

Review

The effect of corrosion inhibitors on stainless steels and aluminium alloys: A review

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This paper summarizes the effect of inhibitors on the corrosion of stainless steels and aluminium alloys in different media. Stainless steels and aluminium alloys have a wide range of applications in construction, transport, domestic appliances, medical, and energy related fields. The exposure of stainless steels and aluminium alloys to corroding environments however, results in the degradation of the materials. Inhibitors are used to mitigate the corrosion of these alloys in various corrosive media and enhance their durability. Corrosion inhibitors can either be anodic inhibitors, cathodic inhibitors, mixed inhibitors, or volatile corrosion inhibitors. This review showed that inhibition efficiency increases with increase in inhibitor concentration irrespective of alloy tested. However, adsorption of inhibitors on the alloys' surface depends on the alloy type. Adsorption of inhibitors on the surface of stainless steels obeyed Langmuir adsorption isotherms, while those of aluminium alloys obeyed Langmuir, Temkin, Flory-Huggins and Freundlich isotherms. This study is important for different industrial fields where stainless steels and aluminium alloys are utilized.

Key words: Aluminium, corrosion, corrosive media, inhibitor, stainless steels.

INTRODUCTION

Corrosion is the deterioration of a material by a chemical attack or reaction under the influence of the surrounding environment. Corrosion is a continuous process which could be difficult to control and terminate (Rani and Basu, 2011). The deterioration of metals is mostly seen in steel and iron materials for gas and transport industries where billions of dollars are spent either to inhibit or replace corroded materials (Herle et al., 2011). To mitigate the deterioration of metals in corrosion-favourable environments, corrosion inhibitors are being introduced in different media. Thus, a corrosion inhibitor is any substance that is either added to the surface of a metal or

within its surrounding to reduce the constant deterioration of that metal.

Stainless steel materials have high corrosion resistance capacity because of the presence of chromium which forms a passive film layer of chromium-rich oxide in the presence of oxygen at lower temperatures; this forms a barrier with its surrounding (Potgieter et al., 2012; Scendo and Trela, 2013; Loto et al., 2012). However, this layer could be damaged in harsh environments. Corrosion inhibitors are added to reduce the rate at which this layer is deteriorated in different media. In acidic media, heterocyclic corrosion inhibitors such as organic

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compounds containing nitrogen, sulfur, and oxygen and their derivatives, are the most effective inhibitors (Rani and Basu, 2011; Herle et al., 2011; Hosseini and Salari, 2009; Hosseini et al., 2010). The efficiency of organic compounds to act as inhibitors is due to the formation of organic film layer on a metal surface. Examples of heterocyclic compounds are N-heterocyclic compounds such as triazole, tetrazole, pyridine, pyrazole, pyrimidine, pyridazine, indole and quinolone used in investigating their inhibition efficiency in acidic media on steel species (Scendo and Trela, 2013). In neutral media, good corrosion inhibitors that are used include benzoate, nitrite, chromate and phosphate. The choice of a corrosion inhibitor depends on several factors including but not limited to cost and amount, availability and its effects on the environment (Rani and Basu, 2011).

On the other hand, aluminum (Al) and its alloys are cheap and significant materials used in various industries due to their light weight, high electrical conductivity, thermal stability as well as high resistance to corrosion in different corrosive environments. In general, the corrosion resistance of Al, steel and their various alloys in corrosive environments is due to the formation of a protective strongly adhered passive film on the metal surface. The passive film usually prevents or reduces the corrosion of the metals. This film is in general stable in solutions with pH ranges from 4.5 to 8.5 (Mak, 2014). However, the passive film is soluble in strong acidic and alkaline solutions, thus, the metal shows high corrosion rate and dissolution under these conditions. As a result of this, inhibitors are used to control corrosion of the metal and reduce acid consumption (Kadhum et al., 2014).

The corrosion inhibition study on stainless steel in acidic media with different additives and inhibitors at room temperature has been critically reviewed by Selvakumar et al. (2013). The authors also reviewed studies on the inhibition of stainless steel using different techniques such as electrochemical studies like polarization, AC impedance and surface morphology such as Scanning Electron Microscope, Atomic Force Microscope and Fourier Transform infrared Spectroscopy. This present work is to supplement the review done by Selvakumar et al. (2013) by reviewing subsequent work carried out after the review done by the authors and also, other work done on stainless steels but were not reported by the previous authors (Selvakumar et al., 2013). This present review will also add information on the work done on corrosion inhibitors on aluminium and its alloys as no review has been done in this regard.

CORROSION INHIBITION OF STAINLESS STEELS

Stainless steels have excellent corrosion resistance in oxidizing acid media; however, they are susceptible to corrosion in reducing acids such as H_2SO_4 and HCl. Varga et al. (1997) reported that the corrosion resistance

of almost all stainless steels against non-oxidizing acids can greatly increase by alloying with nobler metals. Although, the corrosion resistance of stainless steels occurs when the amount of chromium in the stainless steel is greater than 12 wt%, however, this is not adequate to resist corrosion in acids like H_2SO_4 or HCl. Thus, corrosion resistance of stainless steels in these acids can be greatly increased by the addition of different types of inhibitors in these acids or applying them on the surface of the stainless steel.

Herle et al. (2011) studied corrosion inhibition of 304 SS in 2N HCl solution using N-Furfuryl N'-Phenyl Thiourea (FPTU) as inhibitor. This study was carried out using potentiodynamic polarisation method at varied temperatures of 30, 40, 50 and 60°C. FPTU was found to be an effective inhibitor of a 304 SS in acidic media of HCl solution of different concentrations and temperatures. The results showed that corrosion potential (E_{corr}) of a 304 SS was shifted to more anodic potential in the presence of FPTU (Herle et al., 2011). FPTU was confirmed to reduce corrosion rates of 304 SS in HCl to a significant extent, which gave an inhibition efficiency value of over 93% in 2 NHCl. The high inhibition efficiency was reported to be as a result of the passive film formation mechanisms and blocking effect of the metal surface by adsorption, which reduced the effective area of corrosion attack. It was concluded that FPTU acts as anodic inhibitor and a decrease in current density (i_{corr}) was observed which implies the reduction in the rate of corrosion of 304 SS. The inhibition efficiency of FPTU is credited to the presence of N and S atoms which make it possible to form bonds with metal surfaces. Therefore the layer formation prevents further corrosion attack.

