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The Inhibition Effect of Heterocyclic Compounds towards the Corrosion of Metals in Different Media: over view

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Abstract - Most organic compounds contain heterocyclic atoms such as nitrogen, sulfur, oxygen and multiple bonds in the molecules. Heterocyclic compounds have paying attention a significant curiosity for their highly electron-donating and strong coordination abilities, and still receive much consideration because of their applications. One of the vital applications of heterocyclic compounds is corrosion inhibition against metals. The inhibitor forms a film onto the metal surface by either physisorption or chemisorption. The adsorption process, inhibition mechanism, and inhibition efficiency depend on the electronic and structural properties of the inhibitor, the temperature and pressure of the reaction, the nature of the metallic surface, and the flow velocity of corrosive medium. In this review the corrosion inhibition properties of heterocyclic compounds towards the metal surface in different media are focused.

Keywords: corrosion, inhibitor, heterocyclic compounds, adsorption, metal surface.

I. INTRODUCTION

Corrosion is the degradation of materials properties due to chemical or electrochemical reaction with environments [1]. This phenomenon obliges the incessant seek out for better corrosion inhibitors, due to gigantic differences in the media encountered in industry which remains a crucial point in corrosion control as inhibitors slowdown the corrosion process on metals [2]. To evade diminish the cost and damage; the inhibitors are used to protect degradation of materials. Used of inhibitors and their application, does not entail any proficiency it only depends on adding of inhibitor in appropriate proportion [1].

Large numbers of the organic inhibitors used are, contain hetero atoms such as oxygen, nitrogen, sulfur and multiple bonds in their molecules throughout which they are adsorbed on metal surface, and therefore are a good corrosion inhibitors [1]. Heterocyclic compounds have attracted a considerable interest for their highly electron-donating and strong coordination abilities, and still receive much attention because of their applications [3].

These organic inhibitors function on the plane by the asset of adsorption and influenced by the type of the electrolyte, the nature and surface morphology of the metal, as well as their chemical structure [4]. Thermodynamic model is an important tool to study the mechanism of inhibitor on the corrosion of metal, a thermodynamic model for the adsorption process has been suggested [5].

It is a natural propensity of matter to return towards their thermodynamically stable state and most metallic materials form their oxides or sulfides. Providentially, the corrosion rate is slow. Only inert atmospheres or vacuum can make availability of corrosion free environment for most of the metallic materials. Typically, metals are corrode during the presence of oxygen and water and corrosion rate increase with acidity, water velocity, metal motion, temperature, aeration and certain bacteria [3].

Addition of surfactants also adapts the boundaries by domineering, deteriorating, or avoiding reactions between a substrate and environment. The corrosion inhibitory potential of surfactants relies on the classification of surfactants, the substrate type, inhibitor concentration, inhibitor structure, acid type and its pH, salts occurrence, co-surfactant, temperature, and dipping time [3]. The inhibiting properties of many compounds are examined by the electron density at the reaction centre. In the midst of an increase in the electron density at the reaction centre, the chemisorption bonds between the inhibitor and the metal are strengthened. The interaction of ions or neutral molecules at the electrical double layer, changes its properties and structures [5].

1.1 Medium

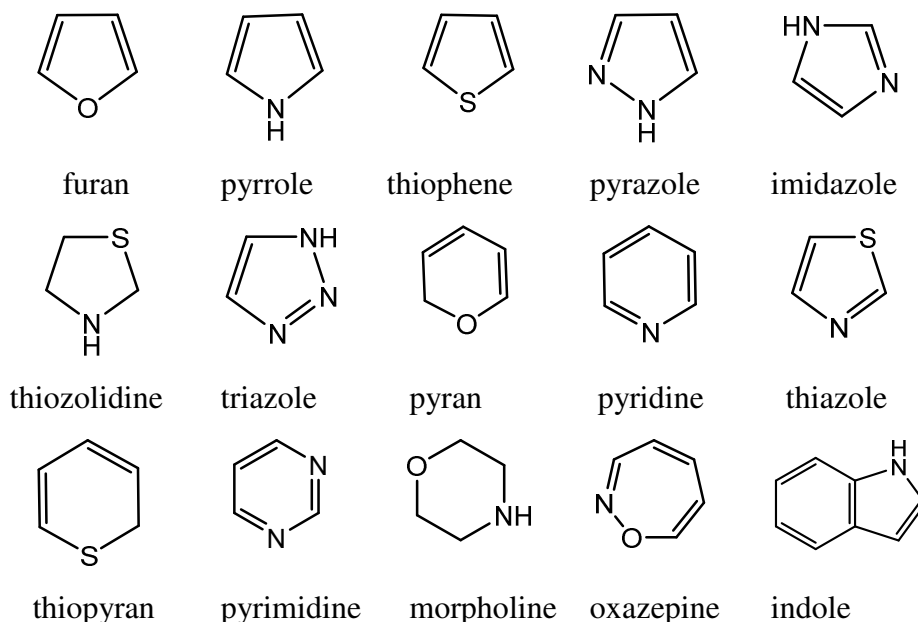
The organic inhibitors like imidazoles, quinones, quinoxaline, thiazole, indole, pyrimidine, pyridine, thiophene, thiosemicarbazide, pyrazole and its derivatives for corrosion inhibitor studied under acidic medium like hydrochloric acid, sulphuric acid, nitric acid, acetic acid and phosphoric acid in various concentrations. The corrosion study of these organic heterocyclic inhibitors as well carry out in other medium such as chloride medium of neutral sodium chloride solution, aqueous sodium chloride solution, saturated sodium chloride (brine) solution, artificial sea water in different concentrations. Some of the inhibitors can give higher efficiency against corrosion in both acid and chloride medium. Moreover the corrosion studies also done in petrol-water mixture and diesel-water mixture solution.

