A Review On Thiazole Derivatives As Corrosion Inhibitors For Metals And Their Alloys

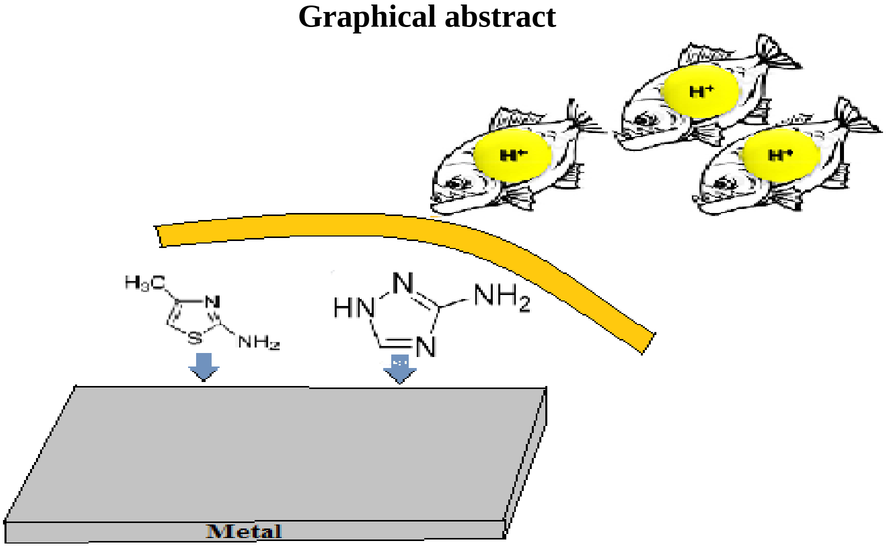
Abhinay Thakur, Ashish Kumar *

School of Chemical Engineering & Physical Sciences, Lovely Professional University, Punjab.
Corresponding Author:
E-mail addresses: drashishchemlpu@gmail.com.

Abstract : Innumerable organic corrosion inhibitors for various metals and their alloys have been persistently reported. The synthetic heterocyclic compounds composed of strong electronegative atoms/ hetero atoms such as oxygen, nitrogen, sulphur, phosphorus was observed to be very effective at preventing metal corrosion. A concept of studying Thiazole derivatives compounds for corrosion inhibition of metals has been formed in recent years as they contains hetero atoms, aromatic ring structure and pi bond in the structural geometry. Throughout this article, the goal is to examine the potential of thiazole derivatives as corrosion inhibitor for various metals and alloys through acidic or basic environment.

Keywords: Thiazoles; Corrosion inhibition; Metals; Alloys; Acid

Graphical abstract



1. Introduction

Thiazole is a five-member, planar, π-excessive aromatic hetero possessing a sulfur atom along a pyridine sort of nitrogen atom in 3rd place of cyclic ring system, serving as a core component for different molecules with variety of applications, especially in medicine. Several natural products which have a thiazole ring with significant therapeutic properties have been persistently reported. Thiamine, commonly recognized as B1 vitamin, has a thiazole ring associated to 2-methylpyrimidine-4-amine as hydrochloride salt as well as shows various agricultural, industrial and biomedical activities such as , anticonvulsant, anti-microbialanticancer, anti-inflammatory, diuretic, antitubercular, antibacterial and antifungal characteristics. Some medications like ketoconazole and fluconazole reported as potential anticadio vascular agents. In addition, one of the recently processed 5-(2,4-dichlorobenzylidene)-2-(naphthalen-1-ylamino)thiazol-4(5H)-one a thiazolin-4-one derivative was reported to be extremely effective towards a series of pathogenic fungi (MIC = 0.015 μg / mL). Due to their strong chemical behavior and less toxicity, such compounds can deemed as environment friendly corrosion inhibitors for metals such as copper, iron, aluminum, zinc etc. [1]. Such compounds are mostly amphoteric, form salts of acids/bases[2]. Also, they have pi electrons which can interact with any metal or alloy's d-orbitals and thus build a protective layer or film [3]. Thus in recent years work on thiazole derivative inhibitors has been a popular trend.