Furthermore, Selvakumar et al. (2013) reviewed the inhibition efficiency of inhibitors on different grades of stainless steel: 4210, AISI 304, AISI 304L, AISI 3164, AISI 316L, UNS316035, austenitic stainless steels and more in acid media of either HCl or H_2SO_4 with different inhibitors such as Thiourea, Allylthiourea and n-Phenylthiourea. Other media in which inhibition of stainless steels were studied as reviewed by Selvakumar et al. (2013) includes ground water, sodium sulphate, pure water, sea water, sodium chloride and sodium sulfide. The results revealed that the efficiency of these inhibitors depends on the structure, chemical properties, and adsorption of film layer formed on the metal surface. They also observed from their data that it is the passive oxide film layer that is responsible for the reduction of the rate of stainless steels corrosion in acid medium.

Another study carried out by Gopi et al. (2007) on the effect of aminotrimethylidene phosphoric acid (ATMP) with Zn^{2+} and Tween 80 used as additives on AISI 304 austenitic stainless steel in aqueous media used Luminescence, Fourier-Transform Infrared Spectroscopy, X-ray Diffraction spectroscopy and Scanning Electron Microscope (SEM) techniques for analyzing the passive film oxide layer. The authors found that aminotrimethylidene

phosphoric acid (ATMP) is a mixed inhibitor which forms a protective film layer on the metal surface by controlling anodic dissolution of a metal. Refaey et al. (2006) discussed effects of 2-Mercaptobenzimidazole (MBI) inhibitor on the pitting corrosion of 316L SS in Sodium Chloride solution at different temperatures. The electrochemical behaviour of 316L in the presence of the MBI inhibitor in NaCl solution revealed that an increase in concentration of the inhibitor lead to the inhibition of 316L pitting corrosion due to the shift of pitting potential to more potential. An increase in MBI causes an increase in pitting potential towards the noble value which means a decrease in pitting corrosion. However, at high temperature; MBI lost its inhibition efficiency (Refaey et al., 2006).

Another study by Naghizadeh et al. (2015) analyzed effects of dichromate ion inhibitor on AISI 316L stainless steel and the results showed that addition of dichromate leads to an increase of pitting corrosion due to a decrease in kinetics of metastable pit dissolution. The inhibition effect of 1-methyl-3-pyridine-2-Y1-thiourea (MPT) on a 302SS grade of austenitic stainless steel in acid media was studied (Hosseini and Salari, 2009). The results from potentiostatic polarization measurements plotted on polarization curves with 1M HCl in different concentrations of MPT revealed that the presence of MPT inhibitor prevent further attack on stainless steel type 302 at 283K compared to the same grade without MPT at the same temperature in acidic solutions. This revealed that an increase in MPT concentrations causes a decrease in anodic and current densities (i_{corr}) and corrosion potential (E_{corr}) shift towards a more positive corrosion potential due to passive film layer formation. The study also analyzed the effect of temperature on inhibition efficiency of MPT and an increase in temperature increases corrosion current densities whereas corrosion potential decreases (Hosseini and Salari, 2009). As a result, it is adsorption of inhibitor on the metal surface that causes the inhibition (Al-Nowaiser, 2010).

According to Devi and Selvarani (2014), Benzyl Triethyl ammonium Chloride (BTEAC) acts as an inhibitor for a 430 stainless steel pitting corrosion. Their experiment was conducted in 1 M HCl with mass loss as electrochemical behaviour study method. BTEAC proved to be an effective inhibitor because of the positive charge of N ions and π electrons in its molecule which is adsorbed on the metal surface (Bentiss et al., 2012). In reference to the weight loss study, they found that the rate of stainless steel deterioration decreases with an increase in BTEAC concentrations in 1 M HCl. This study was compared to 430 stainless steel type in 1M HCl with BTEAC addition at 303 and 313K. It was observed that BTEAC become less effective with increase in temperature (Idris et al., 2013).

Loto et al. (2016) have investigated electrochemical studies of inhibition effect of 2-Dimethylaminoethanol

(DMA) on the corrosion of austenitic stainless steel type 304 in dilute hydrochloric acid. A weight loss, open circuit potential measurement and potentiodynamic polarization techniques were used to carry out the experiment at different DMA concentrations. In the course of this research, the authors found that inhibition efficiency of DMA increase with increase in its concentration for all used techniques. This mainly was due to the fact that presence of more DMA on the alloy surface leads to a formation of a thin layer that prevents the escalation of corrosion process. The results of weight loss techniques and polarization tests showed the DMA inhibitor efficiency to be 79 and 80.9%, respectively at 12.5% DMA. It was also observed that DMA acted as a cathodic inhibitor and obeyed the Langmuir isotherm model.

Albrimi et al. (2016) looked into inhibition effect of heptamolybdate (HM) ions on ASI 304 stainless steel (SS) by means of the gravimetric method at different temperatures (from 293 to 313 K). The effect of temperature and inhibitor concentration was studied. The weight loss measurements showed that the rate of steel deterioration decreases as heptamolybdate ion increases. In addition, 91.2% was found to be the maximum inhibition efficiency observed in presence of 1-3 M HM at ambient temperature, thus HM ions is fully ionic inhibitor for 304 SS in 0.5 M HCl. The results further revealed that inhibitor efficiency reduces as temperature rises.