1.2 Metal

The organic inhibitors such as imidazoles, quinones, quinoxaline, thiazole, indole, pyrimidine, pyridine, thiophene, thiosemicarbazide, pyrazole and its derivatives can form a film on metal surfaces auspiciously in transition metals such as iron, copper, aluminium, zinc and steel (such as mild steel, carbon steel, stainless steel) thus diminishing the corrosion efficiency of metal surfaces.

1.3 Heterocyclic Compounds

Generally a cyclic hydrocarbon containing N, O and S is called heterocyclic compounds. These heterocyclic compounds show better inhibition efficiency. Some of the heterocyclic compounds are



1.4 Experimental Technique

The simplest way of measuring the corrosion rate of a metal is to expose the sample to the test medium and measure the weight loss of the material as a function of time. Even though it has less accuracy, it gives the preliminary data of corrosion rate. The other methods including potentiodynamic polarization, gravimetric method, energy dispersive X-ray spectroscopy, electrochemical impedance spectroscopy, electrochemical frequency modulation, cyclic

voltametryetc. have been utilized to analyze the corrosion inhibition of metal samples by organic inhibitors. The scanning electron microscope is used to analyze the formation of a protective film on the metal surface by the addition of inhibitors. Atomic force microscopy is also used to generate an image of the metal surface, hence concluding the adsorption of inhibitor. The computational approaches such density functional theory also good agreement with the experimental outcomes.

II. LITERATURE SURVEY

The employ of organic compounds to inhibit corrosion has alleged great significance due to their application in preventing corrosion under various corrosive environments. These compounds have shown great effectiveness for inhibiting aqueous corrosion due to film formation on the metal surface. The nitrogen, oxygen and sulphur atoms of the inhibitor molecules of organic derivatives allowed it to be adsorbed readily on the metal surface forming an insoluble stable film on the metal surface thus decreasing metal dissolution[2]. The corrosion behaviour study of metals in different media was summarized in Table 1.

- ❖ The corrosion susceptibility of aluminium probably due to its being a resonance hybride which reduce hydroquinone [6].
- ❖ The influence of the chemical structure is somewhat better expressed than of the electronic one [12].
- ❖ The free Gibbs adsorption energy values, ΔG^0_{ads} , of each compound are negative, which indicated the spontaneity of adsorption processthrough semi-physiosorption and/or semichemisorption [21].
- ❖ The multiple-linear regression analyses fitted the theoretical data well and the calculated inhibition efficiency of the compounds studied was found to be close to their experimental corrosion inhibition efficiencies especially in the protonated form [32].
- ❖ The compound acts as a mixed-type inhibitor retarding the anodic and cathodic corrosion reactions with predominant effect on the cathodic reaction [33].
- ❖ The inhibition efficiencies increase with increasing temperature and increasing concentration of the inhibitors [37].
- ❖ Charge transfer resistance increases with the inhibitor concentration that decreases the rate of corrosion [42].
- ❖ Application of the built model to calculate the theoretical %IE was obtained and is closer to the %IE experimental [47].
- ❖ The substituent charge ability may play a critical influence on inhibition performance when inhibitor molecule with the same primary structure [49].
- ❖ It was found that the API self-assembled monolayer (SAM) was formed with the concentration of 1.0 mM of API at 24 h assembling time and the maximum inhibition efficiency that could be achieved was 93.10% [70].

Table 1: The corrosion behavior study oforganic inhibitors against metals

S. No	Metal	Inhibitor	Hetero cyclic atom	Medium	Methods	Findings	Ref. No
1	carbo n steel type C38	6,12,14-trithia-1,4,8,10-tetraaza-tricyclo [9.4.0.03,9] pentadeca-3(9),10-dien-2-one	N, S	15% HCl	EIS, Weight loss method, XRD, Gasometrical method	The compound adsorbs on carbon steel, the concentration of 500 ppm offers best efficiency to carbon steel	1

						surface by formation of a dense and protective film with increasing transfer resistance and decreasing of the doublelayer capacitance,	
2	J55 Steel	5,10,15,20-tetrakis(pentafluoro phenyl)-21H,23Hporphyrin palladium(II) (PF-1), 4,4',4'',4'''-(porphyrin-5,10,15,20-tetrayl)tetrakis(benzoic acid) (PF-2),	N	sweet corrosion environment (3.5 wt % NaCl + CO ₂)	Weight loss method, EIS, Polarization measurement, SECM, AFM, Langmuir adsorption isotherm.	PF-2 shows a better inhibition efficiency of 95% from the weight loss test, 92% from impedance studies, and 93% from Tafel polarization measurements than PF-1 at 400 ppm concentration.	4
3	1060 Al alloy	p-quinone	O	acetic acid in 6.5% KNO ₃	Polarization measurement	The p-quinone increased the corrosion susceptibility of aluminum probably due to its being a resonance hybrid which readily reduces to hydroquinone.	6
4	iron	2,5-bis(N-2-hydroxyethyl-N-methylamino)-1,4-benzoquinone (AQM-1), tolylenediisocyanate (TDI), polytetrahydrofuran diol	N, O	pH 2 aqueous buffer	Electron microprobe analysis, spectrophotometry	The adsorption behavior and corrosion protection were influenced by the composition of metal particles.	7
5	mild steel	2-amino 4-phenyl thiazide (APT)	N, S	1M HCl	weight loss measurements and potentiodynamic, Auger electron	The adsorption of this compound occurs through the interaction between lone	8

