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Ricinus communis (Castor oil) as Eco-friendly Corrosion Inhibitor for Metals and Alloys - A Review

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Abstract: In this review, study of Ricinus communis (Castor oil) as a green corrosion inhibitor for various metals and alloys such as aluminium, carbon steel, mild steel, stainless steel, iron and copper 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), density functional theory (DFT) and energy dispersive spectroscopy (EDS) and energy dispersive X-ray spectroscopy (EDX) were also used to study the nature of surface film produce on metals. Adsorption of Ricinus communis on metal surface obeys Langmuir, Temkin, Frundlich, El-Awady and Frumkin isotherms depending on nature of metal and corrosive environment. Polarization study reveals that Ricinus communis can function as anodic or cathodic or mixed type of inhibitor depending on nature of metal and corrosive media.

1. Introduction

Corrosion is basically defined as the deterioration of any metallic material due to the chemical or electrochemical attack of the material by its corrosive environment. Metallic materials are still the most widely used group of materials particularly in mechanical engineering, electronics, construction and transportation industry. However, their usefulness is constrained by one common problem known as corrosion. Corrosion can cause higher costs for engineering and transportation systems. The loss suffered from the corrosion of metals is huge for individuals, organizations and even countries. Almost all countries use 0.1-1-3 % of their GDP in solving problems or finding replacement cause due to corrosion. These losses range from components or equipment breakdown, plant shutdown, loss of life and properties (Hmimou *et al.*, 2012, Fayomi *et al.*, 2017).

Aluminium (Al) can be efficiently used in different industries including architectural, transportation, consumer goods, electrical products and especially in aerospace. Carbon steel (CS) is used in construction for building frames, bridges, steel piping, and more. Stainless steel (SS) is used in the food industry because it's resistant to corrosion, can be cleaned and sterilized, and doesn't change the taste or colour of food. Copper (Cu) is used in manufacturing of electric cables and other manufacturing of electric cables and electric appliances, electroplating, utensils, containers and Mild steel (MS) is frequently used in oilfield industries for construction of pipes, storage tanks and processing equipment (Verma *et al*., 2017; Hamidah *et al.*, 2021).

Prevention would be more practical and achievable than complete elimination. There are several methods for reducing or preventing corrosion, such as anodic and cathodic protection, coatings, and the usage of inhibitors. One of the most effective alternatives for the protection of metallic surfaces against corrosion is the use of corrosion inhibitors (Singh & Quraishi, 2015; Zarrok *et al.*, 2012; Fernine *et al.*, 2002). 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). Inhibitors retard metal corrosion by adsorbing on metallic surface and the process is influenced by some factors, which include molecular size of inhibitor, nature of substituents, inhibitor concentration, solution temperature and nature of test solution (Naderi *et al*., 2009; Elmsellem *et al*., 2014; Galai *et al*., 2016). The known hazardous effects of most synthetic corrosion inhibitors are the motivation for the use of some natural products. The recent trend is towards environmentally friendly inhibitors. Most of the natural products are non-toxic, biodegradable and readily available in plenty (Eddy *et al*., 2008; Elmsellem *et al*., 2019; Hbika *et al*., 2023). One of the proposed inhibitory mechanisms consists in the adsorption of the molecules to the metal surface, creating a barrier between the metal and the electrolyte, blocking active sites and reducing the metal dissolution and/or reduction reactions (El-Etre *et al*., 2008). Plant extracts are non-toxic, biodegradable, inexpensive, and not harmful to the environment and human health. Plant extracts contain many organic compounds, having polar atoms such as oxygen (O), phosphorous (P), sulphur (S), and nitrogen (N) in their structures, which can adsorb into active sites of the metal surface through conjugated bonds (Prabakaran *et al*., 2016; Lrhoul *et al.*, 2023).

Ricinus communis Linn belongs to the Euphorbiaceae family popularly known as 'Castor oil plant' and is mainly cultivated in tropical and subtropical regions worldwide (Ogunniyi , 2006). Ricinus communis (Castor oil) leaf shown in **Figure 1** and Ricinus communis (Castor oil) seed is shown in **Figure 2**.

