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Allium Sativum (Garlic) as a Green Corrosion Inhibitor for Protection of Metals and Alloys-A Review

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Abstract: In this review, study of Allium sativum (Garlic) as a green corrosion inhibitor for various metals and alloys such as aluminium (Al), carbon steel (CS), mild steel (MS), stainless steel (SS), brass, zinc (Zn) and copper (Cu) was presented. The percentage inhibition efficiency (I.E. %) of inhibitor was calculated using weight loss (WL) and electrochemical techniques such as potentiodynamic polarization (PDP) and electrochemical impedance spectroscopy (EIS). Nature of surface produce on metals was study by various techniques like scanning electron microscopy (SEM), fourier-transform infrared spectroscopy (FT-IR), gas chromatography mass spectrometry (GC-MS), scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS) and energy dispersive X-ray spectroscopy (EDX), atomic force microscopy (AFM), X-ray diffraction (XRD), atomic adsorption spectroscopy (AAS) and UV-Vis. Spectroscopy were also used to study the nature of surface film produce on metals. Adsorption of Allium sativum on metal surface obeys Langmuir and Temkin adsorption isotherms depending on nature of metal and corrosive environment. Polarization study reveals that Allium sativum can function as anodic or cathodic or mixed type of inhibitor depending on nature of metal and corrosive media.

1. Introduction

Corrosion is a natural process commonly defined as the deterioration of a metal or its properties because of a reaction with its environment. Corrosion can cause dangerous and expensive damage to petrochemical industries, bridges and public buildings etc. It is a constant and continuous problem, often cannot be eliminated completely. Prevention is more practical and achievable than complete elimination. Recently, a study revealed that corrosion causes economic losses of about 2.5 trillion US dollars a year, constituting almost 3.4 % of the worldwide GDP (Verma *et al*., 2018). There are many methods are available to control corrosion. Use of inhibitors is one of the common methods in industries for protection of metallic corrosion. A corrosion inhibitor is generally referred to as a chemical substance that when applied in small quantities to a corrosive medium reduces the rate of corrosion of a metal or a metal alloy (James *et al*., 2007; Tebbji *et al.*, 2007; Zarrok *et al.*, 2012). Plant extracts are viewed as environmentally friendly and ecologically acceptable inhibitors. Plant products are low cost, easily available and non-conventional source of materials (Loukil *et al*., 2023; Gad Allah *et al*., 1992; El Hosary *et al*., 1972; El-Etre *et al*., 1988). Plant extracts contain many organic compounds, having polar atoms such as oxygen (O), phosphorous (P), sulphur (S), and nitrogen (N) as well as heterocycles in their structures, which can adsorb into active sites of the metal surface through conjugated bonds (Prabakaran *et al*. 2016; Serbout *et al*., 2021; Hbika *et al*., 2023). Researchers interpreted the inhibitory process of the extract of natural plants by the synergistic intermolecular effect of the various molecules from major to minor compounds (Salim *et al*., 2022; Bouyanzer *et al*. 2017; Oguzie *et al*., 2008).

Corrosion inhibitors can be classified in the manner they inhibit corrosion: cathodic, anodic, or mixed-type inhibitors. Cathodic corrosion inhibitors decrease the corrosion potential, towards lower values, inhibiting the reactions that take place at the cathode, such as oxygen reduction and hydrogen evolution. Anodic corrosion inhibitors move the corrosion potential towards higher values and interact with the reactive sites on the metal surface, passivating them. Mixed-type inhibitors are those that cannot be classified as cathodic or anodic. These inhibitors can protect the metal surface in three possible manners: physisorption, chemisorption, and film formation. Physisorption is motivated by the electrostatic interaction between inhibitor molecules and the metal surface, whereas chemisorption is due to donor–acceptor interactions between vacant orbitals on the metal surface and free electron pairs in the inhibitor (El Ouafi *et al*., 2002; Richardson *et al*., 2009; Papavinasam *et al*., 2011; Zarrouk *et al*., 2012; Papavinasam *et al*., 2011). Lastly, film formation provides the metal surface with a physical barrier from the corrosive media, protecting it from corrosive attacks.

Allium sativum L. (Garlic) is of the Genus: *Allium L.*; Class: *Equisetopsida* in the family of *Amaryllidaceae* (Subroto *et al*., 2021, Londhe *et al*., 2011). Allium sativum is a perennial flowering plant that grows from a bulb. It has a tall, erect flowering stem that grows up to 1.2 m (4 ft). It is pollinated by bees and other insects (Meredith *et al*., 2014). It produces hermaphrodite flowers. *Allium sativum L*. is a globally popular food spice, known for its culinary and medicinal applications. The composition of one garlic species may vary according to geographical location, climatic conditions, harvest period, the part of the plant, etc. It is a native to Asia, and is also widely cultivated in Egypt, Mexico, Russia, China and Europe (Subroto *et al*., 2021). In India, Gujarat and Madhya Pradesh are major producers of garlic (Raghavan *et al*.,1983). Allium sativum is shown in **Figure 1.**

Figure 1. Allium sativum seeds

***Traditional uses of Allium sativum* (Garlic)**

It is widely used in cooking and for therapeutic purposes all over the world. The plant also has a high medicinal value and is used to cure a variety of human diseases. It has anti-inflammatory, rheumatological, ulcer inhibiting, anticholinergic, analgesic, antimicrobial, antistress, antidiabetes, anticancer, liver protection, anthelmintics, antioxidants, antifungal, and wound healing properties, as well as properties that help with asthma, arthritis, chronic fever, tuberculosis, runny nose, malaria, leprosy, skin discoloration, and itching, indigestion, colic, enlarged spleen, hemorrhoids, fistula, bone fracture, gout, urinary tract disease, diabetes, kidney stones, anemia, jaundice, epilepsy, cataract, and night blindness. Allicin, the major garlic compound, has revealed antibacterial, antiviral and antiparasitic effects (Nakamoto *et al*., 2020, Getti *et al*., 2019). It has been claimed that it can help to prevent cancer risk and platelet aggregation, reduce cholesterol and triglyceride levels, and decrease blood pressure (Getti *et al*., 2019, Wang *et al*., 2015).

Factors influencing metal corrosion

Temperature and immersion time

Temperature is an important factor which influence on the phenomenon of corrosion on metal surfaces. Similarly, the immersion time is another factor that could modify inhibition efficiency (I.E%). I. E. of Allium sativum was calculated by using WL and electrochemical tests, such as PDP and EIS measurement. Polarization tests, such as PDP, are based on the evaluation and analysis of the current produced by a variable potential in a working electrode (Esmailzadeh *et al*., 2018). The protective film has been analyzed by various surface analysis techniques.

2. Results and Discussion

Allium sativum extract were used for prevention of corrosion of various metals and alloys in different acidic and neutral solutions are presented in **Table 1**.

Table 1. Corrosion inhibition of metals and alloys in different media by *Allium sativum* as an inhibitor.