The corrosion susceptibility and resistance of 12Cr martensitic stainless steel was carried out by Loto et al. (2015) in acid medium of sulphuric acid and the acid chloride concentrations. The electrochemical studies were done by potentiodynamic polarization measurement. Potassium dichromate inhibitor was used for testing corrosion inhibition of tested samples in 1 M H_2SO_4 . A slowed corrosion process was achieved at all potassium dichromate concentrations used. However, the slowest reaction was attained when 0.5 g $K_2Cr_2O_7$ concentration was used and 12Cr martensitic stainless steels were found to be susceptible to corrosion in strong sulphuric acid test medium.

Singh and Kumar (2015) studied corrosion and corrosion protection of stainless steel in phosphate fertilizer producing industry by means of weight loss technique and potentiostat techniques. In this type of industry, a large volume of concentrated H_2SO_4 is usually used in different steps during fertilizer production. As a result, it corrodes stainless steel materials that are used in several processing units. Thus, their aim was to look for a method to reduce or prevent rate of corrosion by means of a corrosion inhibitor. Thus, organic inhibitor such as 1-(2-chlorophenyl) methanamine and 1-(2-bromophenyl) methanamine were investigated at 3330, 3430 and 3530K in the presence of 15% H_2SO_4 and 15 mM concentrations of inhibitors. Experimental results revealed that corrosion rate increased in acidic medium in absence of inhibitors and decreased when inhibitors

were introduced. This was due to presence of electron releasing functional on inhibitors which give them the capability to enhance electron charge density towards corroded metal and protected base metal. Finally, these inhibitors form a protective organic thin layer on the surface of the metal.

A study by Mhammedi and Chaini (2007), confirmed that inhibition efficiency of an inhibitor increases with increase in inhibitor concentrations; confirming work was reported by Rahuma et al. (2014) and James et al. (2011). This work studied the effect of Pyrazolo (3, 4-b) Pyridine on corrosion of stainless steel in 1 M HCl solutions using the weight loss method, the electrochemical impedance spectroscopy, and the potentiodynamic polarization methods to analyze the electrochemical behaviour of stainless steels. The results showed that Pyrazolo (3, 4-b) Pyridine prevent weight loss of stainless steel due to the absorption of inhibitor on the stainless steel surface.

Obiukwu et al. (2013), studied the corrosion inhibition of stainless steel in plant extracts (*Azadirachta indica* and *Vernonia amygdalina*) using immersion tests technique. The test was carried out in 2.5 M HCl, nitric acid (HNO₃), H₂SO₄ acid for 24 h and in the atmosphere for 42 days. The results of the investigation showed that the inhibition effect of the leave extracts (*A. indica* and *V. amygdalina*) on the stainless steel depend on the acidic media. The fluid extracted from *V. amygdalina* and *A. indica* proved to be effective inhibitors for stainless steel in both HCl and H₂SO₄. It was discovered that *A. indica* exhibited better inhibiting effect on stainless steel with an inhibitive efficiency of 85% compared to an inhibitive efficiency of 69% exhibited by *V. amygdalina*.

Comparison of the inhibiting effect of the two extracts on stainless steel under atmospheric environment showed that *A. indica* inhibited more effectively compared to *V. amygdalina* with an inhibitive efficiency of 83%. This inhibitive effect was only noted after thirty-five days. It was reported by the authors that investigation in HNO₃ was unsuccessful under every condition studied. This was due to the corrosive nature of nitric acid. Furthermore, in the atmospheric environment, stainless steel was discovered not to corrode within the limit of test.

CORROSION INHIBITION OF ALUMINIUM ALLOYS

Abdulwahab et al. (2011) studied the inhibitor efficiency of an aqueous extract of bitter leaf on aluminum alloy in 0.5 M HCl at different concentrations and temperatures using weight loss measurements method. The study showed at various temperatures and concentrations of an aqueous extract of bitter leaf, the rate of corrosion of the alloy was reduced significantly. At maximum concentrations of inhibitor at higher temperature, corrosion rate tend to increased due to a physical absorption of inhibitor molecules on the surface of the

sample (Derbe and Yilma, 2015). Also, the results confirmed the inhibitor to be of anodic type.

In another study carried out by Ayeni et al. (2012) on the effect of bitter leaf extract as a corrosion inhibitor for aluminium silicon alloy using weight loss method in 0.5 M solution of caustic soda, it was found that the bitter leaf extract reduced the rate of corrosion when it is adsorbed. The inhibition efficiency and surface coverage were methods used to explain inhibition efficiency of this plant extract. The 0.5% concentration of the inhibitor yield 87% inhibition efficiency which were caused by physical adsorption of the bitter leaf extract on the aluminium silicon alloy. With physical adsorption, corrosion site on the alloy are blocked against further attack (Karthikaiselvi and Subhashini, 2014; Khan et al., 2015) thus higher corrosion resistance.

Molina-Ocampo et al. (2015) studied corrosion inhibition behavior of *Hibiscus sabdariffa* L. for aluminium in 0.5 M H₂SO₄. Potentiodynamic polarization curves and electrochemical impedance spectroscopy measurements were techniques used in this study; the study revealed that *H. sabdariffa* is a good inhibitor for pure aluminium at various concentrations and temperatures. Its inhibition efficiency increased with inhibition concentration and decreased with temperature. *H. sabdariffa*, a mixed type of inhibitor, has inhibition characteristics due to the presence of flavonoids compounds with a lone pairs of electrons that tend to mask corrosion sites; thus corrosion rate is decreased (Patni et al., 2013).

Furthermore, Ameer et al. (2012) studied electrochemical corrosion inhibition of potassium chromate K₂CrO₄ for Al-Si Alloy in 0.5 M Phosphoric Acid using different techniques included electrochemical impedance spectroscopy (EIS) and potentiodynamic polarization measurements. The results by these methods have shown K₂CrO₄ acts as a good anodic inhibitor (Ameer et al., 2012) for the alloy A383. Inhibition efficiency increased with potassium chromate concentration. Impedance and polarization methods showed the maximum inhibition efficiency to be 94.7 and 93.9%, respectively at 0.1 M K₂CrO₄. The results also revealed that corrosion potential is shifted towards a more anodic potential with the presence of potassium chromate with respect to its increase in concentration.

