J. Mater. Environ. Sci., 2025, Volume 16, Issue 6, Page 1008-1028

Journal of Materials and Environmental Science ISSN : 2028-2508 e-ISSN : 2737-890X CODEN : JMESCN Copyright © 2025, University of Mohammed Premier Oujda Morocco

http://www.jmaterenvironsci.com



Moringa oleifera as an Eco-friendly Corrosion Inhibitor for Protection of Metals and Alloys-A Review

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Received 07 Apr 2025, **Revised** 09 May 2025, **Accepted** 11 May 2025

Keywords:

- ✓ Corrosion inhibition;
- 🗸 Moringa oleifera
- ✓ WL;
- ✓ Electrochemical methods;
- ✓ SEM

Citation: Vashi R. T., (2025) Moringa oleifera as an Ecofriendly Corrosion Inhibitor for Protection of Metals and Alloys-A Review, J. Mater. Environ. Sci., 16(6), 1008-1028

1. Introduction

Abstract: Corrosion is the deterioration of a metal by a chemical attack or reaction with its environment. Moringa oleifera can control the corrosion of various metals and alloys, such as aluminum, carbon steel, mild steel, stainless steel, copper and zinc. Various techniques like the weight loss (WL) method with time and temperature, Electrochemical methods such as Potentiodynamic polarization (PDP) and electrochemical impedance spectroscopy (EIS) have been used to evaluate the corrosion inhibition efficiency (I.E.) of Moringa oleifera. The protective film has been analyzed by Fourier-transform infrared spectroscopy (FT-IR), Gas chromatography mass spectroscopy (GC-MS), UV-visible spectroscopy (UV-Vis.) and Scanning electron microscopy (SEM) methods. Adsorption of Moringa oleifera on metal surfaces obeys the Langmuir, Frumkin or Temkin isotherms depending on the nature of metal and the corrosive environment. A polarization study reveals that Moringa oleifera can function as cathodic or mixed type of inhibitor.

Corrosion is defined as the deterioration of a metal due to its interaction with the environment. Due to corrosion, many useful properties of a metal, such as malleability, ductility and electrical conductivity, are lost. It is a permanent and persistent problem that cannot be eliminated completely. Prevention is more realistic and achievable than total elimination. Corrosion is therefore one of the significant problems that must be confronted for the safety of our environment and economic reasons (Finsgar *et al.*, 2014; Ouafi *et al.*, 2002), making the investigation of metallic corrosion a subject of immense conceptual and practical concern that has expectedly received a substantial amount of interest (Chukwukere *et al.*, 2020). According to the recent estimation of the NACE (National Association of Corrosion Engineers), the global cost of corrosion is around US\$2.5 trillion, constituting about 3.5% of the world's GDP (Scheme 1). The cost of corrosion may be of a direct or indirect type (Koch *et al.*, 2017; Verma *et al.*, 2018). The direct cost of corrosion includes repairing, storing and replacing the corroded metallic equipment, modifying alloys into metals and vice versa.

Mild steel is widely used in the industries, especially in the construction, metal extraction, oil drilling, and processing and distribution industries as holding tanks, boilers and pipelines. Aluminium and its alloys are finding wide applications in various industries such as automotive, aerospace, construction and electrical power generation due to high energy density. The electrochemical properties of zinc metal were utilized to a large extent. Its utilization in alkaline batteries (primary

alkaline zinc battery, secondary silver-zinc, and both primary and secondary zinc-air batteries) (Hughes *et al.*, 1983).



Scheme 1: Cost of Corrosion (<u>https://www.rustbullet.com/cost-of-corrosion/</u>)

Copper and its alloys are widely used materials for their excellent electrical and thermal conductivities in many applications, such as electronics, and recently in the manufacture of integrated circuits (Tsai et al., 2000). Copper is a relatively noble metal, requiring strong oxidants for its corrosion or dissolution. Acid solutions used in industrial processes, acid cleaning, removal of acid deposition, acid pickling and oil wells acidizing, require a corrosion inhibitor to prevent corrosion of metals (Idenyi et al., 2015b; Barouni et al., 2014; Left et al., 2013; Hammouti et al., 2011; Zarrouk et al., 2011). The use of inhibitors has been well documented as an effective method of protecting metallic materials from corrosion (Tosun et al. 2006). Corrosion inhibitors can be defined as a chemical substance that retards corrosion when added to an environment in small concentration without significantly changing the concentration of any other corrosive agent (Bradford, 1993, Sharma et al., 2008). Many synthetic compounds are highly toxic to both humans and the environment (Singh et al., 2012a; Ramya et al., 2016). The toxic effects associated with the evacuation of these materials have led to the development of other environmentally effective and acceptable inhibitors. Therefore, the recent trend is to look for environmentally friendly inhibitors. In most cases, the products are natural, non-toxic, biodegradable and readily available in many more. Various parts of the plants - seeds, fruits, leaves, flowers etc. have been used as corrosion inhibitors (Selvi et al., 2015, Kamaraj et al., 2014).