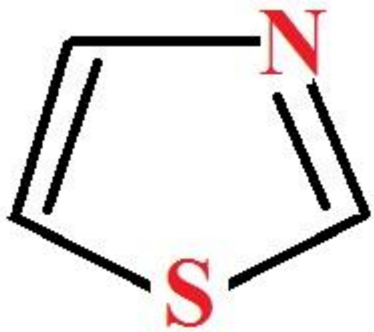


Fig.1. Basic structure of Thiazole

2.Thiazole Derivatives as Corrosion Inhibitors

2.1. Iron and Its Alloys

Iron is relatively inexpensive, high tensile metal. Thus widely used in the manufacture of machine tools, vehicles, medical instruments, large ship hulls, machine parts, as well as building pieces[4]. A mixture of iron with other elements offers advanced mechanical characteristics which are desirable for several use and applications. Major issue though is that it is poor resistant to corrosion, notably in aggressive environments. Industrial operations like de-scaling, acid cleaning, braising and excavation in oil and gas production utilize acidic solution widely so these iron, steel vessels or structures becomes more vulnerable to corrosion in these conditions[5]. Within the literature on organic corrosion inhibitors, the adsorption mechanism and the correlation between the inhibitor structures and their adsorption are listed [6]–[11]. Adsorption has been reported to rely primarily on electronic and structural characteristics of inhibitor molecule i.e. aromaticity, steric factors, functional groups, density of electrons and p orbital behavior [12]. Acid solutions are used widely in manufacturing processes. Within these conditions the corrosion of iron and its prevention is a dynamic phase issue. This is usually highly cost-effective to use organic inhibitors for mitigating mild steel corrosion in acidic environment. Over the past few years, steel inhibition in acidic solutions has also been studied extensively by various kinds of organic inhibitors.

Some thiazoles derivatives, namely 4,4'-(4(ethane-1,2-diylbis(oxy))bis(4-phenylene)dithiazol-2-amine [13], 2-(acetyl-ethoxy carbonyl-methyleno)-3-phenyl-4-(phenylhydrazono)-1,3-thiazolidin-5-one [14], 2-amino-4-(4-chlorophenyl)-thiazole[15], 2-Methoxy-1,3-thiazole (MTT), 4-(4-Methylphenyl)-2-thiazolamine and Thiazole-4-carboxaldehyde (TCA)[16], 2-amino-4-methyl-thiazole[17], 2-salicylidene amino-4-phenylthiazole [18], 4-[1-aza-2-(phenyl)vinyl]-3-phenyl-2- thioxo(1,3-thiazoline-5-yl)[19] revealed as mixed type inhibitor in H_2SO_4 and HCl media. An increases in I.E. was noted with increasing concentration of thiazole derivatives. Analyzed results from gravimetric technique and electrochemical analysis were appropriately acknowledged. Adsorption of the most of thiazole derivatives on metal surface follows Langmuir isotherm model.

Thermodynamic functions were obtained to gather valuable details about inhibition behaviour of thiazole derivatives. For greater perspective on electronic and molecular effects with inhibition efficiencies, molecular modeling has been used. Quantum chemical equations have supported the empirical findings in such investigations[20].

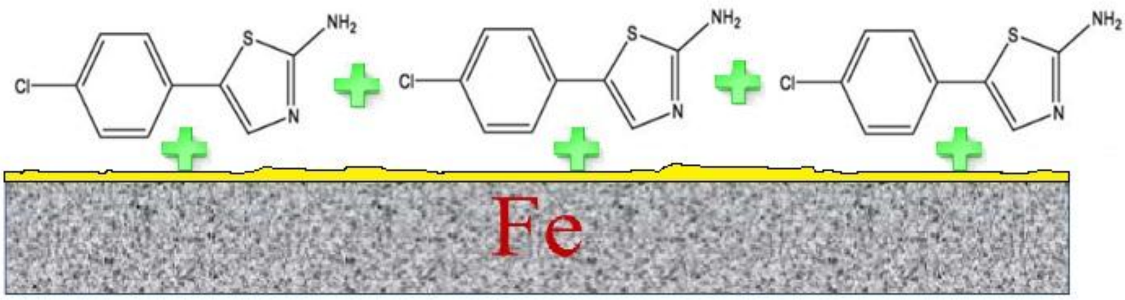


Fig.2. Adsorption of thiazole derivative 2-amino-4-(4-chlorophenyl)-thiazole on the iron surface

2.2. Copper and Its Alloys

Copper and its alloys are seeking out new application area in traditional industries. Copper is an extremely virtuous metal; although, vulnerable to acid corrosion and strong alkaline solution, notably when oxygen or oxidants are present. The deterioration of Cu is incredibly fast in the pH region around 2.5 and 5, and it is impossible to form stable surface oxide layers that can passive metal surfaces. For low acid or alkaline solutions, copper corrosion can be suppress by generating an protective layer on its surface[21]. Some derivatives of thiazole were effectively used to inhibit copper corrosion.