Lamaka et al. (2007) discussed the inhibition effects of different types of organic compounds for 2024 aluminium alloy in a neutral chloride solution. Selected organic inhibitors are compounds that are capable of forming insoluble complexes with components of AA2024. A comparison between organic complexing agents and salt of rare earth elements inhibition effects were carried out and were studied using electrochemical impedance spectroscopy (EIS) test method. The results showed that salicylaldehyde, 8-hydroxyquinoline and quinaldic acid to be the most effective organic inhibitors. Direct current (DC) polarization and localized techniques namely scanning electron microscopy (SEM) coupled with energy

dispersive spectroscopy (EDS), X-ray photoelectron spectroscopy (XPS) and atomic force microscopy coupled with scanning Kelvin probe (SKPFM) were used to investigate the anti corrosion performance of these three organic compounds. Furthermore, the results of this study showed that salicylaldehyde, 8-hydroxyquinoline and quinaldic acid exhibit anti corrosion property due to the thin adsorptive protective layer formed on the surface of the alloy.

Zheludkevich et al. (2005) discussed further the inhibition corrosion for AA2024 aluminium alloy using Triazole and thiazole derivatives. The inhibition effect of 1, 2, 4-triazole, 3-amino-1, 2, 4-triazole, benzotriazole and 2-mercaptobenzothiazole were studied. In this study, the anti-corrosion properties of these derivative organic compounds were also evaluated using similar method used by Lamaka et al. (2016). Voltage potential distribution and the surface topography were investigated by means of SEM and atomic force microscopy (AFM) during corrosion tests. Experimental results revealed that inhibitions effects of these derivative compounds were due to the formation of thin organic layer on the AA2024 substrate surface. In addition, Benzotriazole and 2-mercaptobenzothiazole were seen to be the most effective corrosion inhibitors in comparison with the other two. Finally, all the studied inhibitors decreased the rate of both the anodic and cathodic processes.

Rodič and Milošev (2016) have carried out a study on the inhibition effects of Cerium (III) and Cerium (IV) Salts on pure aluminum and Alloys AA2024-T3 and AA7075-T6 in 0.1 M NaCl. Electrochemical potentiodynamic measurements were used to study inhibition effectiveness of cerium salts. The study was done in two steps: in absence and presence of Ce (III) chloride, Ce (III) nitrate, Ce (III) acetate and Ce (IV) sulfate. For AA7075-T6, the most corrosion protection behavior was seen when Ce(III) acetate was used compared to the other cerium salts. Moreover, the inhibition effects of cerium salts were found to follow this order: Ce (III) acetate > Ce (III) chloride > Ce (III) nitrate. All of these three cerium salts form a cerium hydroxide layer on cathodic sites of the tested pure metal and its alloys. Thus, Ce (IV) sulfate did not prevent or reduce rate of corrosion. Additionally, it was discovered that anti-corrosion property for cerium salts depend on type of substrate, type of anion and salt concentration. Finally, cerium salts exhibit greatest corrosion effectiveness on AA7075-T6, followed by pure Al, and the smallest on AA2024-T3.

Shetty and Shetty (2015) have undertaken a research to study the corrosion inhibition of the ionic- liquid 1,3-bis(2-oxo-2-phenylethyl)-1H-imidazol-3-ium bromide (OPEIB) on 6061 Al-15/SiC composite in 0.1 M H₂SO₄ medium. Electrochemical impedance spectroscopy (EIS) and potentiodynamic polarization techniques were used to carry out the experiment at a temperature range of 30-50°C. In addition, a qualitative assessment of adsorption

of the inhibitor on the composite surface was studied by means of EDS whereas morphology of the as-received sample, corroded, and inhibited surface were investigated by SEM. The results of this study confirmed that an increase in temperature with the increase in concentration led to a greater inhibition efficiency. The inhibitor was found to be under a mixed inhibitor, with predominant cathodic control. At 50°C, the results generated by potentiodynamic polarization and EIS studies revealed the highest inhibition efficiency to be 96.7 and 94% respectively and OPEIB was proven to be a low cost and most promising eco friendly corrosion inhibitor for this alloy type.

Halambek et al. (2012) have carried out an investigation on novel heterocyclic compounds: 4-(methoxymethyl)-1,6-dimethyl-2-oxo-1,2-dihydropyridine-3-carbonitrile (compound A) and 4-amino-3,5-bis(6-(methoxymethyl)-3,4-dimethyl-2-oxo-1,2-dihydropyridine-1-yl)-1,2,4-triazole-2(H) (compound B) as inhibitors of Al-3 Mg alloy corrosion in 0.5 M and 1 M hydrochloric acid. Weight loss method and potentiodynamic polarization measurements were used to study inhibition effects of both newly prepared novel heterocyclic compounds. The results of Tafel plot showed that both compound are of excellent mixed type inhibitor for Al-3 Mg alloy in acidic solutions. The inhibition efficiency of compound B was greater than that of compound A under similar experimental conditions. This behavior may be due to the molecular size and the presence of more nitrogen and oxygen atoms which have a lone pairs of electrons that formed a ring by filling them in a vacant p-orbital of aluminium atom on the surface and probably better protonation in acidic media. Thus, they acted as additional adsorption centers. Furthermore, Fourier transform infrared (FTIR) results showed the adsorption of both compounds involved physisorption and chemisorption. It was discovered that adsorption of compound A and B on the surface of Al-3Mg alloy obeyed the Langmuir adsorption. The summary of other studies done both on stainless steels and aluminium and its alloys are shown in the Table 1.

Conclusions

Effects of corrosion inhibitors on stainless steels and aluminium alloys have been reviewed using different inhibitors under various environmental conditions. Various techniques employed in analyses include weight loss, electrochemical impedance spectroscopy, potentiodynamic polarization, Luminescence, Fourier-Transform Infrared Spectroscopy, X-ray Diffraction spectroscopy, and Scanning Electron Microscope (SEM) to study the passive film oxide layer. All of these methods showed that inhibition efficiency of corrosion inhibitor increases with increase in inhibitor concentrations and decreased with increase in temperature for both stainless steel

Table 1. List of other corrosion inhibition studies of stainless steel and aluminium alloys.