					spectroscopy polarization studies	pairs of sulphur and nitrogen atoms and the mild steel surface	
6	copper	4-methylimidazole, 4-methyl-5-hydroxymethylimidazole, 1-phenyl-4-methylimidazole, 1-(p-tolyl)-4-methylimidazole	N, O	0.5 M hydrochloric acid.	AC Impedance, XPS, and SIMS Studies	1-(p-tolyl)-4-methylimidazole is the best inhibitor in this series and that it acts as mixed inhibitor.	9
7	copper	5-benzylidene-2,4-dioxotetrahydro-1,3-thiazole (BDT) 5-(4'-isopropylbenzylidene)-2,4-dioxotetrahydro-1,3-thiazole (IPBDT), 5-(3'-thenylidene)-2,4-dioxotetrahydro-1,3-thiazole (TDT), and 5-(3',4'-dimethoxybenzylidene)-2,4-dioxotetrahydro-1,3-thiazole (MBDT)	N, S, O	0.1 M Na ₂ SO ₄	EIS), in situ scanning probe microscopy (SPM), in addition to quartz crystal microbalance (QCM) measurements, AFM	The presence of the isopropyl group in the case of IPBDT produced far better protection against copper corrosion in acidic sulfate-containing media than the rest of the derivatives.	10
8	iron	2,5-bis (4,4'-methylenedianiline)-1,4-benzoquinone (AQMDA) and 2,5-bis (4,4'-oxydianiline)-1,4-benzoquinone (AQODA),	N, O	aqueous sodium chloride	EIS	Show an ability to protect iron against corrosion by NaCl electrolyte, similar to that we have reported for amine-quinone polyimides.	11
9	mild steel	2-Phenylbenzimidazole, 2-Pyridylbenzimidazole, 2-(o-Amino)phenylbenzimidazole, 2-	N	1M HCl	gravimetric and polarization techniques, Frumkin adsorption isotherm	The influence of the chemical structure is somewhat better expressed than of the electronic	12

		Benzybenzimidazole, 1-Benzybenzimidazole, 1,2-Dibenzylbenzimidazole				one.	
10	iron	2-aminobenzimidazole (AB), 2-(2-pyridyl)benzimidazole (PB), 2-aminomethylbenzimidazole (MB), 2-hydroxybenzimidazole (HB) and benzimidazole (B)	N	1M HCl	potentiodynamic polarization study, EIS, Langmuir adsorption isotherm	The efficiency of these inhibitors increases in the order AB /PB /MB /HB /B.	13
11	mild steel	Ofloxacin, amifloxacin, enofloxacin, pfloxacin, ciprofloxacin, norfloxacin	N	3.4% sodium chloride	weight loss and electrochemical polarisation, SEM techniques	The inhibition efficiency increased with increasing concentration of inhibitors. At the cocentration of 40 ppm, the inhibition efficiency for mild steel is in the following order: Ofloxacin>amifloxacin>enofloxacin>pfloxacin>ciprofloxacin>norfloxacin.	14
12	carbon steel	(2Z)-3-imino-4-methyl-2-(pyridin-3-ylhydrazono) pentanenitrile; 4-(3,4-dichlorophenyl)-2,6-dimethyl-1,2-dihydropyridine-3,5-dicarbonitrile; 1,4-diamino-5-cyano-2-(4-methoxyphenyl)-6-oxo-1,6-dihydropyridine-3-carboxylic acid;	N	2M HCl	Electrochemical polarization method, weightloss method, Langmuir adsorption isotherm.	The presence of substitution in pyridine ring plays an important role in the percentage inhibition of the compounds under investigation. The adsorption of these compounds on the carbon steel follows a Langmuir	15

		ethyl 4-amino-5-cyano-2-(dicyanomethylene)-6-phenyl-1,2-dihydropyridine-3-carboxylate.				adsorption isotherm.	
13	SAE 1018 steel	N-[2-(2-alkyl-4,5-dihydroimidazol-1-yl)ethyl]alkylamides and N-[2-(2-alkyloylaminoethyl amino)ethyl]alkylamides	N	1 N HCl	Electrochemical study, weightloss measurement	Despite the simplicity of the model, the Monte Carlo simulations reproduce qualitatively many of the experimentally observed features involved in the formation of monolayers and provide a tentative explanation for the mechanism of corrosion inhibition.	16
14	2024 aluminum alloy	1,2,4-triazole, 3-amino-1,2,4-triazole, benzotriazole and 2-mercaptobenzothiazole	N, S	neutral chloride solution	DC polarization and electrochemical impedance spectroscopy (EIS). Scanning Kelvin probe force microscopy (SKPFM) and atomic force microscopy (AFM)	The inhibitors studied act decreasing the rate of both the anodic and cathodic processes. In the latter case the dealloying of the copper-rich particles is hindered, slowing down the oxygen reduction.	17
15	Zn-Al-Cu alloy	2-methyl pyridine, 3-methyl pyridine, 4-methyl pyridine	N	0.5 N HCl	weight loss measurement, galvanostatic polarization, impedance spectra, Frumkin's	This inhibitor behaves as a mixed type and their inhibition efficiency according to the order: $2mp < 3$	18

					isotherm	mp< 4mp. The absorption of the inhibitors on the alloy surface follows frumkin isotherm	
16	carbon steel	Pyridine, 2-methyl pyridine, 4-methyl pyridine, 2,6-dimethyl pyridine.	N	acetic-buffered solution containing chlorides (as [NaCl]) and H ₂ S (until saturation)	potentiodynamic polarization, EIS, SEM	Pyridine compounds show a strong competition toward the species of HAc/acetates, chlorides, and H ₂ S, displaying their greatest effect in the sites where H ₂ S is adsorbed, diminishing the hydrogen recombination but accelerating the acetate adsorption and thus the oxidation reaction rate.	19
17	API 5L-X60 steel	substituted aminoanthraquinone	O	diesel-water mixtures	weightloss study, electrochemical study, AFM.	Oleic acid substituted aminoanthraquinone was found to be the best corrosion inhibitor. It exhibited 92% inhibition efficiency against the corrosion of API 5L-X60 steel in diesel-water mixtures.	20