Figure 1. Castor oil leaf

Figure 2. Castor oil seed

Castor is indigenous to the South Eastern Mediterranean Basin, East Africa, China, Ethiopia, America and India. This plant is common and quite wild in the jungles in India and it is cultivated throughout India, chiefly in the Madras, Bengal and Bombay presidencies. Ricinus communis can vary greatly in its growth habit and appearance. The variability has been increased by breeders who have selected a range of cultivars for leaf and flower colours, and for oil production. It is a fast-growing, suckering shrub that can reach the size of a small tree, around 12 metres (39 feet), but it is not cold hardy. Leaves are green or reddish in colour and about 30-60 cm in diameter. The glossy leaves are 15–45 centimetres (6–18 inches) long, long-stalked, alternate and palmate with five to twelve deep lobes with coarsely toothed segments. In some varieties they start off dark reddish purple or bronze when young, gradually changing to a dark green, sometimes with a reddish tinge, as they mature. The stems are varying in pigmentation. The flowers are monoecious and about 30-60 cm. long. The fruit is a three-celled thorny capsule. The seeds are considerable differences in size and colour. They are oval, somewhat compressed, 8-18 mm long and 4-12 mm broad (Jena *et al.,* 2012).

Traditional uses of Ricinus communis

Ricinus communis has been used worldwide due to its medicinal properties (Scarpa *et al*., 1982). The seed of the plant is used for industrial and cosmetic applications. The principal use of castor oil is as a purgative and laxative. It is also used as a lubricant, lamp fuel, a component of cosmetics, and in the manufacture of soaps, printer's ink, plastics, fibers, hydraulic fluid, brake fluid, varnishes, paints, embalming fluid, textile dyes, leather finishes, adhesives, waxes, and fungicides. There is also significant commercial potential for utilization of the whole castor bean plant such as animal feed, fertilizer, biofuel, and also for phytoremediation (Landoni *et al.,* 2023). Ricinoleic acid is the main component of castor oil and it exerts anti-inflammatory effects. Castor oil is added to many modern drugs for curing various diseases (Marmion *et al*., 1976, Micha *et al*., 2006).

The castor bean plant is effective as, anticancer activity, antiimplantation activity, antinociceptive activity (Taur *et al*., 2011), hepatoprotective activity (Shukla *et al*., 1992), antiinflammatory activity (Ilavarasan *et al.,* 2006), antimicrobial activity (Mathur *et al*., 2011), antidiabetic activity (Shokeen *et al*., 2008), wound healing activity (Prasad *et al.,* 2011), lipolytic activity (Lombard *et al*., 2001), antiulcer activity (Rachhadiya *et al*., 2011), antifertility activity (Sandhykumary *et al.,* 2003), anti-bacterial activity, insecticidal activity, bone regeneration activity, central analgesic activity, antioxidant activity and cytotoxic activity and antidiabetic activity (Bhaumik *et al*., 2018). Nowadays Castor oil can be used as an effective corrosion inhibitor because of its structure (Ouchrif *et al.,* 2003), which has a high percentage of fatty acids and ricin and ricinoleic acid content.

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 efficency (I.E, %). Inhibition efficency of Ricinus communis 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). EIS shows more information, for example, mechanism and different resistance of the system. Various techniques like SEM, FT-IR, EDX and EDS have been used to analyze the nature of protective film formed on the metal surface. SEM provides a clear comparison between the metal surface with and without a corrosion inhibitor, as well as other morphological information. The present review aimed to review the results regarding corrosion inhibition action of Ricinus communis on some metals and alloys such as Aluminium, Mild steel, Carbon steel, Stainless steel and Copper in various acidic and neutral corrosive environments. Different methods have been employed to evaluate corrosion inhibition process. The protective film has been analyzed by various surface analysis techniques.

2. Results and Discussion

Ricinus communis 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 alloys in different media by Ricinus communis as an inhibitor.