The analysis of thiazole derivatives for copper corrosion inhibition was conducted primarily in H2SO4 and HCl solutions with respect to industrial sector uses, where copper subjected to these chemicals is being used. 5-benzylidene-thiazolidine-2,4-dione [22], 2-amino-thiazole (ATZ) and 2-amino- 4,6-dimethyl-pyrimidine (ADMP)[23], 4-(2-ami- nothiazole-4-yl) phenol (ATP), 4,4′-(thiobis(2-aminothiazole-5,4-diyl)) diphenol (TATD) and 4-phenylthiazole-2-amine (PTA) [24], 5- (5'-methylfurfurylidene-2')-2,4-dioxotetrahydro-1,3-thiazole [25], 2-aminobenzothiazole and 2- amino-6-bromobenzothiazole[26], 5-benzylidene-2,4-thiazolidinedione[27], 5-(4’-isopropylbenzylidene)-2,4-dioxotetrahydro-1,3-thiazole[28] have been examined by several techniques such as spectroscopic, gravimetric and electrochemical techniques to investigate their inhibition efficiency against copper corrosion. Results demonstrated that with increasing the inhibitor concentration the inhibition efficiency increases and attains a maximum peak point[29]. For several experiments, activation energies are calculated by measuring temperature independence of corrosion current in inhibitor’s presence/absence. Alterations in impedance parameters confirmed the inhibitor adsorption on the surface of copper, resulting in a protective layer forming[30]. In these experiments, copper surface adsorption of inhibitor observed to obeyed Langmuir adsorption isotherm[31].

Polarization curves from poteniodynamic polarization analysis reveal most of the derivatives as mixed type inhibitors. Adsorption of derivatives obeyed Langmuir’s adsorption isotherm. Analysis indicates that copper corrosion inhibition was caused by thiazole derivative adsorption on the copper surface where adsorbed thiazole derivative formed Cu-complex that suppress the chloride complex formation in copper. The experimental findings from electrochemical polarization showed the high inhibitive performance of the thiazole derivatives being studied.

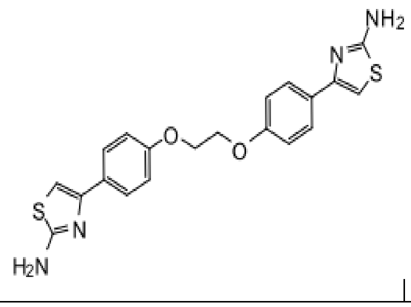
Fig.3. Adsorption of thiazole derivative 5-(5'-methylfurfurylidene-2')-2,4-dioxotetrahydro-1,3-thiazole on Cu surface

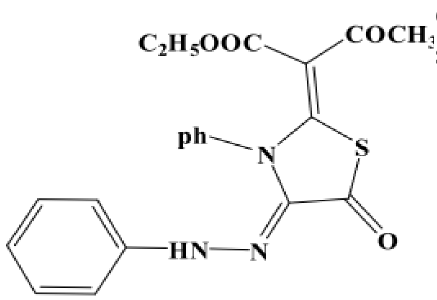
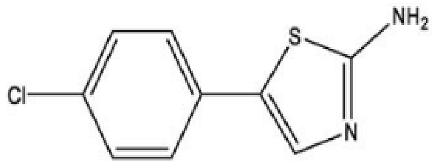
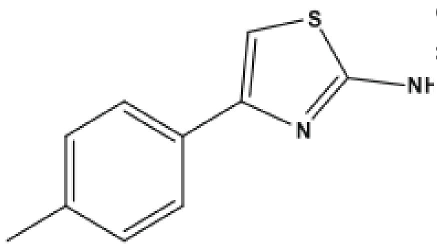
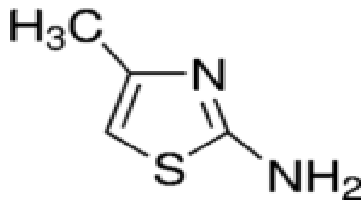
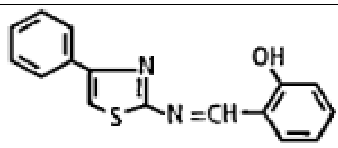
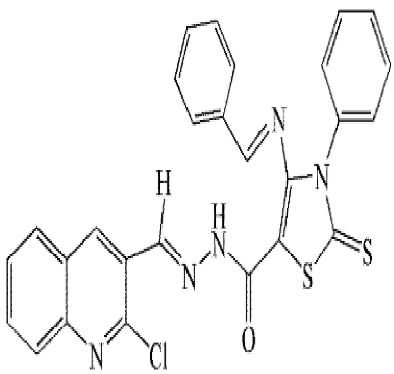
2.3.Aluminium and its Alloys