18		(2-hexyl-4,5-diphenyl-1-vinyl-1Himidazole), (2,4,5-triphenyl-1-vinyl-1H-imidazole), (2-(4-methoxyphenyl)-4,5-diphenyl-1-vinyl-1H-imidazole)	N	1% NaCl solution	electrochemical study, Langmuir isotherm	The planarity of structure, the presence of donating electron groups, the hydrophobic effect of structure, the steric hindrance and the electron density of molecular structure are some crucial factors that would affect the corrosion inhibition activity of 4,5-diphenyl-1-vinylimidazole derivative compounds towards mild steel.	21
19	aluminum	2,3-diaminonaphthalene	N	1M HCl	Quantum chemical calculation, Langmuir adsorption isotherm	It was found that the adsorption of 2,3-DAN onto the Al surface followed the Langmuir adsorption isotherm and 2,3-DAN adsorbed on Al surface probably by physisorption.	22
20	316 stainless steel	[(4-Hydroxy-6-methyl-2-oxo-2H-pyran-3-yl)-phenyl-methyl]-urea (HPU1) and [(4-Hydroxy-6-methyl-2-oxo-2H-pyran-3-yl)-(4-methoxyphenyl)-methyl]-urea (HPU2)	N	Phosphoric media	Potentiodynamic and electrochemical impedance measurements, SEM	The film, act as a barrier to the transport of the metal ions from the metal to the solution at high concentration of inhibitor.	23

21	bronze	3-ethyl-6-méthyl-quinoxalin-2-one, 1-benzyl-6-méthyl-quinoxalin-2-one, 2-benzyloxy-3,6-diméthyl-quinoxaline, 1-benzyl-3-méthyl-quinoxalin-2-one,	N	3% NaCl	electrochemical studies	The corrosion resistance was greatly enhanced in the presence of inhibitor and that the effectiveness depends on some physicochemical properties of the molecule, related to its functional groups. These compounds act through the formation of a protective film on the surface of the alloy.	24
22	carbon steel	1b ((Z)-2-(2-(heptadec-8-enyl)-4,5-dihydroimidazol-1-yl)ethanamine), 2b ((Z)-2-(2-(heptadec-8-enyl)-4,5-dihydroimidazol-1-yl)ethanol) and 3b (2-(2-heptadecyl-4,5-dihydroimidazol-1-yl)ethanamine)	N	1% NaCl	Tafel plot, free Gibbs adsorption	The increase in concentrations of compound 1b, 2b and 3b in 1% NaCl solution tends to improve their corrosion inhibition activities.	25

23	Al-Cu alloy	1-methyl-4[(-X)-styryl] pyridinium iodides (X: -H, -Cl and -OH)	N	0.5MHCl	Potentiodynamic polarization, Electrochemical impedance spectroscopy, Weight loss measurements, Langmiur adsorption isotherm	The data revealed that the studied compounds have good pickling inhibitor's quality as they perform well even at relatively high temperature. The corrosion activation parameters (Ea, H*, S* and G*) were estimated and discussed. It was found that Ea values for Al-Cu alloy corrosion in the inhibited solutions were higher than that for the uninhibited solution, indicating good inhibitor characteristics with physical adsorption mechanism	26
24	API 5L-X60 steel	1-aminoanthraquinone	O	white petrol-water mixture	Weight loss, electrochemical studies. Potentiodynamic polarization studies, AFM	Oleic acid derivative of 1-aminoanthraquinone was found to be the best corrosion inhibitor. It exhibited 86% inhibition efficiency against the corrosion of API 5L-X60 steel	27

25	mild steel	4-methyl-2-propyl-1H-benzimidazole-6-carboxylic acid (MPBI) and 1,4'-Dimethyl-2'-propyl-1H,3'H-2,5'-dibenzimidazole	N	1 N HCl	Conventional weight loss, potentiodynamic polarization, linear polarization and electrochemical impedance spectroscopy.	The change in the impedance parameters, charge transfer resistance and double layer capacitance, with the change in concentration of the inhibitor is due to the adsorption of the molecule leading to the formation of a protective layer on the surface of mild steel.	28
26	C38 steel	2-[3-(2-oxo-2-phenylethylidene)-1,4-dihydroquinoxaline-2(1H)-ylidene]-1-phenylethanone (Qx1) and amino-2-aniline (Diam1)	N, O	1 M HCl	weight loss measurements, potentiodynamic polarisation and impedance spectroscopy (EIS), Langmuir adsorption model	The highest efficiency (85%) is obtained at the 10 ⁻⁴ M Qx1. Qx1 and Diam1 act as mixed inhibitors. Qx1 adsorbs on the steel surface according to Langmuir adsorption model. Effect of temperature is also studied between 308 and 353 K.	29
27	zinc	Acetyl coumarine, Bromo-acetyl coumarine, 7-chloro-4-(((4-(6,8-dibromo-2-oxo-2H-chromen-3-yl)thiazol-2-yl)amino)methyl)quinolin-2(1H)-one, 4-(((4-(6-bromo-2-oxo-2H-chromen-3-yl)thiazol-2-yl)amino)methyl)-8-methylquinolin-2(1H)-one	O, N	0.1 M HCl	weight loss, potentiodynamic polarization and impedance techniques, Langmuir adsorption isotherm	The inhibition efficiency increased with increase in inhibitor concentration upto 5×10 ⁻⁴ M, then gave almost same inhibition efficiency.	30