Moringa stands as the sole genus in the Moringaceae family of flowering plants (Noubissi *et al.*, 2022). In English it is commonly known as Horseradish tree, Drumstick tree, Never Die tree, West Indian Ben tree, and Radish tree (Ramachandran *et al.*, 1980). Among its various species, M. oleifera Lam (Moringa pterygosperma G.) is the most popular and widespread native to Pakistan, India, Bangladesh, and Afghanistan (Lim, 2012). Today it has become naturalized in many locations in the tropics and is widely cultivated in Africa, Ceylon, Thailand, Burma, Singapore, West Indies, Sri Lanka, India, Mexico, Malabar, Malaysia and the Philippines (Fahey, 2005). Moringa is a fast-growing, perennial tree which can reach a maximum height of 7-12 m and a diameter of 20-40 cm at chest height.

It can grow on sandy or loamy soil having relatively low humidity (Ndabigengesere *et al.*, 1995). The stem is normally straight but occasionally is poorly formed. The alternate, twice or thrice pinnate leaves grow mostly at the branch tips. They are 20-70 cm long, grayish-downy when young. The flowers, which are pleasantly fragrant, and 2.5 cm wide are produced profusely in axillary, drooping panicles 10 to 25 cm long. They are white or cream colored and yellow-dotted at the base (Morton, 1991). The fruits are three-lobed pods which hang down from the branches and are 20-60 cm in length. Each pod contains between 12 and 35 seeds. The seeds are round with a brownish semi-permeable seed hull. Moringa oleifera leaf and seed are shown in **Figure 1**.



Figure 1. Moringa oleifera leaf and seed

Traditional uses of Moringa oleifera

All parts of the Moringa oleifera tree-leaves, tender young capsules (pods), immature seeds, flowers, fruits and young roots are edible (Lim, 2012; Didouh et al., 2023). The leaves can be eaten fresh, cooked, or stored as dried powder for many months without refrigeration, and reportedly without loss of nutritional value. It is useful cosmetic, agricultural, and food industries (Hodas *et al.*, 2021). It is generally used in a number of developing countries as a vegetable, medical plant and a source of vegetable oil. It has an impressive range of medicinal uses with high nutritional value (Anwar et al., 2007). On the other hand, Moringa oleifera plants have been found to be a natural coagulant, flocculants, softener, disinfectant, and sludge conditioner (Nand et al., 2012; Suarez et al., 2023). Various parts of Moringa oleifera plant such as the leaves, roots, seed, bark, fruit, flowers and immature pods act as cardiac and circulatory stimulants, possess antitumor, antipyretic, antiepileptic, antiinflammatory, antiulcer, antispasmodic, diuretic, antihypertensive, cholesterol lowering, antioxidant, antidiabetic, hepatoprotective, anti-cancer, Antiulcer, antibacterial and antifungal activities. Antiproperties have shown receiving pain and the ability to heal wounds. In addition, the use of root barks as an analgesic, alexeteric, antihelminthic, and treatment of heart complaints, as well as for eye diseases, inflammation and indigestion (Anwar et al., 2007; Adejumo et al., 2012; Omotoso et al., 2016; Priadarshini et al., 2013; Shukla et al., 2015; Gopi et al., 2015).

2. Bibliometric analysis

Scopus has become an available basis for bibliometric analysis to visualize the most published authors, their affiliation and collaboration (Ansorge, 2024; Laita *et al.*, 2024; Chakir *et al.*, 2023; N'diaye *et al.*, 2022; Moral-Muñoz *et al.*, 2020). Search on Moringa gave more than 10,500 articles from 1866 to present, and 8670 articles on Moringa oleifera; but only 43 articles when Moringa is coupled to corrosion. The most cited (131 on Scopus and 220 on Scholar Google) exposed the corrosion Inhibition

of Carbon Steel in HCl Solution by Some Plant Extracts. Among the studied plants, *Moringa oleifera* extract exhibited an excellent inhibition of mild steel corrosion in 1 M HCl with 98% inhibition efficiency (Singh *et al.*, 2012a). Scheme 1 indicates the considerable increase in articles over the last years to reach more than 1100 in 2024. The first paper on Moringa was published in 1935 (Puri, 1935). He pointed out that this plant was first investigated in 1923 by F. L. Rutgers, who made some astonishing statements regarding the development of the embryo sac and embryo. He states that the archesporial cell is deep-seated in the nucellus and functions directly as the megaspore mother cell without cutting off parietal tissue. This natural plant has attracted researchers in different fields, such as Medicine, pharmacy, chemistry, Materials, etc., as shown in Scheme 2. Bibliometric analysis also indicated that India, Indonesia, China, Nigeria, Egypt, Brazil ... are the most countries interested in Moringa (Scheme 3).