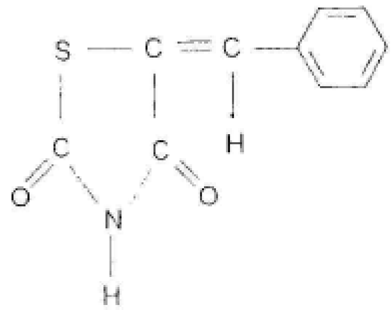
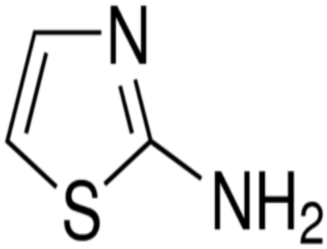
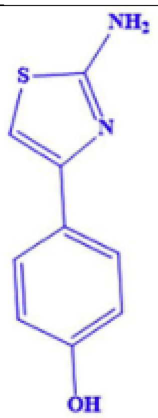
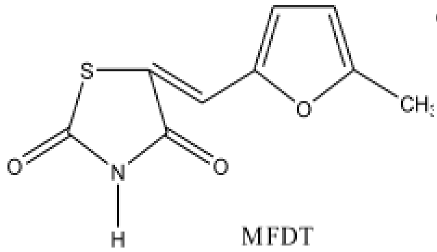
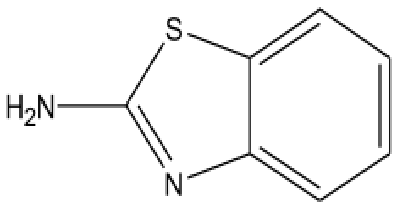
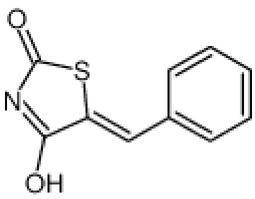
Aluminum as well as its alloys has indeed been extensively used in shipping, construction, electrical engineering, home appliances, packaging, aircraft and aircraft sectors as products. One explanation is that aluminum provides good thermal and electrical conductivity, light mass (density of 2,6 g / cm3) also it have comparatively low price and is roughly twice as efficient as iron. Furthermore, due to emergence of resistive oxide layer, aluminum displays high resistance to corrosion as it is exposed to atmosphere and other unfavorable conditions which give rise to corrosion[32]. A literature survey shows that specific organic inhibitors of corrosion are commonly seemed to avoid aluminum dissolution in basic and acidic media. The corrosion mitigation activity of thiazole derivatives was calculated by thermodynamic parameters e.g. enthalpy/ entropy of adsorption etc.

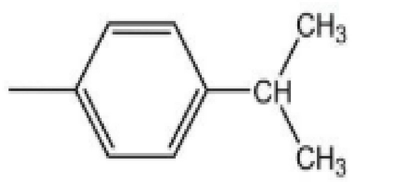
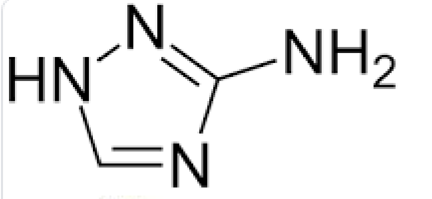
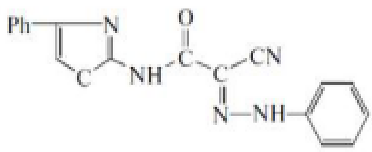
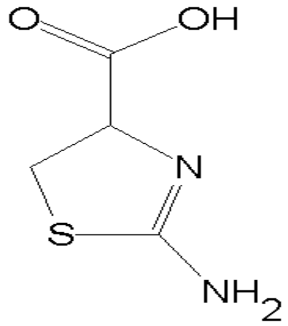
Present potential curves and gravimetric measurements revealed as 1,2,4-triazole, 3-amino-1,2,4-triazole, benzotriazole and 2-mercaptobenzothiazole[33], N-thiazolyl-2-cyanoacetamide[34], 2-amino[4-p-Hydroxyphenyl]Thiazole and 2-amino[4-p-Bromophenyl]Thiazole [35] gives the best inhibition efficiency. The adsorbability and hydrophobicity of the thiazole complexes and the stabilization of the Al-thiazole complex are the significant measures affecting the inhibition performance of thiazole derivatives within various treatments [36].

Table 1. Several derivatives of thiazole as corrosion inhibitors for many metals and alloys in acidic / basic solution

S.No	Inhibitor name	Structure	Metal	Medium	Ref(s)
1.	4,4'-(4(ethane-1,2-diylbis(oxy))bis(4-phenylene)dithiazol-2-amine		Mild steel	0.5M H_2SO_4	[13]

2.	2-(acetyl-ethoxy carbonyl-methyleno)-3-phenyl-4-(phenylhydrazono)-1,3-thiazolidin-5-one		Carbon steel	2M HCl	[14]
3.	2-amino-4-(4-chlorophenyl)-thiazole		Mild steel	0.5 M HCl	[15]
4.	4-(4-Methylphenyl)-2-thiazolamine		Carbon steel	0.5M H_2SO_4	[16]
5.	2-amino-4-methyl-thiazole		Carbon steel	0.5M HCl	[17]
6.	2-salicylidene amino-4-phenylthiazole		Mild steel	1M HCl	[18]
7.	4-[1-aza-2-(phenyl)vinyl]-3-phenyl-2- thioxo(1,3-thiazoline-5-yl)		Carbon steel	15% HCl solutio n	[19]

