylate drug was investigated as the effective corrosion inhibitor for low carbon steel in hydrochloric acid using chemical and electrochemical methods by Fouda et al. [50]. The studied drug acted as a mixed type inhibitor and its adsorption on the metallic surface followed the Langmuir isotherm. Quantum chemical calculations were performed over the studied drug in order to describe the mechanism of inhibition. The inhibition effect of ethambutol on mild steel corrosion in 2M HCl was investigated by Kumar and Bashir [51] using weight loss, quantum chemical studies and FT-IR analyses. The drug showed a maximum inhibition efficiency of 91.30% at 1000 ppm concentration. Ebenso and Obot [52] studied the inhibition performance of secnidazole (SEC) on the corrosion of mild steel in 0.01-0.04 M H_2SO_4 using weight loss method. The results of the gravimetric analysis were supported by DFT based quantum chemical calculation method. The results of gravimetric and DFT analyses were in good agreement. The adsorption of the drug on the metallic surface followed the Langmuir isotherm showing an inhibition efficiency of 93.8% at 5 × 10^{-3} M concentration.

Hoseinpoor and Davoodi[53] studied the inhibition performance of two antithyroid drugs namely methimazole (MMI) and propyl thiouracil (PTU) on mild steel corrosion in 1M HCl using electrochemical and quantum chemical analyses. Both the studied drugs acted as mixed type inhibitors, and their adsorption followed the Langmuir isotherm. The inhibition effect of Mebendazole on mild steel corrosion in 1M hydrochloric acid was studied by Ahmad and Quraishi [54] using several experimental techniques. The mixed nature of the drug was revealed by the potentiodynamic polarization study. Adsorption of the drug on metallic surface obeyed the Langmuir isotherm. The drug exhibited a maximum inhibition efficiency of 96.2% at 2.54 × 10^{-4} M concentration. Verma and coworkers [55] investigated the inhibition property of Abacavir on mild steel corrosion in 1M hydrochloric acid solution using experimental techniques. The adsorption of the drug obeyed the Langmuir isotherm. The studied drug acted as a mixed type inhibitor. The Abacavir drug exhibited a maximum efficiency of 97.7% at 400 ppm concentration. Similar observations were obtained by Reddy et al. [56] and Shahiet al. [57] while studying the inhibition properties of Nitrofurantoin and Tenvir on mild steel corrosion in 1M hydrochloric acid solution. Both Nitrofurantoin and Tenvir exhibited maximum efficiencies of 97.6% and 96.05% at 50 ppm and 400 ppm concentrations, respectively.

2. Drugs as corrosion inhibitors for aluminum in acidic solution

Due to its corrosion resistance behavior, aluminum is widely used as vessels for several industrial processes such as chemical reactions, pipes, machinery and chemical battery [63]. The corrosion resistance behavior of aluminum is attributed to the formation of the protective surface oxide layer. However, aluminum and its alloys readily undergo corrosion by the aggressive acid attack. The use of organic inhibitors is the first line of defense against corrosion. The organic inhibitors form a protective surface film that isolates and protects the metal surface from corrosion [7,8]. The adsorption of these inhibitors depends upon the nature of inhibitors and the electrolytic media. It is recalled that the use of organic corrosion inhibitors is limited due to increasing environmental legislation throughout the world. Therefore, there is an increasing demand of green corrosion inhibitors that protect metals and alloys at low environmental risks. Drugs are the most important alternative candidates for corrosion protection of aluminum in acidic solution as they are generally of biological origin, exhibit a high inhibition performance at relatively low concentration and also are biodegradable in nature.