Metal / Alloy	Medium + Additive	Techniques used	Findings	I.E. max. (in %)	Reference
Aluminium	1.0 M HCl	WL with time.	Mixed type of inhibitor, Langmuir isotherm.	82.61 WL	Onukwuli *et al.*, 2006
Aluminium	0.1 M Na_2CO_3	WL with temperature, PDP, EIS	Mixed type of inhibitor,	87.0 WL, 88.17PDP, 88.34 EIS	Hamdou *et al.*, 2017
Aluminium	3.5 % NaCl	WL, PDP, SEM, EDS.	Mixed type of inhibitor, Langmuir isotherm.	92.7 WL, 89.2 PDP	Sanni *et al.*, 2018
Aluminium	2 M HCl & 2 M H_3PO_4	WL with time, OCP, SEM, EDS.	Langmuir isotherm.	75.75 WL in HCl, 82.35 WL in H_3PO_4	Abdulwahab *et al.*, 2012
Copper	2 M HNO_3	WL with temperature, PDP, EIS	Mixed type of inhibitor, Langmuir isotherm.	94.26 WL, 99.47 PDP, 98.87 EIS	Houbairi *et al.*, 2014
Copper	Neem oil + Biodiesel	WL with temperature, FT-IR, SEM	----	95.0 WL	Priyatharesini *et al.*, 2019
Carbon Steel (C1010)	ASC Water	WL with temperature, PDP, FT-IR	Cathodic type of inhibitor, Langmuir isotherm.	98.0 PDP	Ali *et al.*, 2017
Carbon Steel (AISI1020)	0.5 M HCl	WL with time, PDP, EIS, SEM, FT-IR, SVET	Mixed type of inhibitor,	83.0 WL, 83.0 EIS	Santos *et al.*, 2017
Low Carbon Steel	SOPW	WL, PDP, EIS, SEM	Mixed type of inhibitor,	72.0 WL, 90.3 PDP	Xie *et al.*, 2021
Iron (MS)	0.5 N HCl	WL	Langmuir isotherm.	87.92 WL	Vyas *et al.*, 2011
Mild Steel	1 M H_2SO_4	WL with temperature, PDP, RSM, ANN, GC-MS	Mixed type of inhibitor, Frumkin isotherm.	96.25 WL	Omotioma *et al.*, 2024
Mild Steel	0.5 M H_2SO_4	WL with temperature, SEM	Mixed type of inhibitor, Langmuir, Freundlich and Temkin isotherm.	92.42 WL	Banumathi *et al.*, 2016

Mild Steel	0.5 M H_2SO_4	WL with time, PDP, SEM	Mixed type of inhibitor, Frumkin and Freundlich isotherms.	96.35 WL	Loto *et al.*, 2019
Mild Steel	4 N HCl	WL with time and temperature, SEM	--	82.0 WL	Srivastava *et al.*, 2021
Mild Steel	1 M HCl	WL with time and Temperature, PDP, EIS	Mixed type of inhibitor, Langmuir, Freundlich and Temkin isotherm	97.19 WL, 96.96 PDP, 96.82 EIS	Saratha *et al.*, 2009
Mild Steel	0.5 M HCl	WL with temperature, PDP, EIS, SEM	Mixed type of inhibitor, Langmuir isotherm.	87.7 WL, 86.8 PDP, 87.8 EIS	Goel *et al.*, 2010
Mild Steel	1 M HCl	WL with time, TM, PDP, SEM, FT-IR, RSM	Mixed type of inhibitor, Langmuir, Frumkin, Temkin and Flory-Huggins isotherms.	85.18 WL, 89.38 TM	Omotioma *et al.*, 2016
Mild Steel	1 M HCl	WL with time and temperature, OCP, PDP, EIS, SEM, FT-IR, EDS	Mixed type of inhibitor, Langmuir, Temkin, Flory-Huggins and El-Awady isotherm	97.8 WL, 96.6 PDP, 96.3 EIS	Santana *et al.*, 2020
Mild Steel	100 ppm NaCl	WL, PDP, OCP, EIS	Anodic type of inhibitor,	84.0 WL, 56.0 EIS	Sathiyanathan *et al.*, 2005
Steel	2 M H_3PO_4	WL with temperature, GC-MS.	Cathodic type of inhibitor,	73.0 WL	Bendahou *et al.*, 2006.
Reinforcing Steel	3.5 % NaCl	WL with time, PDP, EIS, AFM, DFT	Mixed type of inhibitor, Temkin isotherm.	---	Palanisamy *et al*, 2018
Stainless Steel (301)	1.5 M HCl	WL with time and temperature, SEM, RSM, XRD	--	95.03 WL	Okewale *et al.*, 2020

Gas chromatography mass spectrometry (GC-MS) study

Omotioma et al. (Omotioma *et al.*, 2024) studied of corrosion inhibition of Mild steel in H_2SO_4 solution by Ricinus communis as corrosion inhibitor. They carried out GC-MS spectra of the castor oil leaf shown in **Figure 3** which indicates various levels of peaks. The peaks represent various compounds as determined by GC-MS spectra. The chromatogram revealed the presence of methyl nicotinate; methyl ester; pyridine-4-carbohydrazide; 4-ketopimelic; 4-oxoheptanedioic acid; succinic acid, ethyl hydrogen succinate. It also contains benzene acetaldehyde, 3-pyridinecarboxylic acid; nicotinic acid, methyl 3-pyridinecarboxylate; methyl ester of pyridine-3-carboxylic acid); butanedioic acid, diethyl ester; 9-hexadecenoic acid.