Scheme 2 Repartition of fields interest on Moringa

Four Brazilian: Bergamasco R. (Scopus ID: 6603524191), Paiva P.M.G. (Scopus ID: 8508958800), Coêlho, L.C.B.B. (Scopus ID: 700671208) and Napoleão T.H. (Scopus ID: 55882735800) are the most published authors, followed by Tian Y. Scopus ID: 57214785405; the list is presented in **Scheme 4**.







Scheme 4. Most profiler authors

3. Methodology

Corrosion inhibition of different metals and alloys in various medium by Moringa oleifera as an inhibitor was shown in Table1.

Metal /	Medium +	Techniques used	Findings	I.E. max.	Reference
Alloy	Additive			(in %)	
Aluminium	$1 \text{ M H}_2 \text{SO}_4$	WL with	Langmuir adsorption	82.35 WL	Abdurrahman
		temperature.	isotherm.		et al., 2021
Aluminium	2 M HCl	WL with time and	Mixed type of	90.3 WL,	Fouda <i>et al.</i> ,
		temperature, PDP,	inhibitor, Langmuir	88.1 PDP,	2025
		EIS, EFM, AFM and	adsorption isotherm.	88.6 EIS	
		FT-IR.	_		
Al- Alloy	1 M NaOH	WL,PDP, EIS, SEM	Mixed type of	85.3 WL,	Chauby <i>et al.</i> ,
		and AFM.	inhibitor, Langmuir	86.5 PDP,	2017
			adsorption isotherm.	85.4 EIS	

Table 1. Corrosion inhibition of metals and alloys in different media by Moringa oleifera as an inhibitor.

Aluminium alloy- AA 8011	0.5 M HCl	WL with temperature, UV Vis and FT-IR	Langmuir adsorption isotherm.	94.0 WL	Nnanna <i>et</i> <i>al.</i> , 2014
Aluminium alloy- AA 8011	1 M HCl	WL with time, PDP, EIS.	Mixed type of inhibitor.	68.0 WL, 69.8 EIS.	Princewill et al., 2021
XC70 - Carbon Steel	1M HCl	WL with time and temperature.	Langmuir and Temkin adsorption isotherms.	97.60 WL	Allaoui <i>et al.</i> , 2020
Carbon Steel (Iron)	1M HCl	PDP, EIS.	Mixed-type of inhibitor, Langmuir, Frumkin and Temkin adsorption isotherms.	86.77 PDP, 84.20 EIS	Allaoui <i>et</i> <i>al.</i> , 2017
A36 Steel	Sea water	WL with time.	Efficient inhibitor.	78.71 WL	Desiasni et al., 2021
Copper	1 M mixture of (HNO ₃ + H ₃ PO ₄).	WL with time and temperature, PDP, EIS, EFM, AFM and SEM.	Mixed-type of inhibitor, Langmuir adsorption isotherm.	89.3 WL, 70.9 PDP, 89.4 EIS.	Fouda <i>et al.</i> , 2018
Copper	3 M HNO ₃	WL with temperature, PDP, EIS.	Mixed-type of inhibitor, Langmuir adsorption isotherm.	71.0 WL, 71.0 PDP, 72.0 EIS.	Savita <i>et al.</i> , 2015
Carbon Steel	1 M HCl	PDP, EIS.	Mixed type of inhibitor	98.6 PDP, 98.1 EIS	Singh <i>et al.</i> , 2012a
Carbon Steel	Sea water	PDP, FT-IR,	Mixed type of inhibitor.	70.47 PDP	Atan <i>et al.</i> , 2022
Carbon Steel	1 M HCl	WL with time and Temperature, PDP, EIS, FT-IR, AFM, EFM.	Mixed type of inhibitor, Langmuir adsorption isotherm.	91.7 WL, 85.3 PDP, 92.7 EIS.	Fouda <i>et al.</i> , 2020
Ductile Cast Iron	Cassava Fluid	WL with temperature, PDP.	Mixed type of inhibitor, Langmuir adsorption isotherm.	73.0 PDP	Olubunmi et al., 2020
Mild Steel	0.2 and 0.5 M HCl and 0.2 and 0.5 HNO ₃	WL with time.	Efficient inhibitor.	93.54 WL for 0.2 M HCl and 95.45 WL for 0.2 M HNO ₃	Garba <i>et al</i> ., 2021
Mild Steel	0.5 M H ₂ SO ₄	WL with temperature, FT-IR.	Langmuir, Temkin and Freundlich adsorption isotherms.	75.19 WL	Farhat <i>et al.</i> , 2022
Mild Steel	0.5 and 1.0 M H ₂ SO ₄	WL with time.	Efficient inhibitor.		Idenyi <i>et al.</i> , 2015a
Mild Steel	0.5 and 1.0 M H ₂ SO ₄	WL with time and Temperature, FT-IR, GC-MS.	Langmuir adsorption isotherm.	83.0 WL	Aspita <i>et al.</i> , 2015
Mild Steel	0.5 M H ₂ SO ₄	WL with time and Temperature, PDP, EIS, FT-IR, GC-MS, DFT, SEM, QCC, HOMO-LUMO.	Mixed-type of inhibitor, Langmuir adsorption isotherm.	96.03 WL, 66.0 PDP, 67.43 EIS.	Akalezi <i>et al.</i> , 2020