8.	5-benzylidene-thiazolidine-2,4-dione		Copper	0.1 M Na_2SO_4	[22]
9.	2-amino-thiazole		Copper	Tap water	[23]
10.	4-(2-ami- nothiazole-4-yl) phenol		Copper	1M HCl	[24]
11.	MFDT		Copper	0.1 M dm^{-3} Na_2SO_4	[25]
12.	2-aminobenzothiazole		Copper	3% NaCl solution	[26]
13.	5-benzylidene-2,4-thiazolidinedione		Copper	0.1 M Na_2SO_4	[27]

14.	(5-(4'-isopropylbenzylidene-2,4)-dioxotetrahydro-1,3-thiazole)		Cu	0.1 M Na_2SO_4	[28]-[34]
15.	3-amino-1,2,4-triazole		AA2024 aluminium alloy	0.005 M NaCl	[35]-[42]
16.	N-thiazolyl-2-cyanoacetamide		Aluminium	0.01M NaOH	[43]-[50]
17.	2-amino[4-p-Hydroxyphenyl]Thiazole		Aluminium	0.02 M NaOH	[51-58]

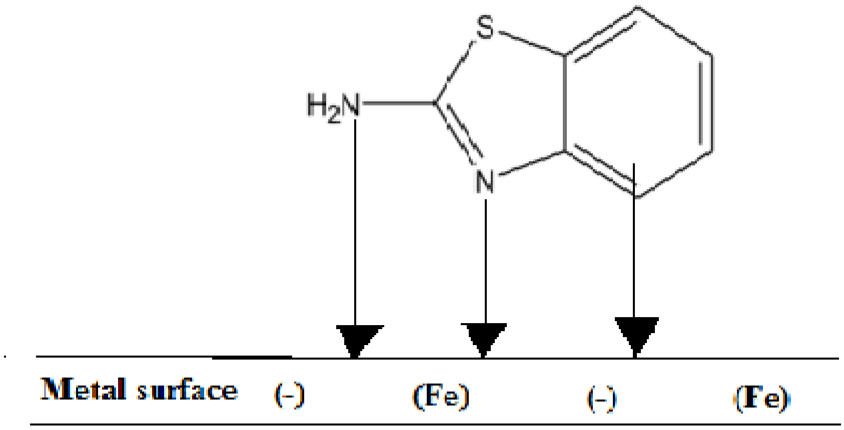


Fig.4. Adsorption of inhibitor molecule on metallic surface

3. Conclusion

Thiazole derivatives as corrosion inhibitors for various metals have been examined in various media. Thiazole derivatives are proven to be efficient inhibitors of corrosion due to the special structural properties of thiazole derivatives such as hetero atoms, aromatic ring structure and pi bond in the structural geometry. Assay from the corrosion analysis using various techniques revealed that these derivatives are strong inhibitors of corrosion (Table 1). The analyses have found that most of thiazole derivatives act as a mixed form inhibitor. It was also noted that the inhibition of corrosion usually rises with increasing inhibitor concentration and follows Langmuir adsorption isotherm.

References

[1] S. Bashir, A. Thakur, H. Lgaz, I.-M. Chung, and A. Kumar, "Computational and experimental studies on Phenylephrine as anti-corrosion substance of mild steel in acidic medium," *J. Mol. Liq.*, vol. 293, p. 111539, 2019.

[2] G. Parveen, S. Bashir, A. Thakur, S. K. Saha, P. Banerjee, and A. Kumar, "Experimental and computational studies of imidazolium based ionic liquid 1-methyl-3-propylimidazolium iodide on mild steel corrosion in acidic solution Experimental and computational studies of imidazolium based ionic liquid 1-methyl- 3-propylimidazolium," *Mater. Res. Express*, vol. 7, no. 1, p. 016510, 2020.

[3] S. Bashir, V. Sharma, H. Lgaz, I.-M. Chung, A. Singh, and A. Kumar, "The inhibition action of analgin on the corrosion of mild steel in acidic medium: A combined theoretical and experimental approach," *J. Mol. Liq.*, vol. 263, pp. 454–462, 2018.

[4] S. Bashir, H. Lgaz, I. I. I. M. Chung, and A. Kumar, "Potential of Venlafaxine in the inhibition of mild steel corrosion in HCl: insights from experimental and computational studies," *Chem. Pap.*, vol. 73, no. 9, pp. 2255–2264, Apr. 2019.

[5] S. Bashir, V.Sharma, G. Singh, H. Lgaz, R. Salghi, A. Singh and A. Kumar, "Electrochemical Behavior and Computational Analysis of Phenylephrine for Corrosion Inhibition of Aluminum in Acidic Medium," *Metall. Mater. Trans. A*, vol. 50, no. 1, pp. 468–479, Nov. 2019.