28	mild steel	3-methyl-2-phenyl quinoxaline(MPQ), 2,3-diphenyl quinoxaline (DPQ), 3-methyl 2(2''hydroxyphenyl)quinoxaline(MHPQ), 3-phenyl-2(2''hydroxyphenyl)quinoxaline (PHPQ), 3-methyl-2(3''-methoxy,4''-hydroxyphenyl)quinoxaline (MMHPQ)	N	1M H ₂ SO ₄	weight loss , gasometry and electrochemical techniques, Langmuir adsorption isotherm	The adsorption of all the quinoxalines on the mild steel surface from the acid solution has been found to obey Langmuir adsorption isotherm. Addition of halide ions synergistically enhanced the inhibition of the quinoxalines.	31
29	mild steel	2-mesityl-1H-imidazo[4,5-f][1,10]phenanthroline (G), 2-(6-methylpyridin-2-yl)-1H-imidazo[4,5-f][1,10]phenanthroline (J) and 2-(pyridine-2-yl)-1H-imidazo[4,5-f][1,10]phenanthroline	N	acidic media	Quantum chemical study, Mulliken atomic charges and Fukui functions,	The multiple-linear regression analyses fitted the theoretical data well and the calculated inhibition efficiency of the compounds studied was found to be close to their experimental corrosion inhibition efficiencies especially in the protonated form (R ₂ = 0.9986).	32
30	mild steel	3-phenyl-4-amino-5-mercapto-1,2,4-triazole	N	Phosphoric media	Potentiodynamic polarization studies, weight loss measurements, Langmuir adsorption isotherm	The compound acts as a mixed-type inhibitor retarding the anodic and cathodic corrosion reactions with predominant effect on the cathodic reaction.	33

31	mild steel	Imidazole, 4-Methylimidazole, 2-Hexylimidazole, 2-Hydroxyimidazol, 4-Hydroxyimidazol, 2-Methylimidazole, 4-Methyl-5-hydroxymethylimidazole, 2-Methyl-5-nitrylimidazole	N		cluster model by using quantum chemical calculations at density functional theory level	It is shown that 90% of inhibition variations of the imidazole derivatives are described by considering perpendicular interaction of the inhibitors by iron atom in the mild steel unit cell	34
32	mild steel	3-(4-((Z)-indolin-3-ylideneamino)phenylimino)indolin-2-one	N	1 M HCl	Electrochemical Impedance Spectroscopy, Scanning Electron Microscopy, Potentiodynamic Polarization Measurements, Weight Loss Measurements, Atomic Force Microscopy, Langmuir adsorption isotherm	The standard free energy of adsorption has been found close to -40 kJ mol^{-1} which indicated that the adsorption is seen more as a chemical form than as physical adsorption.	35
33	mild steel	morpholine	N, O	2N sulphuric acid, phosphoric acid	Mass loss Studies, Potentiostatic Polarization studies, Temkin's adsorption isotherm.	Morpholine shows the better inhibition in 2N phosphoric acid than 2N sulphuric acid. It is found that the Morpholine acting as mixed type inhibitor. Energy of activation (E_a) values indicates physical adsorption of the inhibitor on metal surface.	36

34	Copper	2-mercaptobenzimidazole (MBI) and 2-thiomethylbenzimidazole (TMBI)	N	1M HNO ₃	Weight-Loss Measurements, Langmuir adsorption isotherm.	The inhibition efficiencies increase with increasing temperature and increasing concentration of the inhibitors.	37
35	Mild Steel	2-aminobenzimidazole (ABI), 1,3-benzothiazole (BTH), benzotriazole (BTA), 2-methylbenzimidazole (MBI), 2-(2-pyridyl)benzimidazole (PBI), 2-(amino methyl)benzimidazole (AMBI), 5-amino-3-mercapto-1,2,4-triazole (5AMTZ), 2-hydroxybenzimidazole (HBI), benzimidazole (BI) and 5-amino-1,2,4-triazole (5ATZ)	N	Acidic medium	Weight-Loss Measurements, DFT	Protonation has an influence on the molecular properties (e.g., EHOMO and the ELUMO) of the inhibitors. Hence, in the interaction with the metal surface, the protonated species are most likely to interact with the metal surface through physisorption mechanism while the non-protonated species would preferentially interact with the metal surface through chemisorption mechanism.	38
36	C38 steel	2-phenylimidazo [1,2-a]pyridine (P1) and 2-(m-methoxyphenyl)imidazo[1,2-a]pyrimidine (P5).	N	1 M HCl	Weight loss, potentiodynamic polarization and electrochemical impedance spectroscopy, Langmuir adsorption isotherm	Kinetic parameters activation such as activation energy, pre-exponential factor, enthalpy of activation and entropy of activation were evaluated from the effect of temperature on corrosion and inhibition processes. E (%)	39