Mild Steel	1 M HCl	WL with time and temperature, PDP, EIS, FT-IR.	Mixed-type of inhibitor, Langmuir and Temkin adsorption isotherms.	98.2 WL, 98.1 PDP, 68.6 EIS	Singh <i>et al.</i> , 2010
Mild Steel	2 M HCl	WL with temperature, PDP, AAS, SEM, Rate- constant & Half-life	Mixed-type of inhibitor, Langmuir adsorption isotherm.	82.85 WL, 69.57 PDP.	Adebayo, 2024
Mild Steel	1 M HCl	WL with temperature.	Langmuir adsorption isotherm.		Jalajaa <i>et al</i> ., 2019
Mild Steel	H ₂ SO ₄	WL with temperature, PDP, EIS.	Mixed-type of inhibitor, Langmuir adsorption isotherm.		Jalajaa <i>et al</i> ., 2022
Mild Steel	1 M HCl	WL with time, PDP, EIS.	Mixed-type of inhibitor.	98.0 WL	Mejeh <i>et al.</i> , 2020
Mild Steel	HCl	WL with time.	Langmuir, Temkin and Frumkin adsorption isotherms	91.08 WL	Bam <i>et al.</i> , 2018
Mild Steel	1 M HCl	WL with time and temperature, PDP, EIS.	Mixed-type of inhibitor, Langmuir adsorption isotherm.	98.0 WL, 98.0 PDP, 99.0 EIS	Singh <i>et al.</i> , 2012b
Mild Steel	1 N H ₂ SO ₄	WL with time, PDP, EIS, FT-IR, SEM, EDX.	Mixed-type of inhibitor.	98.1 WL, 56.57 PDP, 64.0 EIS	Subasree <i>et al.</i> , 2018
Mild Steel	0.5 M HCl and 0.5 M H ₂ SO ₄	WL		84.9 WL in HCl & 97.2 WL in H ₂ SO ₄	Loto <i>et al.</i> , 2025
Mild Steel	1 & 2 N HCl and 1 & 2 N H ₂ SO ₄	WL	Efficient inhibitor.	97.0 WL WL in 2N HCl & 53.0 WL in 1 N H ₂ SO ₄	Selvi <i>et al.</i> , 2015
Mild Steel	0.5 and 1 M of H ₂ SO ₄ and NaOH	WL with time.	Efficient inhibitor.	74.0 WL in 1 M H ₂ SO ₄ & 63.0 WL 1 M NaOH	Adagashi et al., 2023
Mild Steel	1 M HCl and 1 M NaOH	WL with time.	Efficient inhibitor.	97.3 WL in 1 M HCl & 99.2 WL 1 M NaOH	Okpaga et al., 2021
Mild Steel	0.5 and 1 M NaOH	WL with time.	Efficient inhibitor.		Idenyi <i>et al.</i> , 2015b
Mild Steel	0.5 and 1 M NaOH	WL with time.	C. R. decreased by > 60% in the 0.5M NaOH and by > 80% in the 1.0M NaOH		Idu <i>et al.</i> , 2016
Mild Steel	Polymer from Coconut Shell	WL with time.	Efficient inhibitor.	91.79 WL	Sadiq <i>et al.</i> , 2024