[6] V. Sharma, P. Cantero-López, O. Yañez-Osses, C. Rojas-Fuentes and A. Kumar, Influence of BSA on micelle formation of SDBS and CPC: An experimental–theoretical approach of its binding properties. *Journal of Molecular Liquids*, vol. 271, pp.443-451,2018.

[7] O. Yan and A. Kumar, "E ff ect of Cosolvents DMSO and Glycerol on the Self-Assembly Behavior of SDBS and CPC : An Experimental and Theoretical Approach."

[8] A. Kumar, "Magnetite Nanoparticle Green Synthesis from Canola Oil," pp. 3–8, 2014.

[9] A. Kumar, "Comparative Study of Kinetics of Catalyzed Oxidation of D (+) galactose and lactose by Ruthenium (III) in Alkaline," no. Iii, 2013.

[10] R. C. Thakur, R. Sharma, A. Kumar, and M. L. Parmar, "Thermodynamic and transport studies of some aluminium salts in water and binary aqueous mixtures of tetrahydrofuran," vol. 6, no. 5, pp. 1330–1336, 2015.

[11] R. R. Hosamani and S. T. Nandibewoor, "Mechanistic study of ruthenium (III) catalysed oxidation of L-lysine by diperiodatoargentate (III) in aqueous alkaline medium," vol. 121, no. 3, pp. 275–281, 2009.

[12] A. Singh, N. Soni, Y. Deyuan, and A. Kumar, "A combined electrochemical and theoretical analysis of environmentally benign polymer for corrosion protection of N80 steel in sweet corrosive environment," *Results Phys.*, vol. 13, p. 102116, Jun. 2019.

[13] M. Abdallah, A. M. El Defrawy, I. A. Zaafarany, M. Sobhi, A. H. M. Elwahy, and M. R. Shaaban, "Inhibition effects and theoretical studies of synthesized novel bisaminothiazole derivatives as corrosion inhibitors for carbon steel in sulphuric acid solutions," *Int. J. Electrochem. Sci.*, vol. 9, no. 5, pp. 2186–2207, 2014.

[14] A. A. Al-Sarawy, A. S. Fouda, and W. A. S. El-Dein, "Some thiazole derivatives as corrosion inhibitors for carbon steel in acidic medium," *Desalination*, vol. 229, no. 1–3, pp. 279–293, 2008.

[15] Z. Cao, Y. Tang, H. Cang, J. Xu, G. Lu, and W. Jing, "Novel benzimidazole derivatives as corrosion inhibitors of mild steel in the acidic media. Part II: Theoretical studies," *Corros. Sci.*, vol. 83, pp. 292–298, 2014.

[16] K. F. Khaled and M. A. Amin, "Corrosion monitoring of mild steel in sulphuric acid

solutions in presence of some thiazole derivatives - Molecular dynamics, chemical and electrochemical studies," *Corros. Sci.*, vol. 51, no. 9, pp. 1964–1975, 2009.

[17] A. Ongun Yüce, B. Doğru Mert, G. Kardaş, and B. Yazici, "Electrochemical and quantum chemical studies of 2-amino-4-methyl-thiazole as corrosion inhibitor for mild steel in HCl solution," *Corros. Sci.*, vol. 83, pp. 310–316, 2014.

[18] M. A. Quraishi, M. Wajid Khan, M. Ajmal, S. Muralidharan, and S. Venkatakrishna Iyer, "Influence of some thiazole derivatives on the corrosion of mild steel in hydrochloric acid," *Anti-Corrosion Methods Mater.*, vol. 43, no. 2, pp. 5–8, 1996.

[19] M. Yadav, S. Kumar, D. Behera, I. Bahadur, and D. Ramjugernath, "Electrochemical and quantum chemical studies on adsorption and corrosion inhibition performance of quinoline-thiazole derivatives on mild steel in hydrochloric acid solution," *Int. J. Electrochem. Sci.*, vol. 9, no. 9, pp. 5235–5257, 2014.

[20] A. Singh, T. Pramanik, A. Kumar, and M. Gupta, "Phenobarbital: A new and effective corrosion inhibitor for mild steel in 1 M HCl Solution," *Asian J. Chem.*, vol. 25, no. 17, pp. 9808–9812, 2013.

[21] A. Singh, A. Kumar, and T. Pramanik, "A Theoretical Approach to the Study of Some Plant Extracts as Green Corrosion Inhibitor for Mild Steel in HCl Solution," *Orient. J. Chem.*, vol. 29, no. 1, pp. 1–7, 2013.

[22] G. Vastag, E. Szocs, A. Shaban, I. Bertóti, K. Popov-Pergal, and E. Kálmán, "Adsorption and corrosion protection behavior of thiazole derivatives on copper surfaces," *Solid State Ionics*, vol. 141–142, pp. 87–91, 2001.