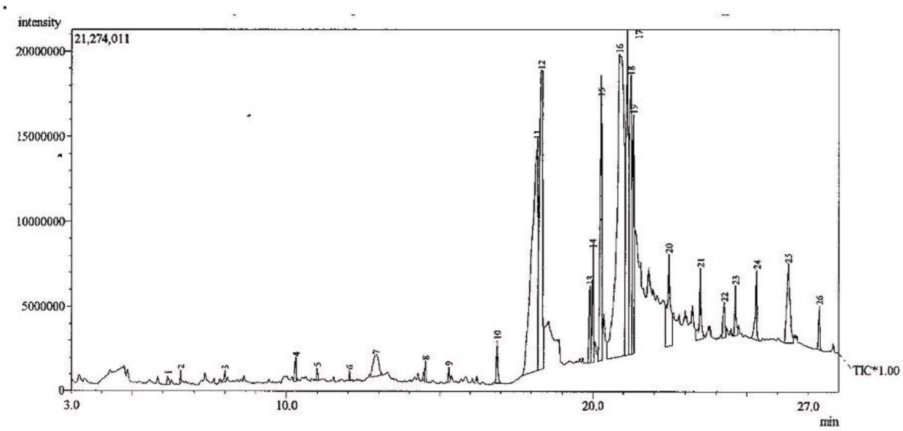


Figure 3. The GC-MS Chromatogram of Castor oil leaf (Omotioma *et al.*, 2024).

FTIR absorption spectral study

Santos et al. (Santos *et al.*, 2017) examined the corrosion inhibition performance of Castor bark powder as a corrosion inhibitor for carbon steel in acidic media. They studied FTIR spectrum of the castor bark powder as shown in **Figure 4**. The large peak centered at 3421 cm^{-1} can be attributed to OH or/and NH from water or amines (Verma *et al.*, 2016, Yetri *et al.*, 2016). Absorption peak at 2923 cm^{-1} can be assigned to C-H and its low intensity indicates that only short chain compounds are detected (Hijazi *et al.*, 2015, Grassino *et al.*, 2016). The band at 1653 cm^{-1} can be assigned to carbonyl group CN or C=O from carboxylates, as unsaturated carboxylic acids (Ricinoleic acid) are present in the Castor oil composition. The absorption band at 1457 cm^{-1} corresponds to CH (Ji *et al.*, 2016). Finally, the functional group C-O can be identified in the band at 1053 cm^{-1} (Yetri *et al.*, 2016, Ji *et al.*, 2016). The absorption band at 1457 cm^{-1} corresponds to CH (Ji *et al.*, 2016).

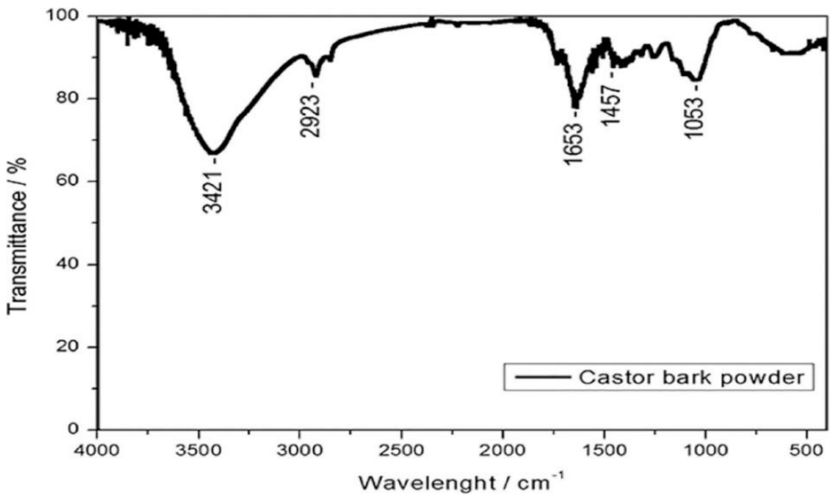


Figure 4. FTIR spectra of castor bark powder (Santos *et al.*, 2017).