Alloy	Inhibitor	Medium	Techniques	Results	References
SS	0.5M Dichromate	NaCl	Potentiostatic	The maximum current density and the pores in lacy cover over the pits mouths decreased. The critical pitting temperature increased up to 38°C	Zakeri et al., 2015
SS	Molybdate, dichromate, tetraborate and nitrate anions	Bromide solution	Polarization	The inhibitors were independent of pH between 3 and 10. There was decreased in inhibition efficiency in order of $\text{NO}_3^- > \text{MoO}_4^{2-} > \text{Cr}_2\text{O}_7^{2-} > \text{B}_4\text{O}_7^{2-}$.	Abd El Meguid and Mahmoud, 2003
SS	<i>Andrographis Paniculata</i>	Natural sea water	Mass Loss	The adsorption of the inhibitor on the surface of stainless steel was spontaneous and exothermic, process. It is consistent with the Langmuir and Temkin isotherms.	Rani and Selvaraj, 2012
SS	Natural oils: parsley, lettuce, sesame, arugula, and sweet almond oils.	0.1 M NaOH	Galvanostatic and potentiodynamic anodic polarization and electrochemical impedance spectroscopy.	Increase in the inhibitor concentration resulted in increased inhibition efficiency. This was as a result of the adsorption of major components	Abdallah et al., 2012
SS	2-cyano-3-hydroxy-4(Ar)-5-anilino thiophene derivatives.	3.5% NaCl	Weight loss, galvanostatic polarization techniques, and potentiodynamic anodic polarization	The anodic and cathodic corrosion reactions reduced after adding the inhibitors. The corrosion mechanisms were hydrogen evolution and stainless steel dissolution.	Fouda et al., 2013
SS	Sulfosalicylic acid dihydrate and SA D (sodium doclecy sulfate)	5% HCl	Electrochemical and weight loss	The SAD showed higher inhibiting efficiency than SDS under similar concentration. The corrosion rate of the stainless steel decreased when 0.015% of the inhibitors were added	Ying et al., 2014
SS	Vitamin C	0.01-5.0 M HCl	Potentiodynamic polarization and electrochemical impedance spectroscopy (EIS)	The inhibitive efficiency for Vitamin C at 10.2 and 10.3 mol L ⁻¹ was good in HCl and limited to concentrations of HCl below 1.0 mol L ⁻¹	Fuchs-Godec et al., 2013
SS	1,1'-Bis(1-methyl pyridinium-2-yl)-4,4'-dipyridinium dichloride diiodide and 1,1'-dimethyl-4,4'-dipyridinium diiodide	0.5 M H ₂ SO ₄	Polarization and weight loss	The inhibitors improved the passivation of the steel by the suppression of the critical current. The quantum chemical calculations gave good explanation of the adsorption of these inhibitors on the steel surface and the greater inhibition efficiency for TPy compared with that of DPy inhibitor	Obaid et al., 2013

Table 1. Contd.

SS	Allylic group (CH ₂ = CH ₂ -)	2-12 M H ₂ SO ₄	Polarization	The reaction rate was obtained at ~6 M. inhibitors' efficiency for 304 SS was between 40-100%. For 430 SS some of these compounds behave as inhibitors at certain concentrations and corrosion accelerator at others. Chloride ion showed improved inhibition efficiency with some exceptions.	Al-Megren and Al-Suhybani, 1993.
SS	Nitrite anion	Acetic acid containing bromide	cyclic potentiodynamic polarization, electrochemical impedance spectroscopy	Pitting potential decreased linearly by increase in the logarithm of bromide ion concentration and increased by increase in the nitrite ion concentration. Appropriate inhibition efficiency was achieved by adding 500 ppm-1,000 ppm of nitrite anion. EIS measurements showed that the charge-transfer resistance (R _{ct}) increased and the constant phase element of the double layer (CPE _{dl}) decreased by increasing the nitrite ion concentration. Nitrite anions act as oxidizing as seen from the cyclic potentiodynamic polarization readings. The inhibition efficiency increased with nitrite ion concentration and the pitting susceptibility depended on nitrite/bromide ion ratio.	Adeli et al., 2010
SS	Amino acid L-Glutamine	4 M HCl solutions at 37 ^o C	weight loss	The highest Inhibition Efficiency (IE %) of 97.42% was obtained in the presence of mixture of 10-1 moles L-Glutamine, 300 mmole Zinc and 1 mmole KI at 37 ^o C for 16hrs.	Shanmugasundaram et al., 2013
SS	N,N'Dimethylaminoehanol	3 M H ₂ SO ₄	Weight loss and linear polarization	The inhibitor efficiency increased with increase in the inhibitor concentration. The inhibitor act through physiochemical mechanism on the stainless steel surface and obeyed Langmuir adsorption isotherm. The inhibition efficiency calculated from the two techniques was in reasonably good agreement. Polarization studies showed that the inhibitor behaved as mixed type inhibitor in the media.	Loto et al., 2012

Table 1. Contd.