Metal / Alloy	Medium + Additive	Techniques used	Findings	I.E. max. (in %)	Reference
Aluminium	0.5 M HCl	WL Temperature.	Langmuir and Temkin adsorption isotherms.	98.0 WL	Al-Mhyawi *et al*., 2014
Aluminium	Rain water, NaOH + Zn^{+2}	WL Time, FT-IR.	---	---	Lakshmi *et al*., 2005
1050 Al-alloy	3.5 % NaCl	PDP, EIS, MDS, ENA.	---	---	Hajsafari *et al*., 2021
α-Brass	0.5 M HCl	WL Time, PDP.	Mixed type of inhibitor.	---	Loto *et al*., 2016a
α-Brass	0.5 M HNO_3	WL Temperature, PDP	Mixed type of inhibitor.	100.0 WL	Loto *et al*., 2016b
Brass (60/40)	1.0 M HNO_3	WL, PDP, EIS, FT-IR, SEM, AFM, XRD.	Mixed type of inhibitor, Langmuir adsorption isotherm.	91.90 WL, 93.98 PDP, 93.74 EIS.	Raeisi *et al*., 2024
Carbon Steel	0.5 M H_2SO_4	PDP, EIS.	Mixed type of inhibitor.	96.0 WL	Rodriguez *et al*., 2015
Carbon Steel	0.5 M H_2SO_4	WL, PDP, EIS, SEM, FT-IR.	Mixed type of inhibitor.	96.0 WL	Rodriguez *et al*., 2014
Carbon Steel	Well water + Zn^{+2}	WL, PDP, FT-IR	Anodic inhibitor	96.0 WL with Zn^{+2}	Rajam *et al*., 2013
Carbon Steel	Well water + Zn^{+2}	WL with Time, PDP, FT-IR, SEM.	Anodic inhibitor	98.0 WL with Zn^{+2}	Rajam *et al*., 2012

API 5LX - CS and 316-SS.	Hyper saline solution	WL, PDP, EIS, GC-MS	---	72 .0 WL for CS and 69.0 WL for SS.	Parthipan *et al.*, 2018
Carbon Steel -1020	0.5 M HCl	WL, PDP, EIS, SEM, FT-IR.	Cathodic inhibitor.	90.65 WL, 81.19 EIS	Barreto *et al.*, 2017
Low Carbon Steel	1.0 M HCl	WL with Temperature, PDP, EIS, EFM.	Mixed type of inhibitor. Temkin's adsorption isotherm.	96.0 PDP, 85.5 EIS.	Fouda *et al.*, 2015
Carbon Steel	1.0 M HCl	WL with Temperature, GC-MS.	Mixed type of inhibitor. Langmuir adsorption isotherm.	---	Pereira *et al.*, 2012
Carbon Steel	1.0 N H_2SO_4	OCP, PDP, EIS	Mixed type of inhibitor.	70.66 PDP, 66.26 EIS.	Cojocaru *et al.*, 2009
Carbon Steel	1.0 M HCl	WL with Temperature., PDP, EIS.	Mixed type of inhibitor. Langmuir adsorption isotherm.	95.8 PDP, 93.3 EIS.	Afia *et al.*, 2014
X 60 Carbon Steel - Stainless Steel	1.0 M H_2SO_4	WL, PDP, EIS	Anodic inhibitor	97.72 WL for SS and 71.01 WL for CS.	Belkaid *et al.*, 2022
Copper	0.5 M H_2SO_4	WL with Temperature, PDP, EIS, SEM, EDX, GC-MS	Cathodic inhibitor.	97.00 WL, 94.60 PDP, 94.80 EIS.	Mzioud *et al.*, 2020
Mild Steel	3.5% NaCl	WL, PDP, EIS, SEM and FT-IR.	Mixed type of inhibitor.	92.0 WL, 95.0 PDP.	Devikala *et al.*, 2019
Mild Steel	1.0 M H_3PO_4	WL, PDP, QCC, MCD.	Mixed type of inhibitor. Langmuir adsorption isotherm.	75.0 WL	Yaro *et al.*, 2014
Mild Steel	Well Water	WL, PDP, EIS, UV-Vis. and FT-IR.	Cathodic inhibitor	90.0 WL	Karthiga *et al.*, 2018
Mild Steel	0.5 M HCl and 0.5 M H_2SO_4	WL with Time, OCP, PDP.	Mixed-type of inhibitor.	100.0 WL, 87.74 PDP.	Loto *et al.*, 2016c
Mild Steel	Simulated Oil Well water $+Zn^{+2}$	WL, PDP, EIS, SEM, AFM.	Cathodic inhibitor	53.0 WL, 87.0 WL with Zn^{+2}	Joycee *et al.*, 2021

Mild Steel	Well water +Sodium Citrate + Zn^{+2}	WL, PDP, EIS, FT-IR, AFM.	Mixed type of Inhibitor.	95.0 WL	Devi *et al.*, 2011
Mild Steel	1 M HCl	WL with Temperature, SEM, UV Vis. Spectroscopy.	Langmuir adsorption isotherm.	76.47 WL	Ojha *et al.*, 2018
Mild Steel	1 M HCl	WL with Temperature, SEM, UV-Vis. Spectroscopy, DFT, QCC, HOMO-LUMO.	Langmuir adsorption isotherm.	76.47 WL	Ojha *et al.*, 2020
Mild Steel	5 % HCl & 5 % Mud acid	WL with Temperature, FT-IR, EIS.	Cathodic inhibitor.	93.26 WL in HCl, 79.2 WL in Mud acid.	Yang *et al.*, 2014
Mild Steel	0.5 M HCl	WL, PDP, EIS, AAS, FT-IR.	Mixed type of inhibitor.	68.1 WL	Mayowa et al., 2020
Mild Steel	5.0 M HCl	WL, PDP, SEM, FT-IR, NMR, DFT, MDS	Langmuir adsorption isotherm.	94.76 WL	Kumar *et al.*, 2021
Mild Steel	H_2SO_4	WL, HE	Langmuir adsorption isotherm.	---	Okafor *et al.*, 2005
AISI 1020 Mild Steel	0.5 M HCl, 0.5 M NaOH, 0.5 M NaCl	WL, PDP, EIS, QCC, SEM, EDS, FT-IR	Mixed type of inhibitor.	---	Maestro *et al.*, 2023
AISI 304-Stainless Steel	0.5 M HCl	WL, PDP, DFT, MCD	Mixed type of inhibitor, Langmuir adsorption isotherm.	88.0 WL	Asfia *et al.*, 2020
Zinc	0.5 N H_2SO_4	WL	Temkin adsorption isotherm.	81.2 WL	Pasupathy *et al.*, 2014

Abbrevations: EFM: electrochemical frequency modulation**, ENA:** electrochemical noise analysis**, HE:** hydrogen evolution**, HOMO:** highest occupied molecular orbital, **LUMO**: lowest unoccupied molecular orbital, **MDS**: molecular dynamics simulation, **MD**: molecular dynamics, **MCD**: mulliken charge distributions, **OCP:** open circuit potential, **QCC:** quantum chemical calculations.

Gas chromatography mass spectrometry (GC-MS) study

The results of GC/MS analyses of the oil led to the identification of the main components with their percentages. Garlic essential oil was particularly rich in monoterpene hydrocarbons. The main component of Allium sativum essential oil has 1(7), 5, 8-o-menthatriene (20.5%), di-2-propenyl disulfide (10.7%) and elemicin (9.5%). Other components such as Oxygenated monoterpenes (6%), Trans-Limone oxide (4%), Sesquiterpene hydrocarbons (0.8 %) and Oxygenated sesquiterpenes (0.9 %) (Afia *et al.*, 2014).