API 5L	1 M HCl	WL with	Mixed-type of	99.0 PDP,	Didouh et
X52 Steel		temperature, PDP,	inhibitor, Langmuir	92.0 EIS.	al., 2023
		EIS, FT-IR, SEM,	adsorption isotherm.		
		UV-Vis.			
SS400	3 % NaCl	WL with time.	Efficient inhibitor.	43.06 WL	Nurhaeni et
Steel					<i>al.</i> , 2021
Stainless-	Artificial	PDP, EIS, SEM, FT-	Mixed-type of	91.2 PDP	Ikhmal et al.,
Steel-316 L	Sea water	IR	inhibitor.		2022
Reinforced	2 M HCl	WL with time, PDP.	Mixed-type of	95.45 WL,	Odusote et
Steel Bar			inhibitor.	81.58 PDP	al., 2016
Zinc	0.5, 1.0, 1.5,	Wl with	Langmuir adsorption	93.4 WL	Ugbe et al.,
	2.0 M HCl	temperature,	isotherm.	with KCl	2015
	+ 0.5 g/l	Synergistic effect.		and 95.2	
	KCl and KI			WL with KI	
				in 0.5M HCl	
Zinc	3.5 %	WL with time and	Mixed-type of	88.4 WL,	Fouda et al.,
	NaCl + 16	temperature, PDP,	inhibitor, Temkin	89.1 PDP,	2014
	ppm Na ₂ S	EIS, EFM .	adsorption isotherm.	88.6 EIS.	
Zinc	0.1-0.5 M	WL with time.	Efficient inhibitor.	67.5 WL	Dass et al.,
	HC1				2015

Abbrevations: AAS: atomic absorption spectroscopy, AFM: atomic force microscope, C.R.: corrosion rate, CS: carbon steel, EDS: energy dispersive spectroscopy, EIS: electrochemical impedance spectroscopy, EDX: energy dispersive X-ray analysis, EFM: Electrochemical frequency modulation, FT-IR: fourier-transform infrared spectroscope, GC-MS: gas chromatography mass spectrometry, I.E.: inhibition efficiency, MO: Moringa oleifera, PDP: potentiodynamic polarization, SEM: scanning electron microscopy, QCC: quantum chemical calculation, UV-Vis.: ultraviolet-visible spectrophotometry, WL: weight loss.

Gas chromatography mass spectrometry (GC-MS) study

Akalezi et al. (Akalezi *et al.*, 2020) studied corrosion inhibition of Mild Steel in 0.5 M H_2SO_4 acid solution in the presence of Moringer oliefera (MO) leaf extract as corrosion inhibitor. They carried out GC-MS spectra of the Moringer oliefera extract shown in Figure 2 which indicates various levels of peaks which revealed the presence of 29 different compounds.



Figure 2. GC-MS Chromatogram for the ethanol extract of M.O leaves (Akalezi et al., 2020).

Potentiodynamic polarization (PDP) Study

The polarization curves for mild steel in 1 N H_2SO_4 in the absence and presence of different concentrations Moringa oleifera are shown in **Figure 3** (Subasree *et al.*, 2018). There is no notable

difference in the corrosion potential (Ecorr) range attained in the absence and presence of inhibitor. The plots show linear shape at lower current densities due to protective layer formed on the metal surface and decreased the transfer of electrons at the interface. Both the anodic and cathodic Tafel slopes were increased with the addition of Moringa oleifera which indicates that Moringa oleifera is a mixed type of inhibitor (Subasree *et al.*, 2018).



Figure 3. Tafel plots for mild steel in 1 N H₂SO₄ in absence and presence of different concentration of Moringa oleifera (Subasree *et al.*, 2018).

Electrochemical impedance spectroscopy (EIS) study

Mejeh et al. (Mejeh *et al.*, 2020) studied EIS diagrams for Mild steel in 1 M HCl and Nyquist plots were shown in **Figure 4**.



The Nyquist plots contain semi-circle and with inhibitor concentration, the size increases. It was observed that there is single semicircle which indicated that steel dissolution is made up of a single process of charge transfer which is not compromised after addition of inhibitors molecules. Again, the high frequencies inductive loop showed that there is relaxation of adsorbed species at metal corrosive solution interface while the typical semicircle with a slight depression and a center located below the real axis presents inhomogeneties of solid electrodes during corrosion, like some degree of roughness and/or others. From the plot it can be deduced that inhibition increased at first as concentration increases but later lost resistance with concentration further thus increases in the inconsistency towards

the end of the graph. In addition, the Nyquist curve showed system stability for the concentrations utilized where the curve counters the real part of the impedance axis (Mejeh *et al.*, 2020).