						values obtained from various methods used are in good agreement.	
37	Zinc, Copper, Brass	1H-benzimidazole, (BIM), 2-methyl-1H-benzimidazole (2-CH ₃ BIM), 5-nitro-1H-benzimidazole [5(6)-NO ₂ BIM] and 5(6)-dinitrobenzimidazole (5,6-diNO ₂ BIM)	N	0.15 M HCl, 0.5 M NaCl	potentiodynamic polarization and electrochemical impedance spectroscopy (EIS).	The efficiency of these inhibitors increases in the order BIM > 5(6)-NO ₂ -BIM > 5,6-diNO ₂ BIM > 2-CH ₃ -BIM in alkaline media (pH:13) and 2-CH ₃ -BIM > 5(6)-NO ₂ -BIM > BIM in the 0.5 M NaCl the solution.	40
38	carbon steel	2-(4-methylphenyl)-1,4-dihydroquinoxaline	N	HCl	weight loss measurements, electrochemical impedance spectroscopy (EIS), Tafel polarization techniques, density functional theory (DFT), Langmuir adsorption isotherm.	The charge transfer resistance increases and the capacitance of double layer decreases with the inhibitor concentration, confirming the adsorption process mechanism.	41
39	mild steel	2,6-bis(2,5-dimethyl-2H-imidazol-4-yl)pyridine (BDIP)	N	1 M HCl	Weight-loss measurements, potentiodynamic polarisation and impedance spectroscopy (EIS), Langmuir adsorption isotherm	Charge transfer resistance increases with the inhibitor concentration.	42

40	mild steel	3-methyl-2-phenyl quinoxaline (MPQ), 2,3-diphenyl quinoxaline (DPQ) and 3-methyl-2(3'-methoxy-4'-hydroxyphenyl)quinoxaline (MMHPQ)	N		DFT	MMHPQ has the highest inhibition efficiency because it had the highest HOMO energy and ΔN values and lowest energy gap it was most capable of offering electrons and it could have a better performance as corrosion inhibitor.	43
41	N80 steel	1-[hydrazyl(4-methoxyphenyl)methyl]-1H-imidazole, 1-[hydrazyl(phenyl)methyl]-1H-imidazole, 1-[hydrazyl(chlorophenyl)methyl]-1H-imidazole,	N	15% HCl	Weight-loss measurements, potentiodynamic polarisation and impedance spectroscopy (EIS), Langmuir adsorption isotherm	The inhibition efficiencies increase with increasing concentration of the inhibitors.	44
42	carbon steel	ethyl 2-(4-(2-ethoxy-2-oxoethyl)-2-p-tolylquinoxalin-1(4H)-yl)acetate (Q3)	N	1.0 M HCl	Weight loss measurements, Adsorption isotherm and thermodynamic consideration, Langmuir adsorption isotherm	The inhibition efficiency was found to increase with increase in Q3 but decreased with temperature, which is suggestive of physical adsorption mechanism although chemisorption may play a part.	45

43	mild steel	1, 4-Bis (3-aminopropyl)-piperazine	N, O	1M H ₂ SO ₄	Electrochemical measurements	Adsorption of inhibitor molecules is often a displacement reaction involving removal of adsorbed water molecules is often a displacement reaction involving removal of adsorbed water molecules from the metal surface.	46
44	mild steel	Thiophenemethylester, thiophenecarboxylic acid, 2-acetylthiophene, 2-chlorothiophene, 2-bromothiophene, 2-methylthiophene, 3-bromothiophene, 3-methylthiophene, 2-hydroxythiophene, Thiophene, thiophenecaboxaldehyde	S		Model validation and interpretation, Descriptors interpretation, interval partial least square (IPLS) method	The values were calculated and found to be > 0.5 and 0.8 respectively for the first and second model and for the external validation the values are found to be > 0.6 and 0.5 respectively and the r ² value was found to be > 0.9. Application of the built model to calculate the theoretical %IE was obtained and is closer to the %IE experimental.	47

45	carbon steel	2-[(2Z)-2-(1-cyano-2-iminopropylidene)hydrazinyl]-4,5,6,7-tetrahydro-1-benzothiophene-3-carboxamide, ethyl 2-[(2Z)-2-(1-cyano-2-iminopropylidene)hydrazinyl]-4,5,6,7-tetrahydro-1-benzothiophene-3-carboxylate, 2-[(2Z)-2-(1-cyano-2-iminopropylidene)hydrazinyl]-4,5,6,7-tetrahydro-1-benzothiophene-3-carbonitrile	S	1MHCl	(weight loss) and electrochemical techniques (potentiodynamic polarization, electrochemical frequency modulation, and electrochemical impedance spectroscopy, Langmuir adsorption isotherm	The inhibition efficiency increased with the increase in inhibitor concentration and temperature. The compounds are chemically adsorbed on the steel surface. These compounds are mixed-type inhibitors.	48
46	Steel	Benzimidazole, 2-Methylbenzimidazole, 2-Mercaptobenzimidazole	N	HCl	DFT	The substituent charge ability may play a critical influence on inhibition performance when inhibitor molecule with the same primary structure.	49
47	mild steel	N-((1H-pyrrol-2-yl)methylene)nicotinamide, N-((methyl(phenyl)amino)methylene)nicotinamide, N-nicotinoylbenzimidothioic acid and N-(4-(methylthio)benzylidene)nicotinamide	N	0.5 M HCl	Potentiodynamic polarization studies, FTIR, EDX, SEM, EIS, Langmuir adsorption isotherm	All the examined inhibitors suppress both anodic and cathodic process and behave as mixed type of corrosion inhibitors. Polarization resistance (RP) increases and double layer capacitance (Cdl) decreases as the concentration of the inhibitors	50