UV-Visible spectroscopy study

UV- Visible absorption spectrum of an aqueous extract of garlic is shown in **Figure 2** (Karthiga *et al*., 2018). A peak appears at 320, 380 nm. This is due to the absorption spectrum of allicin, which is the active ingredients present in the aqueous extract of garlic.

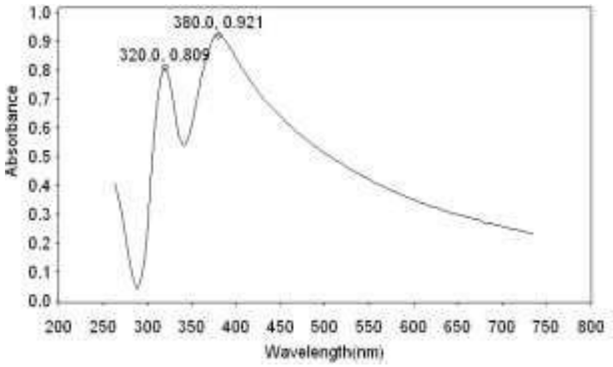


Figure 2. UV-Visible absorption spectrum of an aqueous solution of Garlic (Karthiga *et al*., 2018).

Fourier -transform infrared (FT-IR) absorption spectral study

Mayowa et al. (Mayowa *et al*. 2020) studied the inhibitive effect of garlic on the corrosion of MS in 0.5 M HCl. In this study, the garlic extracts were characterized using FT-IR spectra was shown in **Figure 3**.

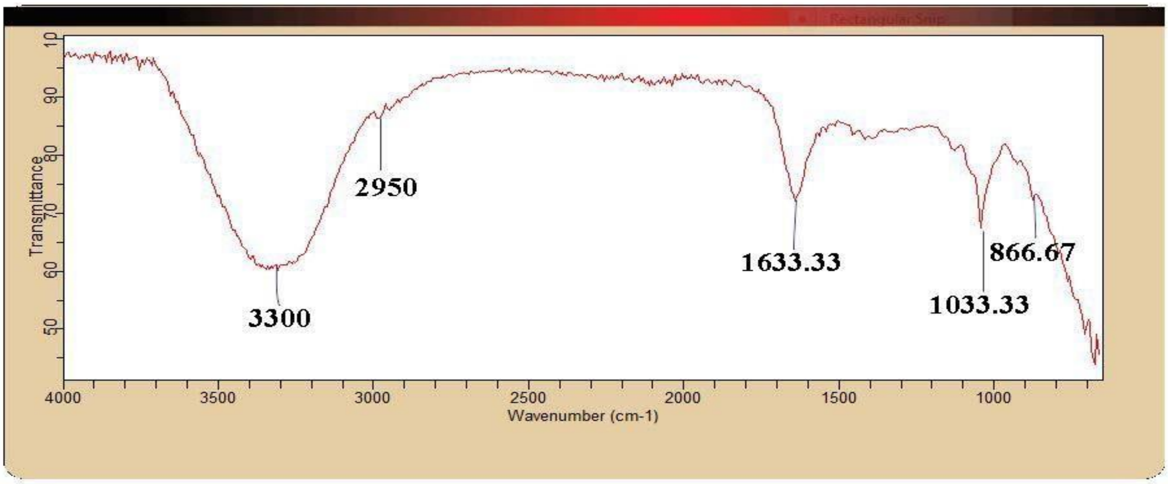


Figure 3. FT-IR spectrum of garlic extract (Mayowa *et al*. 2020).

The spectra show a broadband at 3300 cm^{-1} is attributed to O-H stretching. The frequency at 2950 cm^{-1} corresponds to C-H stretching, and the one at 1633.33 cm^{-1} corresponds to C=C stretching, 1033.33 cm^{-1} corresponds to C-O stretching and the 866.67 cm^{-1} corresponds to C=C bending (Mayowa *et al*. 2020).

Potentiodynamic polarization (PDP) study

The polarization curves for CS in 0.5 M H_2SO_4 with the addition of different *Allium sativum* concentrations are shown in **Figure 4** (Rodriguez *et al*., 2014). Both the anodic and cathodic Tafel slopes were increased with the addition of *Allium sativum* which indicates that *Allium sativum* is a mixed type of inhibitor (Rodriguez *et al*., 2014).

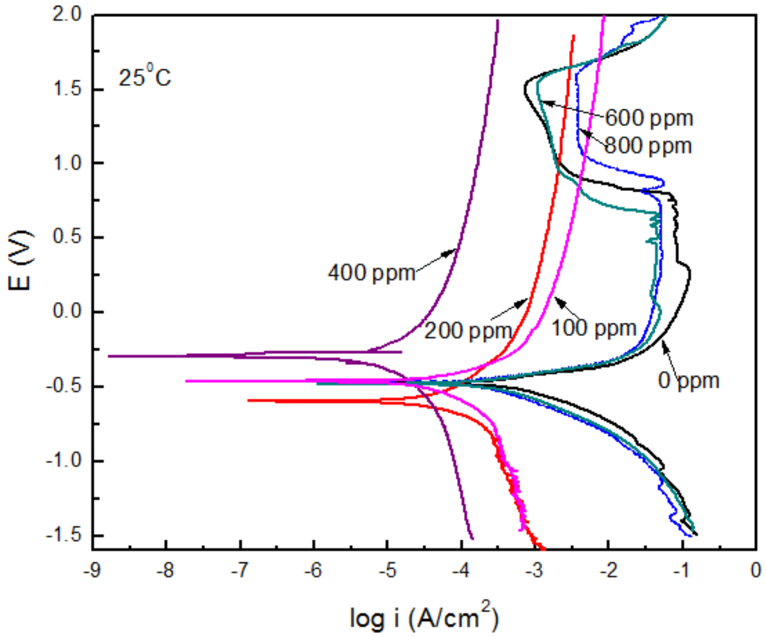


Figure 4. Polarization curves for 1018 CS in 0.5 M H_2SO_4 without and with various concentrations of *Allium sativum* at 25 ± 0.1 °C (Rodriguez *et al*., 2014).

Electrochemical impedance spectroscopy (EIS) study

AC impedance spectra (EIS) have been used to confirm the formation of protective film on the metal surface. The effect of various concentrations *of Allium sativum* on Nyquist diagrams for CS in 0.5 M H_2SO_4 at 25 ^{0}C is shown in **Figure 5** (Rodriguez *et al*., 2014). Nyquist diagrams show that data display a single capacitive like, depressed semicircle with its center in the real axis at all frequency values, **Figure 5**, which indicate that the corrosion process is under charge transfer control from the steel to the electrolyte through the double electrochemical layer. As the inhibitor concentration increases the semicirclediameter increases reaching its maximum value with the addition of 400 ppm, but it decreases with a further increase in the inhibitor concentration (Rodriguez *et al*., 2014).