The FTIR analyses indicates the presence of C, N and O heteroatoms incorporated in different functional groups, which were also identified in compounds of Ricinus communis (Goel *et al.*, 2010). These heteroatoms are generally found in green inhibitors, whose inhibitory properties are commonly attributed to them (Ji *et al.*, 2016). These substances are adsorbed on carbon steel surface forming Fe^{2+}-Green Inhibitor complexes, which could be responsible for retarding the corrosion process (Li *et al.*, 2012).

Potentiodynamic polarization (PDP) study

Hamdou et al. (Hamdou *et al.*, 2017) examined the polarization curves for Aluminium in 0.1M Na_2CO_3 in the absence and presence of different concentrations of the RC extract shown in **Figure 5**. The anodic and cathodic slopes of Tafel curves have greatly decreased with the gradual addition of the inhibitor, this reduction indicates that behave as RC behave as a mixed type of inhibitor (Fuchs-Godec *et al.*, 2015).

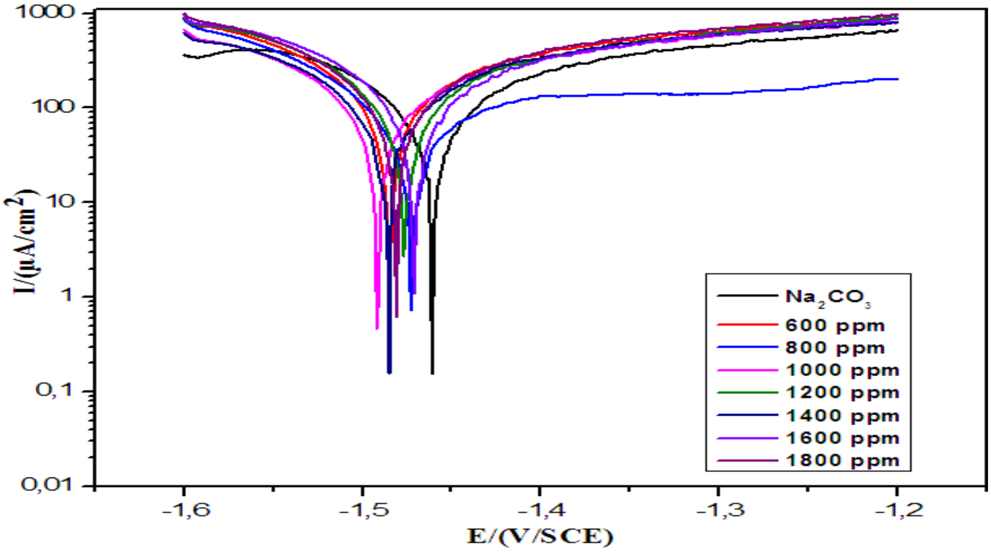


Figure 5. Polarization curves for Aluminium in 0.1 M Na_2CO_3 without and with various concentrations of Ricinus communis (RC) at 25 ± 0.1 °C (Hamdou *et al.*, 2013)

Electrochemical impedance spectroscopy (EIS) study

Santos et al. (Santos *et al.*, 2017) studied the EIS diagrams obtained at the open circuit potential (OCP) after 120 min. immersion of the AISI 1020 carbon steel in 0.5 M HCl in the presence of different concentrations of castor bark powder are presented in **Figure 6**. Initially, the results show that the addition of the powder to the test solution does not change the shape either of the Nyquist (**Figure 6 (a)**) or of the phase angle x log f (**Figure 6(b))** diagrams (Chevalier *et al.*, 2014, Mourya *et al.*, 2014).