Fourier transform infrared spectroscopy (FT-IR) study

Subasree et al. (Subasree *et al.*, 2018) studied the inhibitive effect of Moringa oleifera on the corrosion of mild steel in 1 N H₂SO₄. In this study, Moringa oleifera extract was characterized by using FT-IR spectra was shown in **Figure 5**. FT-IR studies were carried out to qualitatively evaluate the main functional groups responsible for binding with metal surface.



Figure 5. FTIR spectra for (a) Moringa oleifera extract and (b) metal after immersion in $1N H_2SO_4 + 8 ml extract (Subasree$ *et al.*, 2018).

FT-IR of Moringa oleifera leaf extract exhibited peaks at 3471, 2919, 2854 and 1024 cm⁻¹ (**Figure 5a**). FT-IR spectra of film formed on the surface metal exhibited prominent peaks at 3514, 2914, 2864 and 1035 cm⁻¹ (**Figure 5b**). It is seen from the spectrum that the O-H stretching vibration present in Moringa oleifera leaf extract has shifted from 3471cm⁻¹ to 3514 cm⁻¹. Also N-H stretching in MO extract of frequency 2919 cm⁻¹ has shifted to 2941cm⁻¹. The peak at 2854cm⁻¹ was shifted to 2864 cm⁻¹correspond to C–H (methoxy compounds) stretching vibration respectively. The band shifted from 1024 cm⁻¹ to 1035 cm⁻¹ developed for C–C and C–N stretching (Meneghel *et al.*, 2013; Araujo *et al.*, 2010). This indicates Fe²⁺ has coordinated to the lone pair of oxygen and nitrogen atoms resulting in the formation of a complex on metal surface.

Ultra violet (UV) Spectroscopy study

Didouh et al. (Didouh *et al.*, 2023) studied UV-Vis. spectra for steel in 1 M HCl solution with and without MO and KI are shown in **Figure 6**. The analysis of the UV characteristic of MO shows that there was a promotion of an electron from a non-bonding (n) or a π -bonding molecular orbital to a much lower unoccupied π^* anti-bonding molecular orbital. The effect of MO adsorption on the steel was investigated using a UV–Vis. spectrophotometer. To assess the impact of KI on the adsorption of the inhibitor, the measurement was performed in the presence of KI. The UV–visible spectra obtained from immersing steel in solutions of HCl, HCl + MO, and HCl +MO+ KI for 2 and 4 h are shown in **Figure 6**.



Figure 6. UV–Vis. Spectra for steel in 1 M HCl solution with and without M.O. and KI, after immersing steel samples for two different durations:(a) 2 h, and (b) 4 h (Didouh *et al.*, 2023).

The absorption of HCl solution is relatively low, while the spectrum of HCl + M.O. solution has peaks corresponding to π - π^* and n- π^* transitions at 210, 260–290, and 320 nm (Jokar *et al.*, 2016; Odewunmi *et al.*, 2015). The spectra obtained from the samples after 2 and 4 h of immersion also show that the peak at 210 nm is shifted to 245 nm after the addition of KI. The analysis of UV–Visible spectra after adding steel to the solution containing MOLE, and KI reveals a fundamental peak at 225–280 cm⁻¹. The shift in the peaks indicates the adsorption in M.O. onto the metal surface due to its chemical structure. The decrease in absorption intensity observed in the spectrum at the end of 2 and 4 h demonstrates the effective adsorption of M.O. on the metal. Adding KI results in a higher adsorption rate, as observed by a decreased absorption intensity. The results show that increasing the immersion time from 2 to 4 h leads to a further decrease in absorption intensity, particularly at 270–330 nm (Odewunmi *et al.*, 2015).

Atomic force microscopy (AFM) studies

AFM studies offer both qualitative and quantitative information on many physical properties, including size, morphology, surface texture, and roughness. Statistical information, including size, surface area, and volume distributions, can also be determined. The AFM technique supplies photos with atomic or near-atomic-resolution surface topography, which gives the surface roughness of coupons by the angstrom scale. AFM is a very high-resolution type of scanning probe microscopy on the order of fractions of a nanometer, more than 1000 times better than the optical diffraction limit

(Vera *et al.*, 2007). Fouda et al. (Fouda *et al.*, 2020) studied CS surface morphology by using AFM experiments after exposure for 24 h to 1 M HCl in the presence and absence of 600 ppm of *Moringa oleifera* extract (two dimensional (2D) and three dimensional (3D) images) was shown in Figure 7. Figure 7(a) shows the clear CS surface, Figure 7 (b) gives the surface of the metal that was damaged by HCl, and Figure 7(c) displays the surface of the metal in the presence of 600 ppm of *Moringa oleifera* extract that was not affected by corrosion.