Previously, several drugs have been used as effective corrosion inhibitors for aluminum in acidic medium. Abdallah and coworkers [64] studied the inhibition effect of three hypertensive drugs namely, Enalapril maleate (compound I), Atenolol (compound II) and Etilefrine in hydrochloride (compound III) on aluminum and three aluminum–silicon alloys corrosion at different hydrochloric acid concentrations. Results showed that the inhibition performance of these drugs increases with concentration. Adsorption of the drugs over the aluminum surface followed the Langmuir isotherm. It was illustrated that the inhibition effect of these drugs is attributed to the formation of insoluble drugs-metal complex over the metallic surface. The inhibition efficiencies of these drugs followed the order: compound I> compound II > compound III. Adejoro et al. [65] demonstrated the inhibition characteristics of Chloroquine on aluminum corrosion in 1M hydrochloric acid solution using experimental and DFT calculations. Adsorption of the drug on aluminum surface obeyed the Freundlich isotherm at different studied temperatures. The drug exhibited a maximum efficiency of 74.99% at 10×10^{-3} M concentration. Hameed et al. [66] studied the expired voltaren drug as an inhibitor for aluminum corrosion in 1M hydrochloric acid using weight loss and electrochemical methods. Polarization study revealed that the drug acted as a mixed type inhibitor. Adsorption of the drug over metallic surface obeyed the Langmuir isotherm. The voltaren drug exhibited a maximum efficiency of 91.70% at 125 ppm concentration. Obot and OBI-Egbedi [67] investigated the inhibition effect of Nizoral (NZR) on AA 1060 corrosion in 2M hydrochloric using the mylius thermometric technique. Results showed that the adsorption of the drug to the aluminum surface obeyed the Freundlich isotherm. The drug exhibited a maximum efficiency of 65.85% at 10×10^{-5} M concentration. The values of Gibb's free energy of adsorption showed that the drug has a spontaneous tendency of adsorption over the metallic surface. The inhibition effect of four antibacterial drugs namely, ampicillin (Amp), cloxacillin (Clox), flucloxacillin(Fluclox) and amoxycillin (Amox) on aluminum corrosion using hydrogen evolution, weight loss, and potentiostatic polarization techniques in 2M hydrochloric acid was investigated by Abdallah [68]. The adsorption of these drugs on aluminum surface obeyed the Langmuir isotherm. The inhibition characteristics of these drugs are attributed to the blocking of the active sites present over the metallic surface via formation of drugs-metal complex. The inhibition efficiencies of these drugs obeyed the following order: compound IV > compound I> compound II > compound III. Li and coworkers [69] demonstrated the inhibition effect of o-phenanthroline on aluminum corrosion in 1M HCl using experimental and theoretical means. The drug inhibited metallic corrosion by becoming adsorbate at metal/ electrolyte interface, and its adsorption obeyed the Langmuir isotherm. The inhibition mechanism of the drug was confirmed by scanning electron microscopy. The drug exhibited a maximum efficiency of 98.2% at 2.0 mM concentration. Obot et al. [70] demonstrated the inhibition performance of two antifungal drugs namely, Clotrimazole (CTM) and Fluconazole (FLC) on aluminum corrosion in 0.1 M HCl using the gravimetric method. Adsorption of both the drugs on the metallic surface followed the Langmuir adsorption isotherm. The CTM and FLC drugs exhibited maximum efficiencies of 88% and 82%, respectively, at 1×10^{-4} M concentration. The inhibition effect of meclizine hydrochloride, an antiemetic drug on aluminum corrosion in 1 M HCl has been investigated by Bhat and Alva [71] using weight loss and electrochemical methods. Adsorption of the drug on the metallic surface followed the Langmuir isotherm. Polarization study revealed that the investigated drug acts as mixed type inhibitor. The drug exhibited a maximum efficiency of 95.40% at 200 ppm concentration.

3. Drugs as corrosion inhibitors for zinc in acidic solution

Zinc is an important metal which is being utilized for several applications such as constructional material in structural and civil engineering such as facades and roofs[72,73]. Zinc is also utilized as a sacrificial coating material for the protection of iron and steel during their production and processing [74-76]. However, similar to most of the metals, zinc is very sensitive to corrosion, particularly in aggressive acidic solution. The use of synthetic corrosion inhibitors is one of the most promising methods against corrosion. These inhibitors adsorb over metallic surface through several adsorption centers and form a protective surface film that that isolates and protect the metal from corrosion. Several drugs and their derivatives have been utilized as effective inhibitors for zinc corrosion in hydrochloric and sulphuric acid media. The inhibition effect of these chemical species is attributed to the presence of several heteroatoms in the form of polar functional groups which act as adsorption centers [77-79]. Abdallah et al. [80] demonstrated the inhibition effect of three drugs namely, paromomycin (compound I), streptomycin (compound II) and spectinomycin (compound III) on the corrosion of zinc in 1M hydrochloric acid solution using potentiodynamic polarization, electrochemical impedance (EIS) and gravimetric techniques. Polarization study revealed that the studied drugs acted as mixed type inhibitors. The adsorption of these drugs over zinc surface followed the Temkin isotherm. The inhibition efficiency at 500 ppm concentration followed the order: compound I (93.03%) > compound II (91.46%) > compound III (89.66%). Adil [81] studied the inhibition effect of guaifenesin drug on zinc metal corrosion in 2M hydrochloric acid using experimental and theoretical studies. The inhibition efficiency of the drug increases with increase in its concentration and a maximum efficiency of 81% was obtained at 300 ppm concentration. The quantum chemical analysis was performed using semi-empirical quantum chemical calculations. Hebbar and coworkers [82] studied the inhibition effect of ketosulfone for zinc in acidic solution using polarization and AC impedance spectroscopic techniques. The results showed that the adsorption of the drug on the metallic surface obeyed the Langmuir isotherm. Polarization study revealed that the ketosulfone is a mixed type inhibitor. The drug exhibited a maximum efficiency of 52.50% at 20 ppm concentration. The cefuroxime axetil drug as a green corrosion inhibitor for zinc corrosion in 1M sulphuric acid solution using weight loss and electrochemical methods was evaluated by Sani, and Ameh [83]. Results showed that the investigated drug acted as a mixed type inhibitor and its adsorption over metallic surface obeyed the Langmuir isotherm. The drug exhibited a maximum efficiency of 69.37% at a 0.01M concentration at 303K temperature. Floctafenine was investigated as effective corrosion inhibitor for zinc corrosion in 0.1M hydrochloric acid using empirical and theoretical methods by Hebbar et al. [84]. Adsorption of the drug on metallic surface obeyed the Langmuir isotherm. Polarization study suggested that the studied drug acted as a mixed type inhibitor and exhibited a maximum efficiency of 88.9% at 25 mgL^{-1} concentration at 323K.