SS	Myristyltrimethylammonium bromide, Myristyltrimethylammonium chloride and trioctylmethyl ammonium bromide, trioctylmethylammonium chloride	2.0 M H ₂ SO ₄	Electrochemical polarization		The polarization data showed that both surfactants used in this study acted as mixed type inhibitors. The adsorption mechanism obeys the Flory-Huggins adsorption isotherm. The number of clustered chain surfactants (-CH ₂ groups) had shown a significant effect on the inhibition efficiency of the studied system. The inhibitory action of <i>n</i> -alkyl quaternary ammonium salts in 2.0 M H ₂ SO ₄ resulted from the electrostatic adsorption of the <i>N</i> -alkyl ammonium ions on the negatively charged surface of stainless steel.	Fuchs-Godec, 2010
AA	Leaf extract of <i>Euphorbia hirta</i>	HCl and NaOH at 30 and 60°C	gravimetric		The leaf extract was effective as inhibitors in HCl and NaOH. Corrosion reaction was suppressed in both media. Inhibition efficiency of the extract varied with concentration, exposure time and temperature. The inhibitor showed better inhibition efficiency in HCl than in NaOH. The adsorption characteristics of the inhibitor fitted into the Langmuir isotherm. The free energy of adsorption Gads showed that the adsorption was spontaneous.	Nnanna et al., 2011
AA	[3-(4-Hydroxyphenyl)-1-phenylprop-2-en-1-one as an inhibitor (1) and 3-(4-hydroxyphenyl)-1-(4-Nitrophenyl)prop-2-en-1-one	0.5 M HCl	potentiodynamic electrochemical spectroscopy(EIS), frequency modulation (EFM) and weight loss	polarization, impedance electrochemical	Weight loss results showed that inhibitor efficiency increased with increasing inhibitor concentration and decreased with increasing the temperature. Polarization studies showed that the inhibitors acted as mixed type inhibitors. The surface coverage of the inhibitors obeyed Langmuir adsorption isotherm.	Fouda et al., 2014
AA	<i>Newbouldialeavis</i> leaf extract	0.5 M H ₂ SO ₄	gravimetric		The inhibition efficiency depended on the concentration of the inhibitor and the time of exposure. The experimental data obeyed the Langmuir adsorption isotherm. The value and sign of the Gibb's free energy of adsorption indicated that inhibitor spontaneously adsorbed on the surface of the aluminium by a physical adsorption mechanism	Nnanna et al., 2011
AA	Flowers of <i>Cassia Auriculata</i>	2M HCl	weight loss, impedance	polarization study and	Inhibition efficiency increased with the increase in concentration of the inhibitor and with an increase in temperature. The inhibitive effect of the extract of flowers of <i>Cassia Auriculata</i> was linked to the presence of some phytochemical constituents in the inhibitor which is adsorbed on the surface of the aluminum	Rajendran and Karthikeyan, 2012

Table 1. Contd.

AA	Anionic polyelectrolyte pectates (PEC)	HCl	gasometric and weight loss	Similarities were seen in the results obtained from the two methods used. The inhibition efficiency increased with increasing inhibitor concentration, but decrease with increasing temperature. The inhibition action of PEC obeyed the Freundlich isotherm	Hassan and Zaafarany, 2013
AA	<i>Ocimum Gratissimum</i>	1M HCl, Distilled H ₂ O and C ₂ H ₅ OH	Gravimetric	The inhibition efficiency of the inhibitor increased with increase in the concentration of inhibitor and decreased with increase in degree of surface coverage and temperature. The inhibition efficiency was in order of distilled H ₂ O > C ₂ H ₅ OH > HCl. The apparent activation energy E _a increased as inhibitor concentration increased	Alinnor and Ejikeme, 2012
AA	Red onion skin	2M H ₂ SO ₄ at 30, 40 and 50°C	Hydrogen gas evolution and weight loss	Inhibition increased with increasing inhibitor concentration and decreasing temperature. The results showed that acetone extract of red onion is effective in improving the corrosion resistance of aluminium in sulphuric acid medium	James and Akaranta, 2014

*AA, alloys are aluminium types; SS, stainless steel types.

and aluminium alloys. Various inhibitors also level off at a given critical temperature. The data obtained from the adsorption of various inhibitors showed that adsorption properties of most inhibitors used for SS corrosion obeyed Langmuir isotherms, while those used for AA obeyed Langmuir, Temkin, Flory-Huggins and Freundlich isotherms.

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REFERENCES

- Abd El Meguid EA, Mahmoud NA (2003). Inhibition of bromide-pitting corrosion of type 904L stainless steel. *Corrosion* 59:104-111.
- Abdallah M, Zaafarany I, Khairou KS, Emad Y (2012). Natural oils as corrosion inhibitors for stainless steel in sodium hydroxide solutions. *Chem. Technol. Fuels Oils* 48:234-245.
- Abdulwahab M, Kasim A, Bello KA, Gaminana JO (2011). Corrosion inhibition of multi-component aluminium alloy in hydrochloric acid solution by aqueous extracts of bitter leaf (*Verninia amygdalina*) powder. *Adv. Mater. Res.* 367:319-325.
- Adeli M, Raeissi K, Golzar MA (2010). Corrosion inhibition of 2205 duplex stainless steel in acetic acid solution by nitrite anions. *Corros.* 66:075002-075002-8.
- Albrimi YA, Addi AA, Douch J, Hamdani M, Souto R (2016). Studies on the adsorption of heptamolybdate ions on aisi 304 stainless steel from acidic hcl solution for corrosion inhibition. *Int. J. Electrochem. Sci.* 11:385-397.
- Alinnor IJ, Ejikeme PM (2012). Corrosion inhibition of aluminium in acidic medium by different extracts of *Ocimum Gratissimum*. *American Chem. Sci. J.* 2:122-135.
- Al-Megren HA, Al-Suhybani AA (1993). Polarization resistance studies on Corrosion inhibition of 304 austenitic and 430 ferritic stainless steels in H₂SO₄ solutions. *Materialwissenschaft und Werkstofftechnik* 24:26-31.
- Al-Nowaiser F (2010). Corrosion inhibition of type 430 stainless steel in HCl solution by dipyrindinium salts. *King Abdulaziz University* 22:89-100.
- Ameer MA, Ghoneim AA, Fekry AM (2012). Electrochemical corrosion inhibition of Al-Si alloy in phosphoric acid. *Int. J. Electrochem. Sci.* 7:4418-4431.
- Ayeni FA, Madugu IA, Sukop P, Ihom AP, Alabi OO, Okara R (2012). Effect of aqueous extracts of bitter leaf powder on the corrosion inhibition of Al-Si alloy in 0.5 M caustic soda solution. *J. Miner. Mater. Charact. Eng.* 11:667-670.
- Bentiss F, Outirite M, Traisnel M, Lagrenée M, Hammouti BS, Jama C (2012). Improvement of corrosion resistance of carbon steel in hydrochloric acid medium by 3,6-bis(3-Pyridyl) Pyridazine. *Int. J. Electrochem. Sci.* 7:1699-1723.
- Derbe T, Yilma B (2015). Investigation of the anti-corrosion activities of aloe vera extract on iron metal sheets. *J. Nat. Sci. Res.* 5:18-24.
- Devi MK, Selvarani FR (2014). Benzyl triethylammonium chloride as an inhibitor for the corrosion of 430 stainless steel in HCl solutions. *Int. J. Sci. Technol. Res.* 3:276-279.
- Fouda AS, ShalabiK, Mohamed NH (2014). Corrosion inhibition of aluminum in hydrochloric acid solutions using some chalcone derivatives. *Int. J. Innov. Res. Sci. Eng. Technol.* 3:9861-9875.
- Fouda AS, Alsawy TF, Ahmed ES, Abou-elmagd BS (2013). Performance of some thiophene derivatives as corrosion inhibitors for 304 stainless steel in aqueous solutions. *Res. Chem. Intermed.* 39:2641-2661.
- Fuchs-Godec R (2010). The erosion-corrosion inhibition of AISI 431 martensitic stainless steel in 2.0 M H₂SO₄ solution.