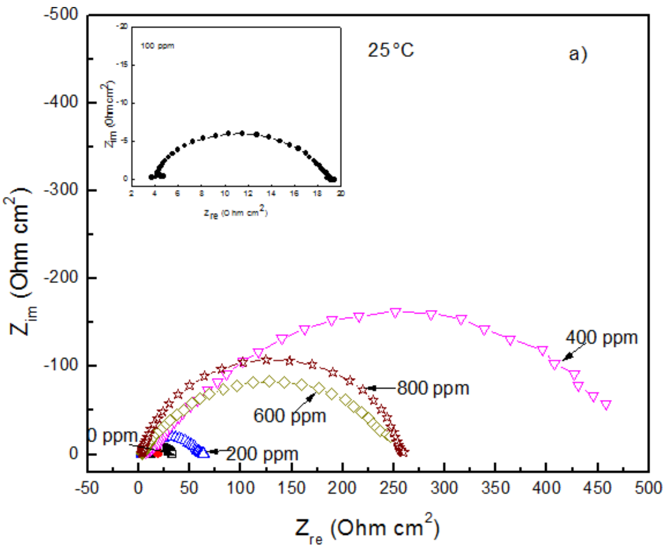


Figure 5. Nyquist diagrams for 1018 CS in 0.5 M H_2SO_4 in absence and presence of different concentration of *Allium sativum* at 25^{0}C (Rodriguez *et al*., 2014).

X -Ray diffraction (XRD) study

X-ray diffraction patterns of the corrosion products on the brass alloy surface with and without the addition of the inhibitor (Garlic extract) in the 1 M HNO_3 solution is shown in **Figure 6** (Raeisi *et al.,* 2024). As shown in Fig. 6, it is observed that the two different phases are identified on the surface sample without the inhibitor. One of the mention phases, is the dominant phase, a rhombohedral crystal structure, the diffraction planes of the (111), (200), and (220) are observed at the angles of the 42.4, 49.3, and 72.4°, respectively. The second phase identified in this sample is the copper nitrate phase and has a monoclinic crystal structure, which belongs to the I2/c space group. In this structure, the diffraction planes of (202) and (404) can be seen at the angles of the 15.2 and 30.7°, respectively.

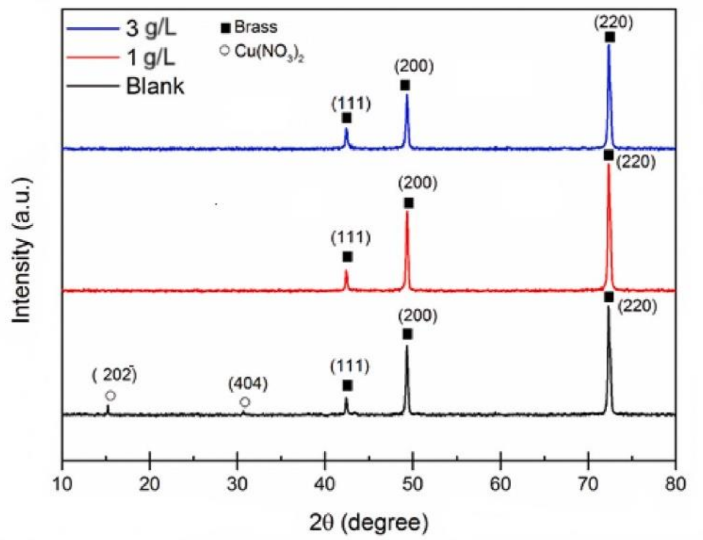


Figure 6. X-ray diffraction patterns related to the samples of the brass alloy immersed in HNO_3 solution without and containing 1 and 3 *g/L* inhibitor (Raeisi *et al.,* 2024).

Furthermore, the results of the XRD analysis can been proved both the formation of a barrier layer due to the adsorption of the inhibitor (Garlic extract) on the alloy surface (Raeisi *et al.,* 2024).

2.8 *Quantum chemical studies*

The quantum chemical parameters were estimated by AM1 method. The optimized minimum energy geometrical configurations of test compounds are given in **Figure 7** (Yaro *et al.,* 2014).
It has been well documented in literature that (Ma *et al.,* 2006) higher the value of E_{HOMO} of the inhibitor, greater is the ease of inhibitor to offer electrons to unoccupied d-orbital of metal atom and higher is the I. E. of the inhibitor. Further lower the E_{LUMO}, easier is the acceptance of electrons from the metal surface (Obot *et al.,* 2009). The gap between HOMO–LUMO energy levels of molecules was another important parameter that needs to be considered. Smaller the value of ΔE of an inhibitor, can indicate a good stability of the formed complex on the metal surface (Xia *et al.,* 2008), therefore give higher I.E. of that inhibitor (Gao *et al.,* 2007).

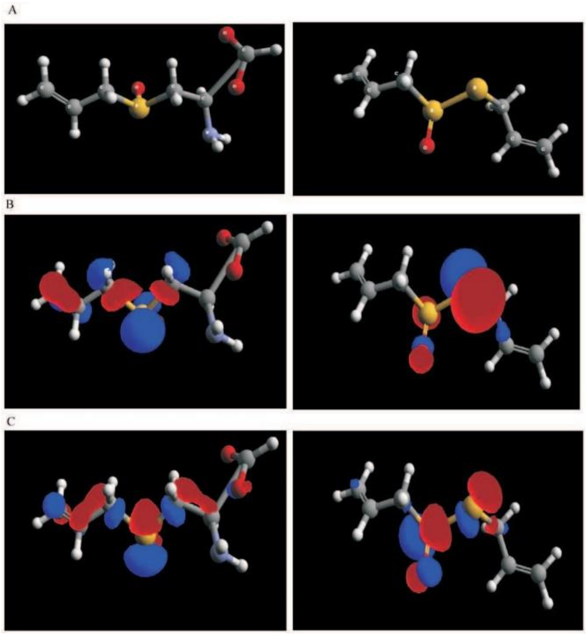
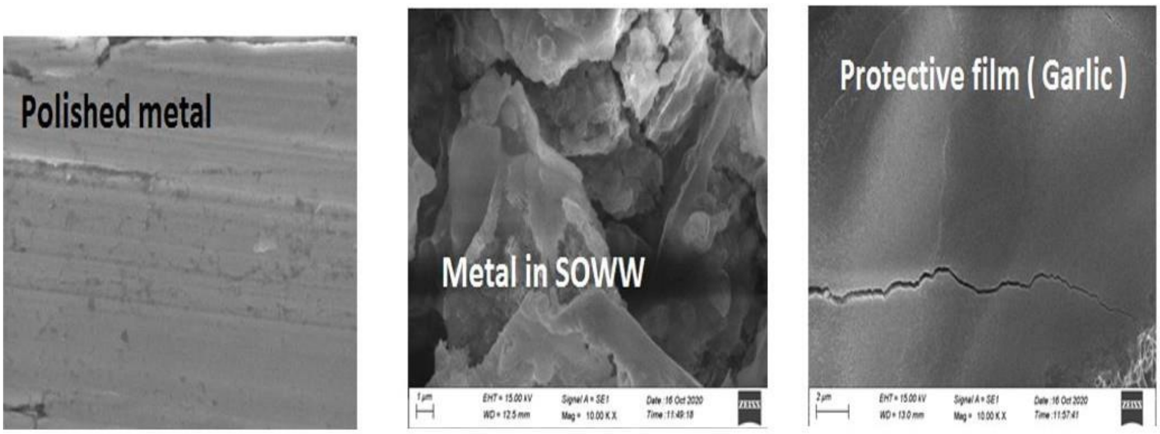


Figure 7. A: Optimized geometry of Alliin and Allicin, B: HOMO distribution, C: LUMO distribution (Yaro *et al*., 2014).