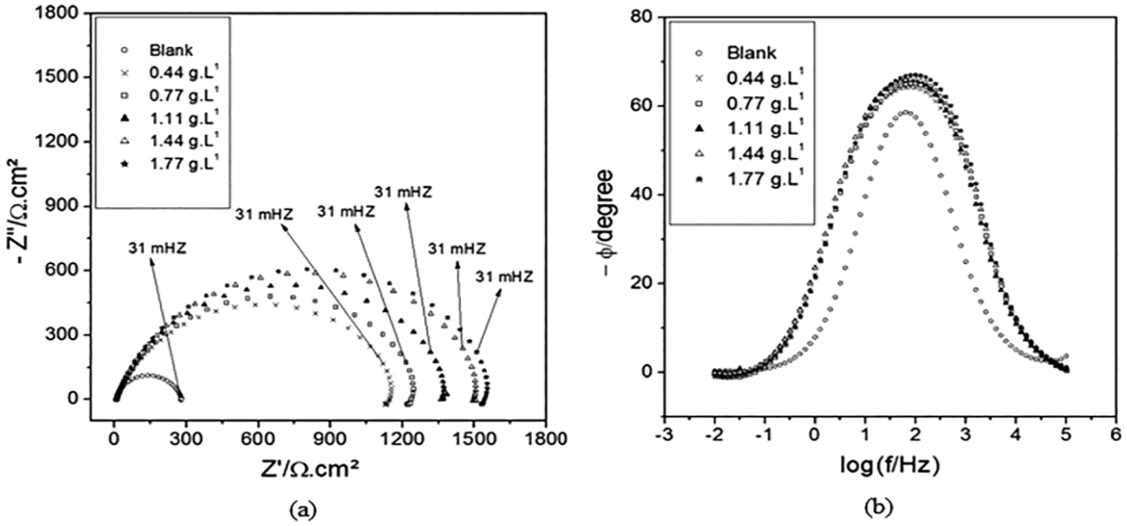


Figure 6. EIS diagrams obtained for AISI 1020 Carbon steel after 120 min of immersion in 0.5 M HCl in absence and presence of different amounts of castor bark powder: (a) Nyquist and (b) phase angle x log f plots (Santos *et al.*, 2017).

Nyquist plots (**Figure 6 (a)**) are composed by a single depressed capacitive loop, which diameter and capacitive behavior (**Figure 6(b)**) increases with increasing amount of powder added to the electrolyte, evidencing enhanced corrosion resistance. The semicircle nature of the plots indicates that the corrosion of carbon steel alloy is mainly controlled by charge transfer process. These capacitive loops are not perfect semicircles, which can be attributed to the frequency dispersion effect caused by the roughness and inhomogeneity of the electrode surface. Furthermore, in the presence of an inhibitor, the diameter of the capacitive loop is larger than in blank solution and increases with inhibitor concentration (Hernández *et al.*, 2020). This result indicates that the castor bark powder inhibits the corrosion of the substrate, which must be a consequence of increased adsorption of molecules with inhibitory properties to the metallic surface hindering the electrochemical process. This hypothesis is in accordance with the adsorption behaviour already verified for other green inhibitors (Pereira *et al.*, S. S. A. A *et al.*, 2012, Abiola *et al.*, 2010).

Scanning electron microscopy (SEM) study

Omotioma et al. (Omotioma *et al.*, 2016) studied the micrographs of the corroded mild steel in 1.0 M HCl in the presence and absence of the castor oil extract were presented in **Figure 7**. **Figure 7(a)** shows the metal surface was strongly damaged owing to corrosion in the absence of the inhibitor, while **Figure 7(b)** shows little damage on the surface in the presence of inhibitor. This is attributed to the formation of a good protective film on the mild steel surface (Loto *et al.*, 2012). It might be concluded so that the adsorption film can efficiently inhibit the corrosion.