Figure 7 (a). AFM images (3D and 2D) of CS before exposure to the 1 M HCl (Fouda *et al.*, 2020).



Figure 7(b). AFM images (3D and 2D) of corroded CS surface after exposure to 1 M HCl (blank solution alone) (Fouda *et al.*, 2020).



Figure 7(c). AFM images (3D and 2D) of the inhibited CS surface after exposure to 1 M HCl solution with 600 ppm of *Moringa oleifera* extract for 24 hours at 25°C (Fouda *et al.*, 2020).

Scanning Electron Microscopy (SEM) Study

Akalezi et al. (Akalezi *et al.*, 2020) studied SEM image of mild steel samples after being corroded in $0.5 \text{ M H}_2\text{SO}_4$ solution without and with addition of 1.5 g/L of Moringa oliefera (MO) leaf extract is shown in **Figure 8**.



Figure 8. SEM images of mild steel after immersion in 0.5 M H₂SO₄ for 24 h (a) without and (b) with MO extract at 303 K (Akalezi *et al.*, 2020).

It is observed that the mild steel surface was strongly damaged without inhibitors (Figure 8a), but the surface was smoothened when 1.5 g/L inhibitor was added (Figure 8b), indicating that MO extract formed a protective physical barrier on the mild steel surface and suppressed the acid aggression (Akalezi *et al.*, 2020).

Electrochemical frequency modulation (EFM) measurements

The EFM is a nondestructive corrosion measurement technique that can directly give values of the corrosion current without prior knowledge of Tafel constants. Fouda et al. (Fouda *et al.*, 2014) studied EFM spectra of Zinc in 3.5 % NaCl and 16 ppm Na₂S solution in the absence was shown in **Figure 9a**, while in presence of moringa extract was shown in **Figure 9b**. The results obtained from EFM showed good agreement with the obtained from weight loss, polarization and EIS methods.



Figure 9a: EFM spectra obtained for zinc corrosion in 3.5 % NaCl and 16 ppm Na₂S solution in the absence of moringa at 30°C (Fouda *et al.*, 2014).



Figure 9b. EFM spectra obtained for zinc corrosion in 3.5 % NaCl and 16 ppm Na₂S solution in the presence of 500 ppm of moringa at 30°C (Fouda *et al.*, 2014).

Phytochemical constituents of Moringa oleifera

Phytochemical constituents of Moringa oleifera leaves extract contains Alkaloids, Cardiac glycosides, Tannins, Saponin, Anthraquinones, Flavonoids, Terpenoids, Anthraquinone, Oxalate, Phenols (Kasolo *et al.*, 2010; Bamishaye *et al.*, 2011; Ugbe *et al.*, 2015; Odusote *et al.*, 2016; Bam *et al.*, 2018) which are very important in inhibition of corrosion of metals. Different parts of this plant contain a large amount of minerals and considered as suitable source of proteins, vitamins and beta-carotene, amino acids and various phenolic compounds. It also provides rich and rare collection of zeatin, quercetin, beta-sitosterol, caffeoylquinic acid, kaempferol (Anwar *et al.*, 2007). The study of Natsir et al. (Natsir *et al.*, 2019) shows that M. oleifera leaves contained 18 types of amino acids include threonine, lysine, leucine, isoleucine, phenylalanine, valine, methionine, tryptophan while non-essential amino acids include histidine, proline, tyrosine, aspartate acid, glycine, arginine, alanine, glutamate acid, serine, cysteine (Adagashi *et al.*, 2023). Extraction of phenolic compound showed presence of quercetine and kaemferal. Also, Vitamin C content in fresh samples of leaves of M. oleifera was characterized by Khalaf et al. (Khalaf *et al.*, 2021). The presence of the numerous components rich in aromatic rings, double and triple bonds as well as heteroatoms as S, N, O... favorized the adsorption on the metal surface.