Scanning electron microscopy (SEM) study

Joycee et al. (Joycee *et al*., 2021) studied SEM micrographs of the corroded MS in the presence and absence of simulated oil well water (SOWW) before and after addition of garlic as an inhibitor was shown in **Figure 8**. The SEM micrograph of **Figure 8(a)** shows the smooth surface of MS without any corrosion product on the metal surface. Inspection of **Figure 8(b)** reveals that the MS immersed in SOWW shows an aggressive attack of the corroding medium on the steel surface. In contrast, in the presence of 10 ml. *Allium sativum* and 50 ppm Zn^{2+} the MS surface coverage increases which in turn results in the formation of insoluble complex on the metal surface (*Allium sativum* + Zn^{2+} inhibitor complex) **Figure 8(c)** (Joycee *et al*., 2021, Sangeetha *et al*., 2015).



a **b** **c**

Figure 8. SEM micrographs of (a) Polished MS; (b) MS immersed in SOWW; (c) MS immersed in SOWW containing 10 mL *Allium sativum* and 50 ppm Zn^{2+} (Joycee *et al*., 2021).

This is attributed to the involvement of the compounds in the interaction with the active sites of metal surface; this reduces the contact between metal and the aggressive medium, it might be concluded so that the adsorption film can efficiently inhibit the corrosion.

Phytochemical constituents of Allium sativum (Garlic)

Garlic contains a higher concentration of sulphur compounds than any other *Allium* species (Al-Mhyawi *et al.*, 2014, Loto *et al*., 2016a, Loto *et al*., 2016b, Loto *et al*., 2016c). Garlic contains at least 33 sulphur compounds like alliin, allicin (diallyl thiousulphinate or diallyl disulphide), diallyl sulphide, ajoene, dithiins, allylpropl, diallyl trisulphide, S-allyl cysteine, vinyl dithiines, S-allyl mercapto cystein, and others (Loto *et al*., 2016a, Loto *et al*., 2016b). Besides sulphur compounds garlic contains 17 amino acids and their glycosides, arginine and others. The molecular structure of these compounds shows the presence of many hetero atoms and double bonds. Garlic also contains minerals such as selenium (Se), zinc (Zn), iron (Fe) and magnesium (Mg), and enzymes, such as allinase, peroxidase and myrosinase (Al-Mhyawi *et al.*, 2014, Ali *et al*., 2019, Block *et al.*, 1985). It is known to consist of calcium, Vitamin C, Vitamin B-6. It also contains protein, carbohydrates, potassium and sodium among many others. With the major chemical constituents, garlic contains 0.1-0.36% of a volatile oil (Loto *et al*., 2016a, Loto *et al*., 2016b). The two major compounds in aged garlic, S-allyl cysteine and S-allyl mercapto-L-cysteine, had the highest radical scavenging activity (Loto *et al*., 2016b, Loto *et al*., 2016c). In addition, some organo sulphur compounds derived from garlic, including S-allyl cysteine, have been found to have significant medical value (Motteshard *et al.*, 2016). Water-soluble compounds include cysteine derivatives, such as S-allylcysteine (SAC), S-allyl mercapto cysteine (SAMC) and S-methyl cysteine, and gamma-glutamyl cysteine derivatives (Loto *et al*., 2016a, Loto *et al*., 2016c, Kyolic *et al*., 2015).

Mechanism of corrosion inhibition by *Allium sativum*

The molecular structures of main constitutes of *Allium sativum* are shown in **Figure 9**.

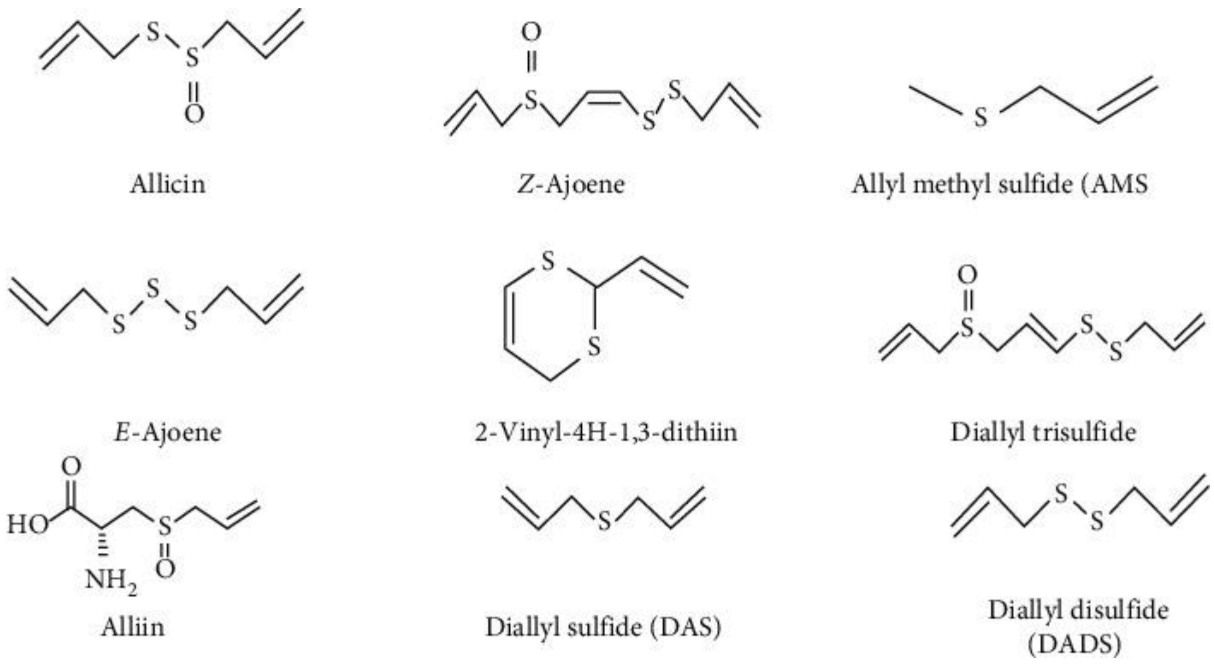


Figure 9. Structure of the main constituents of *Allium sativum* extract (Tesfaye *et al*., 2021).

The composition of garlic is very complex. Garlic consists among others, of sulphur (S), nitrogen (N), and oxygen (O) and double bonds, and also unsaturated π electron bonds (Raeisi *et al.*, 2024, Loto *et al.*, 2016b, Loto *et al*., 2016c). The Hetero atoms that induce non-bonding pair or lone pair and then they react with the vacant d-orbitals of the surface of metal and form a complex barrier layer (Raeisi *et al.*, 2024) which can be separated the surface of metal from the corrosive environment. Since the *Allium sativum* extract contains many organic compounds, it is very difficult to attribute the inhibitive activity to any one of these compounds. The inhibitive activity of the extract is attributed to the combined action of all the compounds present in the extract.

The I.E. of an inhibitor such as garlic extract, therefore, depends not only on the characteristic of the environment in which it acts and the nature of the metal surface. It also depends on the structure of the inhibitor itself which has been described to include the number of adsorption active centers in the molecule, the charge density, the molecular size, the mode of adsorption and the formation of metallic complexes (Chetouani *et al*., 2005). The high inhibitive performance of this extract suggests a strong bonding of the *Allium sativum* derivatives on the metal surface due to presence of lone pairs from heteroatom (oxygen) and p-orbitals, blocking the active sites and therefore decreasing the corrosion rate.