						increases.	
48	mild steel	(1-hexadecyl-1H-benzo[d]imidazol-2-yl)thiazole (TBZ1), 1,3-dihexadecyl-2-(thiazol-4-yl)-1H-benzo[d]imidazol-3-ium bromide(TBZ2)	N, S	1MHCl	Weight loss measurements, Tafel polarization measurements, Electrochemical impedance spectroscopic studies, SEM, Langmuir adsorption isotherm	The corrosion rates of the mild steel decrease as the concentration of TBZ derivatives increases. The inhibition efficiency increases with the increase of inhibitor concentration and the maximum inhibition efficiency is approximately 95% in 10 ⁻³ M of TBZ2. The TBZ derivatives act as a mixed inhibitor for corrosion of mild steel in 1M HCl retarding the anodic and cathodic corrosion reactions with predominant effect on the cathodic reaction.	51
49	AISI 316 Stainless Steel, AISI 1010 Carbon Steel	Imidazole, Benzimidazole	N	3.0 % chloride solution	Laser-induced plasma emission spectroscopy (LIPS), X-ray diffraction (XRD), scanning electron microscopy (SEM), energy dispersive X-ray (EDX), potentiodyna	The results showed that at any inhibitor concentration (25 ppm to 1000 ppm), there was an increase in the polarisation resistance of both steels. The highest efficiency of corrosion inhibition was obtained using imidazole at a	52

					mic polarisation.	concentration of 50 ppm for both steels, with values of 96% for stainless steel and 73% for carbon steel.	
50	mild steel	1,4-dihydroquinoxaline-2,3-dione, (3E)-3-hydrazinylidene-3,4-dihydroquinoxalin-2(1H)-one, 1-[(2E)-3-oxo-3,4-dihydroquinoxalin-2(1H)-ylidene]urea and 1-[(2E)-3-oxo-3,4-dihydroquinoxalin-2(1H)-ylidene]thiourea	N	1M H ₂ SO ₄	Potentiodynamic Polarization Studies, Weight loss measurements, AAS, SEM, EDS, FT-IR, EIS, Langmuir adsorption isotherm	The investigated 1,4-dihydroquinoxalin-2,3-dione derivatives are found to perform well as corrosion inhibitors in 1M H ₂ SO ₄ solution. The order of inhibition as follows: ODQDTU > ODQDU > HDQD > DQD	53
51	mild steel	2,6-diphenylpiperidin-4-one (DPP) (1A) and 2,6-diphenyldihydro-2H-thiopyran-4(3H)-one (DPDT) (1B)	N	1 M H ₃ PO ₄	Weight loss method, Electrochemical Impedance Studies, Potentiodynamic Polarization Studies, Quantum Studies, Langmuir adsorption isotherm.	The parameters hardness (η), softness (S), dipole moment (μ), electron affinity (A), ionization potential (I), the absolute electronegativity (χ), the fraction of electron transferred (rN) confirms the inhibition efficiency in order of 1A > 1B.	54

52	carbon steel	5-Amino-1,3,4-thiadiazole-2-thiol, 2-Amino-5-tert-butyl-1,3,4-thiadiazole, 2-amino-5-ethyl-1,3,4-thiadiazole, 2-Amino-1,3,4-thiadiazole	N, S	1 M HCl	Weight Loss Measurements, EIS, EFM, SEM, EDX, Langmuir adsorption isotherm	The investigated compounds are good inhibitors and act as mixed type inhibitors for C-steel corrosion in 1 M HCl. 2. The order of % IE of these investigated compounds is in the following order: 1 > 2 > 3 > 4.	55
53	carbon steel	2-thiophene carboxylic acid (A) 2-thiophene carboxylic acid hydrazide(B)	S	1 M HCl	Weight Loss Measurements, EIS, EFM, Langmuir adsorption isotherm	The order of % IE of these investigated compounds is in the following order: B > A.	56
54	mild steel	dibenzo[b,d]thiophene (DBTDA) (E,E)-N,N'-dibenzo[b,d]thiophene-2,8-diylbis[1-(thiophen-2-yl)methanimine] (SB)	S	1 M HCl	Gravimetric measurement, Electrochemical measurements, scanning electron microscopy (SEM), Quantum chemical calculations, Langmuir adsorption isotherm.	Their inhibition efficiencies increase with inhibitors concentration in the order: SB > DBTDA.	57
55	mild steel	1-acetyl-4,5-dihydro-5-phenyl-3-(thiophen-2yl) pyrazoles	N, S	1M H ₂ SO ₄ , 1M HCl	Weight loss method, Potentiodynamic Polarization Studies, Langmuir adsorption isotherm.	The corrosion inhibition rate was increased in increasing the concentration of our synthesized inhibitor (1-acetyl-4, 5-dihydro-5-methyl phenyl-3-(thiophen-2yl) pyrazoles).	58

56	Mild Steel	benzimidazole, 2-methylbenzimidazole and 2-aminobenzimidazole	N	3.5% NaCl solution	Electrochemical impedance spectroscopy, DC polarization, Temkin isotherm.	The inhibition efficiency of imidazoles follows the order: 2-ABIM>2-MBIM> BIM. These compounds act as poor corrosion inhibitors even at high concentrations. The more basic the inhibitor the higher is its activity.	59
57	Mild Steel	6-ethoxybenzo[d]thiazol-2-amine (EBT), 5-bromothiazol-2-amine (BTA) and 4,5-dimethylthiazol-2-amine (DTA).	N, S	aqueous sulfuric acid	Potentiodynamic polarization, DFT	A comparison of the ΔE values of the studied compounds shows that the trend is such that EBT < DTA < BTA.	60
58	mild steel	3-[(4-{4-[(1H-Indol-3-ylmethylene)-amino]-benzenesulfonyl}-phenylimino)-methyl]-1H-indole (IABPI) and 5-[(4-{4-[(Thiophen-2-ylmethylene)-amino]-benzenesulfonyl}-phenylimino)-methyl]-thiophene (TABPT)	N	0.5 M H ₂ SO ₄	Energy dispersive X-ray spectroscopy (EDX), scanning electron microscopy (SEM), mass loss measurement, potentiodynamic polarization studies, Langmuir isotherm.	These two inhibitors behaved as mixed type. These inhibitors were found to obey Langmuir isotherm model.	61