- using *n*-alkyl quaternary ammonium salts as inhibitors. *Ind. Eng. Chem. Res.* 49:6407-6415.
- Fuchs-Godec R, Pavlović MG, Tomić MV (2013). The inhibitive effect of Vitamin-C on the corrosive performance of steel in HCl solutions. *Int. J. Electrochem. Sci.* 8:1511-1519.
- Gopi D, Manimozhi S, Govindaraju KM, Manisankar P, Rajeswari S (2007). Surface and electrochemical characterization of pitting corrosion behaviour of 304 stainless steel in ground water media. *J. Appl. Electrochem.* 37:439-449.
- Halambek J, Jukić M, Berković K, Vorkapić-Furač J (2012). Investigation of novel heterocyclic compounds as inhibitors of Al-3Mg alloy corrosion in hydrochloric acid solutions. *Int. J. Electrochem. Sci.* 7:1580-1601.
- Hassan RM, Zaafarany IA (2013). Kinetics of corrosion inhibition of aluminum in acidic media by water-soluble natural polymeric pectates as anionic polyelectrolyte inhibitors. *Materials* 6:2436-2451.
- Herle R, Shetty P, Shetty SD, Kini UA (2011). Corrosion inhibition of 304 SS in hydrochloric acid solution by N - Furfuryl N'- phenyl thiourea. *Portugaliae Electrochim. Acta* 29:69-78.
- Hosseini S, Azimi A, Salari M, Sheikhshoei I (2010). Corrosion inhibition of 302 stainless steel with schiff base compounds. *J. Iranian Chem. Soc.* 7:799-806.
- Hosseini SM, Salari M (2009). Corrosion inhibition of stainless steel 302 by 1-methyl-3-pyridine-2-Y1-thiourea in acidic media. *Indian J. Chem. Technol.* 16:480-485.
- Idris MN, Daud AR, Othman NK, Jalar A (2013). Corrosion control by benzyl triethylammonium chloride: effects of temperature and its concentration. *Int. J. Eng. Technol.* 13:47-51.
- James AO, Akaranta O (2014). Corrosion inhibition of aluminium in 2M sulphuric acid using acetone extract of red onion skin. *Int. J. Appl. Chem. Sci. Res.* 2:1-10.
- James O, Jannatu K, Ogunniran KO, Ajani O, Siyanbola TO (2011). Adsorption behaviour of pyrazolo [3,4-b]on corrosion of stainless steel in HCl solutions. *Trends Appl. Sci. Res.* 6:910-917.
- Kadhum AAH, Mohamad AB, Hammed LA, Al-Amiery AA, San NH, Musa AY (2014). Inhibition of mild steel corrosion in hydrochloric acid solution by new coumarin. *Mater.* 7:4335-4348.
- Karthikaiselvi R, Subhashini S (2014). Study of adsorption properties and inhibition of mild steel corrosion in hydrochloric acid media by water soluble composite poly (vinyl alcohol-*o*-methoxy aniline). *J. Association of Arab Uni. Basic and Appl. Sci.* 16:74-82.
- Khan G, Newaz KMS, Basirun WJ, Binti H, Ali M, Faraj FL, Khan GM (2015). Application of natural product extracts as green corrosion inhibitors for metals and alloys in acid pickling processes-a review. *Int. J. Electrochem. Sci.* 10:6120-6134.
- Lamaka S, Zheludkevich M, Yasakau K, Montemor M, Ferreira M (2007). High effective organic corrosion inhibitors for 2024 aluminium alloy. *Electrochim. Acta.* 52:7231-7247.
- Loto A, Fayomi OS, Loto RT, Popoola AP (2015). Electrochemical corrosion resistance and susceptibility of 12Cr martensitic stainless steel in H₂SO₄. *J. Chem. Pharm. Res.* 7:39-48.
- Loto R, Loto C, Popoola A (2012). Corrosion inhibition of thiourea and thiazole derivatives: A review. *J. Mater. Environ. Sci.* 3:885-894.
- Loto RT, Loto CA, Fedotova T (2012). Inhibition effect of N, N'-Dimethylaminoethanol on the corrosion of austenitic stainless steel type 304. *Proceeding of ICCEM* pp. 72-88.
- Loto RT, Loto CA, Popoola AP, Fedotova T (2016). Electrochemical studies of the inhibition effect of 2-dimethylaminoethanol on the corrosion of austenitic stainless steel type 304 in dilute hydrochloric acid. *Silicon.* 8:145-158.
- Mak A (2014). Corrosion of steel, aluminum and copper in electrical applications, General Cable. www.stabiloy.com/NR/rdonlyres/E5F38E54-48BF-43C1-9415-865B903605EE/0/CorrosioninElecApplications.pdf. Accessed 14th November, 2015.
- Mhammedi MA, Chaini A (2007). Investigation of the inhibitive effect of pyrazolo [3, 4-b] pyridine on corrosion of stainless steel in 1 M HCl solutions. *Leonardo EI J. Pract. Technol.* 11:37-46.
- Molina-Ocampo LB, Valladares-Cisneros MG, Gonzalez-Rodriguez JG (2015). Hibiscus *Sabdariffa* as corrosion inhibitor for Al in 0.5 M H₂SO₄. *Int. J. Electrochem. Sci.* 10:388-403.