Conclusion

In this review, various research works on corrosion inhibition of various metals in different acidic, neutral and alkaline media by *Allium sativum* as green inhibitor was presented. The percentage I.E of inhibitors was calculated using WL, PDP and EIS methods. Other methods like SEM, FT-IR, AFM), UV-Vis. Spectroscopy, AFM, EDS and EDX were also used to study the nature of surface film produce on metals. Langmuir and Temkin adsorption isotherms were observed. *Allium sativum* extract behaved as anodic, cathodic or mixed-type of inhibitor. Plant extracts obtained corrosion I.E. above 53.0 %, most of them around 75.0 to 100.0 % (WL). Results obtained from WL data were in good agreement with the results obtained from PDP and EIS methods.

Disclosure statement

Conflict of Interest: The author declares that there are no conflicts of interest.

Compliance with Ethical Standards: This article does not contain any studies involving human or animal subjects.

References

Afia, L., Benali, O., Salghi, R., Ebenso E.E., Jodesh S., Zougagh M, Hammouti B. (2014) Steel Corrosion Inhibition by Acid Garlic Essential Oil as a Green Corrosion Inhibitor and Sorption Behavior, *Int. J. Electrochem. Sci*., 9, 8392 – 8406.

Al-Mhyawi S. R. (2014) Corrosion inhibition of Aluminum in 0.5 M HCl by garlic aqueous extract, *Orien. J. Chem*., 30(2), 541-552, http://dx.doi.org/10.13005/ojc/300218.

Ali M. and Ibrahim I. (2019) Phytochemical screening and proximate analysis of Garlic (Allium Sativum). *Arch of Organ. and Inorgan. Chem. Sci*., 4, 478-482. https://doi.org/10.32474/AOICS.2019.04.000180.

Asfia M.P., Rezaei M., Bahlakeh G. (2020) Corrosion prevention of AISI 304 stainless steel in hydro chloric acid medium using garlic extract as a green corrosion inhibitor: electrochemical and theoretical studies, *J. Mol. Liq*., 315, 113679. https://doi.org/10.1016/j.molliq.2020.113679.

Block E. (1985) The chemistry of garlic and onions. *Scientific American*, 252, 114-119. https://doi.org/10.1038/scientificamerican0385-114

Barreto L. S., Tokumoto M. S., Guedes I. C., de Melo H.G., Rico Amado F. D. and Capelossi V. R. (2017) Evaluation of the anticorrosion performance of peel garlic extract as corrosion inhibitor for ASTM 1020 carbon steel in acidic solution, *Revista Matéria*, 22(3), https://doi.org/10.1590/S1517-707620170003.0186

Belkaid S., Hamdani S. and Mansour D. (2022) Garlic Extract as an Environmentally Corrosion Inhibitor of API X60 Carbon Steel and 316L Stainless Steel in Sulphuric Acid, *Port. Electrochim. Acta*, 40, 259-272. https://doi.org/10.4152/pea.2022400403

Bouyanzer A., Bouklah M., Chetouani A., et al. (2017), Valorization of essential oil and extracts of Artemisia herba alba in the inhibition of corrosion and antibacterial and other effects-Review, *Arab. J. Chem. Environ. Res.* 04, 31-45

Chetouani A., Hammouti B., Benhadda T. and Daoudi M. (2005) Inhibitive Action of Bipyrazolic Type Organic Compounds towards Corrosion of Pure Iron in Acidic Media, *Appl. Surf. Sci.*, 249(8), 375-385. http://dx.doi.org/10.1016/j.apsusc.2004.12.034

Cojocaru A., Maior I., Vaireanu D., Lingvay I., Lingvay C. and Caprarescu S. (2009) Estimation of Inhibition Efficiency for Carbon Steel Corrosion in Acid Media by Using Natural Plant Extracts, *Rev. Chim. (Bucureºti)*, 60(11), 1175-1180. https://doi.org/10.37358/Rev.Chim.1949.

Devikala S., Kamaraj P., Arthanareeswari and Patel M. B. (2019) Green corrosion inhibition of mild steel by aqueous Allium sativum extract in 3.5% NaCl. *Mater Today Proc.*, 14, 580-589. https://doi.org/10.1016/j.matpr.2019.04.182.

Devi B. S. and Rajendran S. (2011) Influence of garlic extract on the inhibition efficiency of sodium citrate—Zn^{2+} system, *Int. J. of Chem. Sci. and Tech.*, 1, 79–87.

El Hosary A. A., Saleh R. M. and Shams El Din, A. M. (1972) Corrosion inhibition by naturally occurring substances-I. The effect of Hibiscus subdariffa (Karkade) extract on the dissolution of Al and Zn, *Corro. Sci.*, 12(12), 897-904. https://doi.org/10.1016/S0010-938X(72)80098-2

El-Etre A.Y. (1988) Natural honey as corrosion inhibitor for metals and alloys. I. copper in neutral aqueous solution, *Corros. Sci.*, 40(11), 1845-1850.

El Ouafi A., Hammouti B., Oudda H., Kertit S., Touzani R., Ramdani A. (2002), New pyrazole derivatives as effective Inhibitors for the corrosion of mild steel in HCl medium, *Anti-Corros. Meth. Mater.* 49 N°3, 199-204. https://doi.org/10.1108/00035590210426463

Esmailzadeh S., Aliofkhazraei M., Sarlak H. (2018) Interpretation of Cyclic Potentiodynamic Polarization Test Results for Study of Corrosion Behavior of Metals: A Review, *Prot. Met. Phys. Chem. Surf.*, 54. 976- 989. https://doi.org/10.1134/S207020511805026X

Fouda A. S., Attia A. A. and Ghoneim S. M. (2015). Allium sativum (Garlic) as green corrosion inhibitor for low carbon steel in HCl solutions, *J. Electrochem. and Plating Tech.*, http://dx.doi.org/10.12850/ISSN2196-0267.JEPT4166.

Gad Allah A. G. and Mostafa H. (1992). Quantum mechanical calculations of amino pyrazole derivatives as corrosion inhibitors for zinc, copper and α-brass in acid chloride solution, *J. Appl. Electrochem.*, 22, 644-648. https://doi.org/10.1007/BF01092613

Gao, G. and Liang, C. (2007) Electrochemical and DFT studies of β-amino-alcohols as corrosion inhibitors for brass, *Electrochim. Acta*, 52 (13), 4554-4559. https://doi.org/10.1016/j.electacta.2006.12.058

Getti G. T. M. and Poole P. L. (2019) Allicin causes fragmentation of the peptidoglycan coat in Staphylococcus aureus by effecting synthesis and aiding hydrolysis: A determination by MALDI-TOF mass spectrometry on whole cells, *J. Med. and Microb*., 68, 667-677. https://doi.org/10.1099/jmm.0.000950.

Hajsafari N., Razaghi Z. and Tabaian S. H. (2021) Electrochemical study and molecular dynamics (MD) simulation of aluminum in the presence of garlic extract as a green inhibitor, *J. Mol. Liq.*, 336, 116386. https://doi.org/10.1016/j.molliq.2021.116386.