[23] F.H. Al-Hajjar and F.M. Al-Kharafi,"2 - a M I N O - T H I a Z O L E a N D 2-Amino-4 , 6-Dimethyl- P Y R I M I D I N E As C O R R O S I O N Inhibitors for Copper," *Corrosion*, vol. 28, no. 2, pp. 163–171, 1988.

[24] R. Farahati, A. Ghaffarinejad, S. M. Mousavi-Khoshdel, J. Rezania, H. Behzadi, and A. Shockravi, "Synthesis and potential applications of some thiazoles as corrosion inhibitor of copper in 1 M HCl: Experimental and theoretical studies," *Prog. Org. Coatings*, vol. 132, no. April, pp. 417–428, 2019.

[25] J. Nakomčić, G. Vastag, A. Shaban, and L. Nyikos, "Effect of thiazole derivatives on copper corrosion in acidic sulphate solution," *Int. J. Electrochem. Sci.*, vol. 10, no. 7, pp. 5365–5381, 2015.

[26] Y. Qiang, S. Zhang, S. Xu, L. Guo, N. Chen, and I. B. Obot, "Effective protection for copper corrosion by two thiazole derivatives in neutral chloride media: Experimental and computational study," *Int. J. Electrochem. Sci.*, vol. 11, no. 4, pp. 3147–3163, 2016.

[27] A. Shaban, I. Felhősi, and E. Kálmán, "Study of inhibition properties of some thiazole derivatives against copper corrosion," *Zaštita Mater.*, vol. 53, no. 1, pp. 29–32, 2012.

[28] A. Shaban, G. Vastag, A. Pilbáth, I. Kék, and L. Nyikos, "Electrochemical study of copper corrosion inhibition in acidic environment by 5-(4'-isopropylbenzylidene)-2,4-dioxotetrahydro-1,3-thiazole," *J. Mater. Environ. Sci.*, vol. 7, no. 7, pp. 2572–2582, 2016.

[29] A. Kumar and S. Bashir, "Ethambutol: A new and effective corrosion inhibitor of mildsteel in acidic medium," *Russ. J. Appl. Chem.*, vol. 89, no. 7, pp. 1158–1163, 2016.

[30] V. S. and A. K. Pooja Dhaundiyal, Sumayah Bashir, "An Investigation On Mitigation Of Corrosion Of Mildsteel By Origanum Vulgare In Acidic Medium," *J. Chem. Inf. Model.*, vol. 33, no. 1, pp. 159–168, 2019.

[31] K. A. Sharma V, Kumar S, Bashir S, Ghelichkhah Z, Obot IB, "Use of Sapindus (reetha) as corrosion inhibitor of aluminium in acidic medium," *Mater. Res. Express*, vol. 5, no. 7, p. 076510, 2018.

[32] S. Bashir, G. Singh, and A. Kumar, "An Investigation on Mitigation of Corrosion of Aluminium by Origanum Vulgare in Acidic Medium," *Prot. Met. Phys. Chem. Surfaces*, vol. 54, no. 1, pp. 148–152, 2018.

[33] M. L. Zheludkevich, K. A. Yasakau, S. K. Poznyak, and M. G. S. Ferreira, "Triazole and thiazole derivatives as corrosion inhibitors for AA2024 aluminium alloy," *Corros. Sci.*, vol. 47, no. 12, pp. 3368–3383, 2005.

[34] X. Y. Zhang, Q. X. Kang, and Y. Wang, "Theoretical study of N-thiazolyl-2-cyanoacetamide derivatives as corrosion inhibitor for aluminum in alkaline environments," *Comput. Theor. Chem.*, vol. 1131, pp. 25–32, 2018.

[35] S. Abdul and M. Aziz, "Corrosion Inhibition of Aluminum in Sodium Hydroxide Solutions by Some Thiazole Derivatives."

[36] S. Bashir, G. Singh, and A. Kumar, "Shatavari (Asparagus Racemosus) as green corrosion inhibitor of aluminium in acidic medium," *J. Mater. Environ. Sci.*, vol. 8, no. 12, pp. 4284–4291, 2017.

[37] P.K. Sharma , Synthesis of Starting Heterocycles: 2-Aminobenzothiazoles, 2-Aminothiazoles and 2 Aminobenzenethiols – Potential Precursors for Macroheterocycles, *Macroheterocycles*, vol. 11,pp. 316-321,2018.

[38] P.K. Sharma , Antimicrobial and antioxidant activities of substituted 4H-1, 4 benzothiazines AIP Conference Proceedings,1860(1), 2017.

[39] P.K. Sharma , A review: Different approach of bioactive pyrimidobenzothiazoles synthesis, Drug Invent. Today, 9(3), 18-22, 2017.

[40] P.K. Sharma , A review on antimicrobial activities of important thiazines based heterocycles, *Drug Invent. Today*, 9(3), 23-25, 2017.

[41] P.K. Sharma andM. Kumar, Synthesis of Bioactive substituted pyrazolylbenzothiazinones" *Res.Chem.Intermed*,41,(9), 6141-6148, 2015.