- Naghizadeh M, Nakhaie D, Zakeri M, Moayed M (2015). The effect of dichromate ion on the pitting corrosion of AISI 316 stainless steel Part II: Pit initiation and transition to stability. *Corros. Sci.* 94:420-427.
- Nnanna LA, Anozie IU, Avoaja AGI, Akoma CS, Eti EP (2011). Comparative study of corrosion inhibition of aluminium alloy of type AA3003 in acidic and alkaline media by *Euphorbia Hirta* extract. *Afr. J. Pure Appl. Chem.* 5:265-271.
- Nnanna LA, Nwadiuko OC, Ekeke ND, Ukpabi CF, Udensi SC, Okeoma KB, Onwuagba BN, Mejeha IM (2011). Adsorption and inhibitive properties of leaf extract of *New bouldia Leavis* as a green inhibitor for aluminium alloy in H₂SO₄. *Am. J. Mater. Sci.* 1:143-148.
- Obaid AY, Ganash AA, Qusti AH, ElrobySAK, Hermas AA (2013). Corrosion inhibition of type 430 stainless steel in an acidic solution using a synthesized tetra-pyridinium ring-containing compound. *Arabian J. Chem.* Mar 25.
- Obiukwu OO, Opara IO, Oyinna BC (2013). Corrosion inhibition of stainless steel using plant extract *Vernoniaamygdalina* and *Azadirachtaindica*. *Pac. J. Sci.Technol.* 14:31-35.
- Patni N, Agarwal S, Shah P (2013). Greener approach towards corrosion inhibition. *Chinese J. Eng.* 2013:1-10.
- Potgieter JH, Adams FV, Maledi N, Van Der Merwe J, Olubambi PA (2012). Corrosion resistance of type 444 ferritic stainless steel in acidic chloride media. *J. Chem. Mater. Sci.* 2:37-48.
- Rahuma MN, Al-Sonosy FM, Al-Frjany AM (2014). Corrosion inhibition of 316 stainless steel in 20% (w/w) HCl solution using dithizone. *American J. Appl. Chem.* 2:1-5.
- Rajendran A, Karthikeyan C (2012). The inhibitive effect of extract of flowers of *Cassia Auriculata* in 2 M HCl on the corrosion of aluminium and mild steel. *Int. J. Plant Res.* 2:9-14.
- Rani BE, Basu BB (2011). Green inhibitors for corrosion protection of metals and alloys: An overview. *Int. J. Corros.* 2011 Sep 26; 2012.
- Rani PD, Selvaraj S (2012). Alcoholic extract of *Andrographis Paniculata* as corrosion inhibitor on stainless steel in natural sea water environment. *Int. J. Chem. Res.* 2:6-18.
- Refaey SA, Taha F, El-Malak AM (2006). Corrosion and inhibition of 316L stainless steel in neutral medium by 2-Mercaptobenzimidazole. *J. Electrochem. Sci.* 1:80-91.
- Rodić P, Milošev I (2016). Corrosion inhibition of pure aluminium and alloys AA2024-T3 and AA7075-T6 by Cerium(III) and Cerium(IV) Salts. *J. Electrochem. Soc.* 163:C85-C96.
- Scendo M, Trela J (2013). Adenine as an effective corrosion inhibitor for stainless steel in chloride solution. *Int. J. Electrochem. Sci.* 8:9201-9221.
- Selvakumar P, Karthik B, Thangavelu C (2013). Corrosion inhibition study of stainless steel in acidic medium – an overview. *Res. J. Chem. Sci.* 3:87-95.
- Shanmugasundaram P, Sumathi T, Chandramohan G, Ramesh Babu GNK (2013). Corrosion inhibition study of 2205 grade duplex stainless steel in 4M HCl by L-glutamine; weight loss, ICP-OES and SEM-EDX studies. *Int. J. Chem. Eng. Appl. Sci.* 3:10-19.
- Shetty SK, Shetty AN (2015). Ionic liquid as an effective corrosion inhibitor on 6061 Al-15 vol. pct. SiC(p) composite in 0.1 M H₂SO₄ Medium- an ecofriendly approach. *Canadian Chem. Trans.* 3:41-65.
- Singh RK, Kumar R (2015). Study of corrosion and corrosion protection of stainless steel in phosphate fertilizer industry. *American J. Eng. Sci. Technol. Res.* 3:1-8.
- Varga K, Baradlai P, Barnard WO, Myburg G, Halmos P, Potgieter JH (1997). Comparative study of surface properties of austenitic stainless steels in sulfuric and hydrochloric acid solutions. *Electrochim. Acta* 42:25-35.
- Ying YY, Jun LC, Yang SP, Fa JM (2014). Corrosion inhibition control of ferritic stainless steel in hydrochloric acid electrolytes. *J. Northeastern Uni. Nat. Sci.* 35:1556-1559.
- Zakeri M, Nakhaie D, Naghizadeh M, Moayed MH (2015). The effect of dichromate ion on the pitting corrosion of AISI 316 stainless steel, Part I: Critical pitting temperature. *Corros. Sci.* 93:234-241.
- Zheludkevich M, Yasakau K, Poznyak S, Ferreira M (2005). Triazole and thiazole derivatives as corrosion inhibitors for AA2024 aluminium alloy. *Corros. Sci.* 47:3368-3383.