Hbika, A., Bouyanzer, A., Jalal, M., Setti, N., Loukili, E., Aouniti A., et al. (2023). The Inhibiting Effect of Aqueous Extracts of Artemisia Absinthium L. (Wormwood) on the Corrosion of Mild Steel in HCl 1 M, *Analytical and Bioanalytical Electrochemistry*, 15(1), 17-35. https://doi.org/10.22034/abec.2023.701392

James A. O., Oforka N. C. and Abiola K. (2007) Inhibition of Acid Corrosion of Mild Steel by Pyridoxal and Pyridoxol Hydrochlorides., *Int. J. Electrochem. Sci*., 2, 278-284. https://doi.org/10.1016/S1452-3981(23)17073-8

Joycee S. C., Raja A. S., Amalraj A. S. and Rajendran S. (2021) Inhibition of corrosion of mild steel pipeline carrying simulated oil well water by Allium sativum (garlic) extract, *Int. J. Corros. Scale Inhib.*, 10(3), 943–960. https://doi.org/10.17675/2305-6894-2021-10-3-8

Karthiga N., Rajendran S., Prabhakar P., Al-Hashem A. and Shanmugapriya S. (2018) Corrosion inhibition of mild steel by an aqueous extract of Allium sativum, *European J. Biomed. and Pharma. Sci.*, 5(2), 838-843. http://www.ejbps.com

Kyolic, www.kyolic.com, Chemistry of Garlic – Key Compounds in Garlic. November 29, 2007. Retrieved 26th Dec., 2015.

Kumar H., Yadav V., Sourav A. Kr. and Kang S. N. (2021) Adsorption and inhibition mechanism of efficient and environment friendly corrosion inhibitor for mild steel: Experimental and theoretical study, *J. Mol. Liq.*, 338, 116634, https://doi.org/10.1016/j.molliq.2021.116634.

Lakshmi P. S., Chitra A., Rajendran S. and Anuradha K. (2005) Corrosion behavior of aluminum in rain water containing Garlic extract, *Surf. Eng.*, 21(3), 229-231. https://doi.org/10.1179/174329405X50073.

Loukili H., Azzaoui K., Bouyanzer A., et al. (2023) Corrosion Inhibition using Green Inhibitors: An Overview, *Maghrebian Journal of Pure and Applied Science*, 8 (2), 82-93

Loto C. A., Loto R. T. and Oshogbunu O. J. (2016a) Effect of Allium Sativum Extracts on the Corrosion and Inhibition of α-Brass in HCl. *Mor. J. Chem.*, 4(3), 711-721. https://doi.org/10.48317/IMIST.PRSM/morjchem-v4i3.4961.

Loto C. A., Loto R. T. and Oshogbunu O. J. (2016b) Corrosion inhibition effect of Allium sativum extracts on mild steel in HCl and H_2SO_4, *J. Chem. and Pharm. Res.*, 8(2), 216-230. http://eprints.covenantuniversity.edu.ng/7307/#.X K8Z95hKjIU.

Loto C. A. and Loto R. T. (2016c) Inhibition effect of garlic extracts on the corrosion of alpha brass in nitric acid. *Der Pharma Chem.*, 8(2), 162-171. http://derpharmachemica.com/archive.html.

Londhe V. P., Gavasane A.T., Nipate S. S., Bandawane D. D. and Chaudhari P. D. (2011) Role of garlic (*Allium sativum L.*) in various diseases: an overview, *J. Pharm. Res. and Opinion*, 1(4), 129-134. http://www.innovativejournal.in/index.php/jpro.

Ma H., Chen S., Liu Z. and Sun Y. (2006) Theoretical elucidation on the inhibition mechanism of pyridine-- pyrazole compound: A Hartree Fock study, *J. Mol. Struct. (Theochem*), 774(1), 19–22.

Maestro C. A. R., Malafaia A. M. S., Silva C. F., Nascimento Jr. C. S., Borges K. B., Simões T. A., Capelossi V. R. and Bueno A. H. S. (2023) Corrosion resistance improvement of mild steel in different pH using peel garlic green inhibitor, *Mater. Chem. and Phy.*, 305, 127971. https://doi.org/10.1016/j.matchemphys.2023.127971.

Mayowa L. C., Alfred A. A., Grace K. T. (2020) Mitigating Corrosion in Mild Steel Using Garlic (Allium Sativum) as Corrosion Inhibitor in HCl Medium, Journal of Multidisciplinary Engineering Science and Technology (JMEST), Vol. 7 (8), 2020, 12545-12550.

Meredith, Ted Jordan and Drucker, Avram. (2014) Growing Garlic from True Seed, *Garlic Analecta*. Retrieved May 24, 2014.

Mzioud K., Habsaoui A., Ouakki M., Galai S., El Fartah M. and Touhami E. (2020) Inhibition of copper corrosion by the essential oil of Allium sativum in 0.5 M H_2SO_4 solutions, *SN Appl. Sci.*, 2(9), 1611 https://doi.org/10.1007/s42452-020-03393-8

Motteshard T. D. (2016) Garlic: Garlic Chemical Constituents of Garlic Natural Healing with Herbs for a Healthier You, *www.herballegacy.com/Motteshard_Chemical.html*, Retrieved: 2-04-2016

Nakamoto M., Kunimura K., Suzuki J. I. and Kodera Y. (2020) Antimicrobial properties of hydrophobic compounds in garlic: Allicin, vinyldithiin, ajoene and diallyl polysulfides (Review), *Experim. and Therap. Med.*, 19(2), 1550-1553. https://doi.org/doi.org/10.3892/etm.2019.8388 .

Obot I. B., Obi-Egbedi N. O. and Umoren S. A. (2009) The synergistic inhibitive effect and some quantum chemical parameters of 2,3-diaminonaphthalene and iodide ions on the hydrochloric acid corrosion of aluminium, *Corros. Sci.*, 51(2), 276–282. https://doi.org/10.1016/j.corsci.2008.11.013

Ojha L. K., Kaur R., Saharan H. and Bhawsar J. (2018) Effect of Allium sativum Extracts on Mild Steel in 1 M HCl-An Eco-friendly Corrosion Inhibitor, *Der Pharma Chemica*, 10(S1), 7-14. http://www.derpharmachemica.com/archive.html

Ojha L. K., Tüzün B. and Bhawsar J. (2020) Experimental and Theoretical Study of Effect of Allium sativum Extracts as Corrosion Inhibitor on Mild Steel in 1 M HCl Medium, *J. Bio and Tribo-Corros.*, 6, Article No. 39, https://doi.org/10.1007/s40735-020-00336-z.