[42] N.Chakraborty, H.Manchanda, K. Kaur and K. Juglan "Volumetric and ultrasonic studies on interactions of glycol in aqueous solutions of xylitol at different temperatures" *J. Chem. Eng.* Data 2020.

[43] K. Kaur, K. C. Juglan, H. Kumar and V. Sharma "Ultrasonic Velocities of Binary Mixtures of Homologous Series of Ethylene Glycol and Glycerol at Different Temperatures: A Comparative Study" *Materials Today: Proceedings* 21,1875–1881, 2020.

[44] A.Thakur, K.C. Juglan, H. Kumar and K. Kaur, "Intermolecular investigation of polyethylene glycols with butyl paraben in methanol medium attributing volumetric, ultrasonic and thermophysical properties" *Journal of Molecular Liquids*, Volume 298, 15, 112000,2020.

[45] Mukherjee, R., Lawes, G., & Nadgorny, B. (2014). Enhancement of high dielectric permittivity in CaCu3Ti4O12/RuO2 composites in the vicinity of the percolation threshold. Applied Physics Letters, *105*(7), 072901.

[46] Mukherjee, R., Huang, Z. F., & Nadgorny, B. (2014). Multiple percolation tunneling staircase in metal-semiconductor nanoparticle composites. Applied Physics Letters, *105*(17), 173104.

[47] A. Thakur, K.C. Juglan, H. Kumar and K. Kaur, "Apparent molar properties of glycols in methanol solutions of propyl 4 hydroxybenzoate (propylparaben) at T = (293.15 to 308.15) K: an acoustic and volumetric approach" *Physics and chemistry of liquids*, doi.org/10.1080/00319104.2019.1660980.

[48] A. Thakur, K.C. Juglan and H. Kumar, "Volumetric and ultrasonic investigation of polyethylene glycols (PEG-200 and PEG-600) in aqueous solutions of sodium methylparaben at various temperatures" *Journal of Chemical Thermodynamics*, doi.org/10.1016/j.jct.2019.105916

[49] Mukherjee, R. (2020). Electrical, thermal and elastic properties of methylammonium lead bromide single crystal. Bulletin of Materials Science, *43*(1), 1-5.
[50] A. Thakur, K.C. Juglan, H. Kumar and K. Kaur, "Investigatio onmolecular interaction of glycols in methanol solutions of methylparaben (methyl 4 hydroxybenzoate) at different temperatures through thermo-acoustical analysis" *Journal of Molecular Liquids* 288 ,111014, 2019.
[51] K.Kaur, K. Juglan, H. Kumar and I. Behal, "Thermodynamic Interactions Study of Some Ethylene Glycols in Aqueous Aniline Solutions at Different Temperatures: An Acoustical and Volumetric Approach" *J. Chem. Eng. Data*, 63, 3237−3251, 2018.
[52] K. Kaur, K.Juglan and H. Kumar "Temperature dependent physicochemical studies of polyethylene glycols (PEG-400 and PEG-4000) in aqueous sorbitol solutions" *Journal of Molecular Liquids* 268, 700–706, 2018.
[53] K. Kaur, K. Juglan and H. Kumar "Acoustical and volumetric investigation of polyethylene glycol 400 and polyethylene glycol 4000 in aqueous solutions of glycerol at different temperatures", *Journal of Chemical Thermodynamics* 127, 8–16, 2018.
[54] N. Chakraborty, H. Manchanda, K. Kaur and K. Juglan "Acoustic and thermodynamic study of D-Panthenol in aqueous solutions of glycol at different temperatures", *Journal of Chemical Thermodynamics*, 126, 137–146, 2018.
[55] K. Kaur, I. Behal, K. C. Juglan and H. Kumar "Volumetric and ultrasonic studies on interactions of ethylene glycol, diethylene glycol and triethylene glycol in aqueous solutions of glycerol at temperatures T = (293.15 K _ 308.15) K" *J. Chem. Thermodynamics* 125, 93–106, 2018.
[56] K. Kaur, K. C. Juglan and H. Kumar "Investigation on Temperature-Dependent Volumetric and Acoustical Properties of Homologous Series of Glycols in Aqueous Sorbitol Solutions" *J. Chem. Eng. Data*, 62, 3769-3782, 2017.
[57] K. Kaur, K. C. Juglan and H. Kumar "Thermo-acoustical molecular interaction study in binary mixtures of glycerol and ethylene glycol" AIP Conference Proceedings 1860, 020026 ,2017. doi: 10.1063/1.4990325.
[58] P. Manon, K. C. Juglan, K. Kaur, N. Sethi and J. P. Kaur "Intermolecular interaction studies of glyphosate with water" AIP Conference Proceedings 1860, 020018, 2017; doi: 10.1063/1.4990317.