Mechanism of corrosion inhibition by Moringa oleifera

Generally, it is assumed that the first stage in the action mechanism of the inhibition in acid medium is the adsorption of the inhibitor onto the metal surface. The process of adsorption is influenced by the nature and the charge of the metal, by the chemical structure of the organic inhibitor and the type of aggressive electrolyte (Fouda *et al.*, 2018). The essential effect of moringa as corrosion inhibitor is due to the presence of free electron pairs in the N, O and S atoms, π -electrons on the aromatic rings, molecular size, heat of hydrogenation, mode of interaction with the metal surface, and formation of metallic complexes (Sangeetha *et al.*, 2011). The anodic inhibition may be due to the adsorption of principle phytochemical constituents present in the extract through nitrogen atom/or oxygen atoms/or ring oxygen atom in glucosinolate and /or oxygen atoms of –OH group in moringa phytochemical constituents and forms a protective coating on the metal surface, thus prevents the contact between the metal and corrosive media (Fouda *et al.*, 2014).

The transition of metal/solution interface from a state of active dissolution to a passive state is attributed to the adsorption of the inhibitor molecules at the metal-solution interface, forming a protective film. The rate of adsorption is usually rapid and hence, the reactive metal surface is shielded from the aggressive environment (Chao *et al.*, 1981). Adsorption process can occur through the replacement of solvent molecules from metal surface by ions and molecules accumulated in the vicinity of the metal/solution interface. Ions can accumulate at the metal/solution interface in excess of those required to balance the charge on the metal at the operating potential. These ions replace solvent molecules from the metal surface and their centers reside at the inner Helmholtz plane. This phenomenon is termed specific adsorption (Keles *et al.*, 2008). The anions are adsorbed when the metal surface has an excess positive charge in an amount greater than that required to balance the charge oparticularly strong adsorption on many electrode surfaces. The bonding can occur between metal surface atoms and the aromatic ring of the adsorbate molecules or ligand substituent groups (Singh *et al.*, 2012b).

Moringa oleifera fruit extract contains amino acids such as arginine, alanine, glycine, serine, threonine, valine, glutamic acid, aspartic acid, sucrose, glucose, benzyl isothiocyanate derivative (a glycoside of mustard oil), and 4(4-acetyl-L-L rhamnosyloxy)-benzo isothiocyanate (Rajangam et al. 2001). These chemical constituents are rich in hetero atoms, functional group, and pi-electrons. The structures of one of the constituents of Moringa oleifera fruit extract is given in Figure 10. The high performance of shahjan (Moringa oleifera) extract could also be due to the large size of the constituent molecules, which cover wide areas on the metal surface, thus retarding corrosion (Trabenelli and Mansfeld, 1987). Also, the high inhibition efficiency shown by Moringa oleifera fruit extract can be attributed to the presence of imine (C=N) group, hetero atoms, and long alkyl chain. It is not possible to consider a single adsorption mode between inhibitor and metal surface because of the complex nature of adsorption and inhibition of a given inhibitor. The adsorption of main constituents of fruit extract can be attributed to the presence of O-atoms, pi-electrons, and aromatic/heterocyclic rings. The presence of methoxy group also enhances the inhibition efficiency. Therefore, the possible reaction centers are unshared electron pair of hetero atoms and pi-electrons of the aromatic/heterocyclic ring. In aqueous acidic solutions, main constituents exist either as neutral molecules or as protonated molecules (cations). The inhibitors may adsorb on the metal/acid solution interface by one and/or more of the following ways: (i) electrostatic interaction of protonated molecules with already adsorbed chloride ions, (ii) donor-acceptor interaction between the pi-electrons of the aromatic ring and vacant d-orbital of surface iron atoms, and (iii) interaction between unshared electron pairs of hetero atoms and vacant d-orbital of metal (Iron) surface atoms (Singh et al, 2012b).



Figure 10. Structure of Arginine, one of the constituents of shahjan (Moringa oleifera) fruit extract (Singh *et al.*, 2012b).

The inhibition process is generally interpreted by the synergistic intermolecular effect of the various molecules contained in the leaf and seed extracts as stated by Ezeh et al. (Ezeh *et al.*, 2023) and Lrhoul et al. (Lrhoul *et al.*, 2023).

Conclusion

In this review, various research works on the corrosion inhibition of different metals and alloys in different acidic, neutral and seawater media by Moringa oleifera as green inhibitor were presented. Langmuir, Frumkin, Freundlich and Temkin adsorption isotherms were observed. Moringa oleifera extract behaved as a cathodic or mixed-type of inhibitor. The maximum inhibition efficiency for Moringa oleifera was found to be 98.2 % (WL data). The results obtained from weight loss data were in good agreement with the results obtained from the PDP and EIS methods. Various techniques such as SEM, FT-IR, GC-MS, DFT, UV-Vis. etc. were used to study the corrosion mechanism.

Disclosure statement: *Conflict of Interest:* The authors declare that there are no conflicts of interest.

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

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(2025); http://www.jmaterenvironsci.com