Okafor P. C., Ekpe U. J., Ebenso E. E., Umoren E. M. and Leizou K.E. (2005) Inhibition of mild steel corrosion in acidic medium by Allium sativum extracts. *Bull. Electrochem.*, 21(8), 347-352. https://www.researchgate.net/publication/28838166

Oguzie E. E., (2008), Evaluation of the inhibitive effect of some plant extracts on the acid corrosion of mild steel, Corrosion Science, Volume 50, Issue 11, 2993-2998, ISSN 0010-938X, https://doi.org/10.1016/j.corsci.2008.08.004

Papavinasam S. (2011) Corrosion Inhibitors. In Uhlig's Corrosion Handbook; Revie, R.W., Ed.; John Wiley & Sons Inc.: Hoboken, NJ, USA, 1021–1032. ISBN 978-0-470-87286-4. https://doi.org/10.1002/9780470872864.ch71

Tebbji K., Bouabdellah I., Aouniti A., Hammouti B., Oudda H., Benkaddour M., Ramdani A. (2007), N-benzyl-N,N-bis[(3,5-dimethyl-1H-pyrazol-1-yl)methyl]amine as corrosion inhibitor of steel in 1 M HCl, *Mater. Let.* 61N°3, 799-804. https://doi.org/10.1016/j.matlet.2006.05.063

Parthipan P., Elumalai P., Narenkumar J., Machuca L., Murugan K., Karthikeya O. P. and Rajasekar A. (2018) *Allium sativum* (garlic extract) as a green corrosion inhibitor with biocidal properties for the control of MIC in carbon steel and stainless steel in oilfield environments, *Int. Biodeter & Biodegrad.*, 132, 66-73, https://doi.org/10.1016/j.ibiod.2018.05.005.

Pasupathy A., Nirmala S., Sakthivel P., Abirami G. and Raja M. (2014) Inhibitive Action of *Allium Sativum* Extract on the Corrosion of Zinc in 0.5N H_2SO_4 Medium, *Int. J. Sci. and Res. Publ.*, 4(2), 1-4.

Pereira S. S. A. A., Pêgas M. M., Fernández T. L., Magalhães M., Schöntag T. G., Lago D. C., de Senna L. F. and D' Elia E. (2012) Inhibitory action of aqueous garlic peel extract on the corrosion of carbon steel in HCl solution, *Corros. Sci.*, 65, 360-366. https://doi.org/10.1016/j.corsci.2012.08.038.

Prabakaran M., Kim S. H., Hemapriya V. et al. (2016) Rhus verniciflua as a green corrosion inhibitor for mild steel in 1 M H_2SO_4, *RSC Adv.*, 6(62), 57144-57153

Raghavan B., Abraham K. 0. and Shankaranarayana M. L. (1983) Chemistry of garlic and garlic products, *J. Sci. Ind. Res.*, 42, 401-409.

Raeisi S. and Yousefpour M. (2024) The electrochemical study of the garlic extracts as a corrosion inhibitor for brass in the nitric acid solution, *Mater. Chem. and Phy.*, 312, 1-13, 128516. https://doi.org/10.1016/j.matchemphys.2023.128516.

Richardson J. A. (2009) Management of Corrosion in the Petrochemical and Chemical Industries. In Shreir's Corrosion; Elsevier: Amsterdam, The Netherlands, 201, 3207–3229. ISBN 978-0-444-52787-5.

Rodriguez-Clemente E., Gonzalez-Rodriguez J. G., Valladares-Cisneros M. G. and Chacon-Nava J. G. (2015) Evaluation of Allium sativum as corrosion inhibitor for carbon steel in sulphuric acid under hydrodynamic conditions, *Green Chem. Letters and Rev.*, 8(2), 49-58, https://doi.org/10.1080/17518253.2015.1071435.

Rodriguez E. C., Gonzalez J. G. R. and Valladares M. G. C. (2014) Allium sativum as Corrosion Inhibitor for Carbon Steel in Sulfuric Acid, *Int. J. Electrochem. Sci.*, 9 (11), 5924–5936. https://doi.org/10.1016/S1452-3981(23)10859-5

Rajam K., Rajendran S. and Saranya R. (2013) Allium Sativum (Garlic) Extract as Nontoxic Corrosion Inhibitor, *J. Chem.*, 743-807. http://dx.doi.org/10.1155/2013/743807.

Rajam K., Rajendran S., Manivannan M. and Saranya R. (2012) Corrosion inhibition by Allium sativum (garlic) extract, *J. of Chem., Bio. and Phy. Sci.*, 2(3), 1223-1233.

Salim R., Azzaoui K., Loukili E. H., Ech-chihbi E. (2022) Green corrosion inhibitors of carbon steel in acid medium: Plant extracts, *J. Appl. Sci. Envir. Stud.* 5(2), 75-86

Sangeetha M., Rajendran S., Sathiyabama J., Umasankareswari T., Krishnaveni A. and Joany R. M. (2015) Corrosion inhibition by flower extracts: an overview, *Int. J. Nano Corr. Sci. Eng.*, 2(3), 14-21.

Serbout J., Touzani R., Bouklah M., Hammouti B. (2021), An insight on the corrosion inhibition of mild steel in aggressive medium by henna extract, *Int. J. Corros. Scale Inhib.*, 10(3), 1042–1068

Subroto E., Cahyana Y., Tensiska M., Filianty F., Lembong E., Wulandari E., Kurniati D., Saputra R.A. and Faturachman F. (2021) Bioactive compounds in garlic (Allium sativum L.) as a source of antioxidants and its potential to improve the immune system: a review, *Food Res.*, 5, 1-11. https://doi.org/10.26656/fr.2017.5(6).042

Tesfaye A. (2021) Revealing the Therapeutic Uses of Garlic (*Allium sativum*) and Its Potential for Drug Discovery, *Scientific World J.*, 8817288. https://doi.org/10.1155/2021/8817288

Verma C., Ebanso E., Bahadur I. and Quraishi M. A. (2018) An overview on plant extracts as environmental sustainable and green corrosion inhibitors for metals and alloys in aggressive corrosive media. *J. Mol. Liq.*, 266, 577-590. https://doi.org/10.1016/j.molliq.2018.06.110

Wang H. P., Yang J. and Qin L. Q. (2015) Effect of Garlic on Blood Pressure: A Metal Analysis, *J. Clin. Hypertens*., 17(3), 223-231. DOI: https://doi.org/10.1111/jch.12473..

Xia S., Qiu M., Yu L., Liu F. and Zhao H. (2008) Molecular dynamics and density functional theory study on relationship between structure of imidazoline derivatives and inhibition performance. *Corros. Sci.*, 50, 2021–2029. DOI:10.1016/j.corsci.2008.04.021

Yang B., Chen W., Mu D.H. (2014) Study of garlic extract as a green corrosion inhibitor for mild steel in acidic media, *Adv. Mater. Res.*, 960-961, 118-125. DOI:10.4028/www.scientific.net/AMR.960-961.118

Yaro A. S., Khadom A. A. and Wael R. K. (2014) Garlic Powder as a Safe Environment Green Corrosion Inhibitor for Mild Steel in Acidic Media; Adsorption and Quantum Chemical Studies, *J. Chin. Chem. Soc*., 61, 615-623. DOI: 10.1002/jccs.201300480.

Zarrok H., Oudda H., El Midaoui A., Zarrouk A., et al. (2012) Some New Bipyrazole Derivatives as Corrosion Inhibitors for C38 Steel in Acidic Medium, *Res. Chem. Interm.,* 38 N°8, 2051-2063. *Res Chem Intermed* 38, 2051–2063 DOI 10.1007/s11164-012-0525-x

Zarrouk A., Hammouti B., Al-Deyab S.S., et al. (2012), Corrosion Inhibition Performance of 3,5-Diamino-1,2,4-triazole for Protection of Copper in Nitric Acid Solution, *Int. J. Electrochem. Sci.,* 7 N°7, 5997-6011. https://doi.org/10.1016/S1452-3981(23)19457-0

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