59	aluminum	Imidazole (A) Methyl imidazole (B)	N	0.5 M HCl	potentiodynamic polarization, electrochemical impedance spectroscopy (EIS) and electrochemical frequency modulation (EFM), scanning electron microscopy (SEM), Frumkin adsorption.	Inhibition efficiencies increases by increasing the inhibitor concentration and inhibition occurs through adsorption of the inhibitor on the aluminum surface.	62
60	Copper	Imidazole (IM), 2-Methylimidazole (MIM), Benzimidazole (BIM)	N	1.0 M Sulfuric acid	Weight loss measurements and UV-Spectroscopy, Density functional theory (DFT), Langmuir's isotherm.	Results obtained reveal that BIM is the best inhibitor and the inhibition efficiency (EW%) follows the sequence: BIM > MIM > IM.	63
61	carbon steel	(E)-3-(4-methoxystyryl)-7-methylquinoxalin-2(1H)-one (SMQ) and 2-(4-methoxyphenyl)-7-methyl-thieno[3,2-b] quinoxaline (TMQ)	O	Chlorohydric acid molar media	Electrochemical impedance spectroscopy, Polarization measurements, Quantum chemical calculations, Langmuir isotherm	The order of inhibition efficiency, for the studied compounds is as follows: TMQ > SMQ	64
62	P110 carbon steel	thiosemicarbazide-imidazole	N	saturated NaCl solution	potentiodynamic polarization study, electrochemical impedance spectroscopy, scanning electron microscope,	In the aggressive condition of CO ₂ saturated Wt. NaCl solution at 333 K for 72 h with 400 ppm inhibitor dosage, the efficiency of inhibition increases	65

					thermodynamic study.	approximately 98 per cent through the method of weight loss.	
63	carbon steel	(E)-N(2-Chlorobenzylidene)-2-Fluorobenzeneamine (NCF) and (E)-N(2-Chlorobenzylidene)-3-Chloro-2-Methylbenzenamine (NCCM)	N	1 M HCl	Polarization measurements, Electrochemical impedance spectroscopy (EIS), Adsorption isotherms, Effect of temperature, SEM investigation, DFT and Molecular Dynamics Simulations, Langmuir isotherm	The order of inhibition efficiency for the studied compounds is as follows: NCF>NCCM	66
64	iron	2-acetyl-thiazole, 2-isobutyl-thiazole, 4-methyl-5-(2-hydroxyethyl)-thiazole, 2,4,5-trimethyl-thiazole	S, N		Monte Carlo simulations, DFT	Corrosion inhibition effectiveness can be classified in decreasing order: ATZ > TMTZ SFR > ISTZ.	67
65	copper	imidazole, purine, adenine, 6-benzylaminopurine	N	sea water	Cyclic voltammetry, Open circuit potential measurements, Potentiodynamic polarization measurements, Chronoamperometry, Quantum chemical calculation, Langmuir isotherm	Imidazole, purine, adenine and 6-benzylaminopurine act as inhibitors of copper corrosion in artificial seawater. Inhibition efficiency at corrosion potential increases in the following order imidazole < purine < adenine < 6-	68

						benzylaminopurine.	
66	J55 steel	2-(4-methoxyphenyl)-4,5-diphenyl-imidazole, 4,5-diphenyl-2-(p-tolyl)-imidazole, 2-(4-nitrophenyl)-4,5-diphenyl-imidazole	N	CO ₂ saturated brine solution	EIS, AFM, SECM, XPS, quantum chemical calculation, Langmuir isotherm.	2-(4-methoxyphenyl)-4,5-diphenyl-imidazole exhibited the best inhibition efficiency of 93% at 400 mg/L concentration.	69
67	Copper	1-(3-aminopropyl) imidazole	N	3% NaCl	Fourier transform infrared spectroscopy (FT-IR), energy dispersive X-ray analysis (EDX), X-ray photoelectron spectroscopy (XPS), atomic force microscopy (AFM), electrochemical polarization study (EPS) and scanning electron microscopy (SEM)	The API behaves as mixed type inhibitor, predominantly anodic in nature with IE value of 94.27%. The API SAM on Cu increased the anticorrosion properties of Cu.	70

III. CONCLUSION

Corrosion inhibition of metal samples in different media by organic inhibitors having heteroatom has been reviewed. From the above discussion, it is evident that such organic inhibitors derivatives are effective corrosion inhibitors against metals in all media. Weight loss, electrochemical impedance, and potentiodynamic polarization techniques were mainly used to confirm corrosion inhibition. It has been observed that the corrosion inhibition generally increases with increase in the concentration and temperature of inhibitor. Quantum chemical calculations were helped in ascertained detailed mechanisms for corrosion inhibition. Scale-up experiments for industrial applications are essential to be done so as to commercialize these organic inhibitor derivatives to effectively replace the conservative chemicals currently used to have power over the corrosion of metal.

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