4. Drugs as corrosion inhibitors for copper in acidic solution

Due to their relatively noble properties, mechanical workability and high electrical and thermal conductivity, copper and its alloys are widely used in industries [85-87]. Copper and its alloys have several uses including a conductor in electrical power lines in electronic industries and communications, pipelines for industrial and domestic water utilities along with sea water, heat exchanger and conductors, etc. [88-90]. Therefore, the corrosion of copper and its inhibition has attracted great deal of attention. Several synthetic organic compounds have been investigated as efficient corrosion inhibitors for copper and its alloys in acidic solution. However, obviously, their use as corrosion inhibitors is limited due to increasing ecological legislation all around the world. Because this, several chemical medicines have been investigated as effective corrosion inhibitors for copper in acidic solution. Fouda et al. [91] studied the inhibition effect of unused Meropenem drug on copper corrosion in 1M HNO_3 using EIS, polarization, EFM and mass reduction techniques. Polarization study revealed that the studied drug acted as a mixed type inhibitor. Adsorption of the drug over metallic surface followed the Temkin isotherm. The Meropenem drug exhibited a maximum efficiency of 98.7% at 300 ppm concentration. The inhibition performance of three pharmaceutically active compounds namely, 6-Chloro-1,1-dioxo-3,4-dihydro-2H-1,2,4-benzothiadiazine-7-sulfonamide (I), 1-((s)-3-mercapto-2-methyl propanoyl) pyrrolidine-2- carboxylic acid (II) and 3-(2-methoxy phenoxy) propane 198.22 1,2-diol (III)was investigated on copper corrosion in 2 M nitric acid solution at 30 °C using weight loss, electrochemical and quantum chemical calculations. The adsorption of these drugs obeyed the Temkin isotherm and the drug exhibited a mixed type

inhibition behavior. At 11×10^{-6} M concentration, the inhibition efficiencies of these drugs followed the order: I (82.6%) > II (79.4%) > III (75.9%). The inhibition effect of two antibiotic drugs namely, streptoquin and septazole on copper corrosion in 0.1 M HCl has been demonstrated by Fouda and Gadow [93] using electrochemical techniques. The adsorption of both the drugs followed the Langmuir isotherm, and polarization study revealed that both the drugs acted as mixed type inhibitors. Some quantum chemical calculation parameters were derived in order to explain the mechanism of inhibition. The experimental and computational results were in good agreement. El-Haddad [94] illustrated the adsorption behavior of Cefotaxime drug on the copper surface in 0.1 M hydrochloric acid solution by potentiodynamic polarization, electrochemical frequency modulation (EFM), electrochemical impedance spectroscopy (EIS), scanning electron microscopy (SEM) and energy dispersive X-ray (EDX) and quantum chemical calculation methods. Results showed that the studied drug acted as a good corrosion inhibitor and its adsorption followed the Langmuir isotherm. Polarization study revealed that Cefotaxime acted as a mixed type inhibitor and exhibited a maximum efficiency of 90.2% at 12×10^{-5}M concentration. Fouda and coworkers [95] investigated the inhibition effect of septazole, an antibacterial drug on copper corrosion in 0.1M hydrochloric acid using electrochemical techniques. Results showed that septazole acts as mixed type inhibitor and its adsorption on copper surface follows the Langmuir isotherm. Quantum chemical calculations carried out using semi-empirical model provide good insight on the inhibition mechanism of the drug. The drug exhibited a maximum efficiency of 84.8% at 900 ppm concentration.

Conclusions and outlook

The present review features the collection of a few earlier works on drugs that have been investigated as effective corrosion inhibitors for metallic corrosion in acid solutions. From the present discussion, it is clear that the drugs are ideal and environmental friendly candidates to replace the traditional toxic corrosion inhibitors. Extensive literature survey reveals that several drugs and their derivatives have been effectively investigated as corrosion inhibitors for mild steel, aluminum, zinc, and copper alloys as well as for their alloys in acidic solution. The drugs exhibited relatively higher inhibition efficiency due to their complex molecular structures and the presence of several heteroatoms such as nitrogen, oxygen and sulfur atoms as well as due to the presence of non-bonding and π-electrons in their structures.

Acknowledgments-Chandrabhan Verma, gratefully acknowledges Ministry of Human Resource Development (MHRD), New Delhi (India) for support.

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