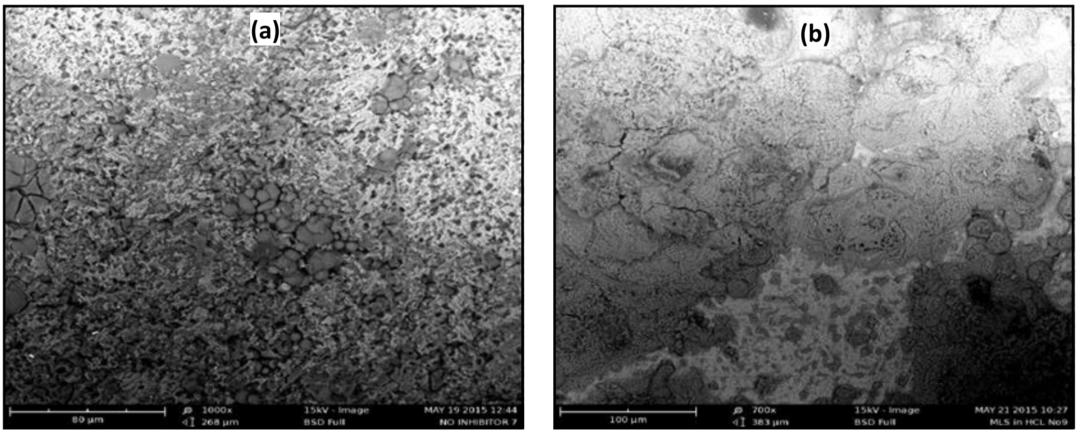


Figure 7. The micrograph of corroded Mild steel surface in 1.0 M HCl (a) in absence and (b) in presence of castor oil leaf extract (Omotioma *et al.*, 2016).

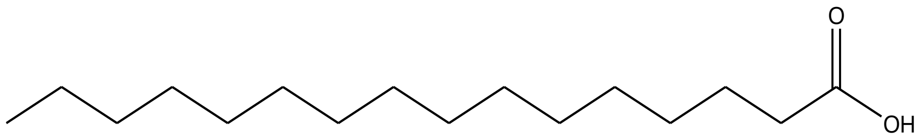
Phytochemical constituents of Ricinus communis

The preliminary phytochemical study of Ricinus communis extract revealed the presence of steroids, saponins, alkaloids, flavonoids, phenolics, phytates, tanins and glycosides in it at various degrees (Onukwuli *et al.*, 2020). The dried leaves showed the presence of two alkaloids, ricinine (0.55%) and N demethylricinine (0.016%) and six flavones: glycosides kaempferol-3-O-β-D-Xylopyranoside, kaempferol-3-O-β D-glucopyranoside, quercetin-3-O-β-D-xylopyranoside, quercetin-3-O-β-D-glucopyranoside, kaempferol-3-O-β rutinoside and quercetin-3-O-β-rutinoside (Kang *et al.*, 1985). The monoterpenoids (1, 8-cineole, camphor and α-pinene) and asesquiterpenoid (β-caryophyllene), gallic acid, quercetin, gentisic acid, rutin, epicatechin and ellagic acid are the major phenolic compounds isolated from the leaves. Indole-3-acetic acid has been extracted from the roots

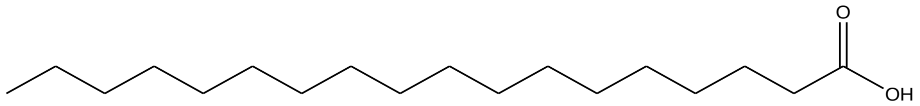
(Darmanin *et al.*, 2009, Singh *et al.*, 2009). The seeds and fruits contain 45% of fixed oil, which consist glycosides of ricinoleic, isoricinoleic, stearic, dihydroxystearic acids, and also lipases and a crystalline alkaloid, ricinine (Khogali *et al.*, 1992). The GLC study of CO showed the presence of ester form of palmitic (1.2%), stearic (0.7%), arachidic (0.3%), hexadecenoic (0.2%), oleic (3.2%), linoleic (3.4%), linolenic (0.2%), ricinoleic (89.4%) and dihydroxy stearic acids (Kang *et al.*, 1985). The ergost-5-en-3ol, stigmasterol, Y-sitosterol fucosterol; and one probucol isolated from the ether extract of seeds (Jena *et al.*, 2012).

Mechanism of corrosion inhibition by Ricinus communis

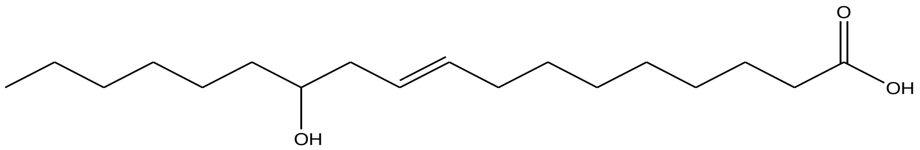
The structures of the main active chemical compounds present in Ricinus communis oil extract are given below in **Figure. 8** (Houbairi *et al.*, 2014). The presence of heteroatoms in their chemical structure could account for their inhibitive action in combination.



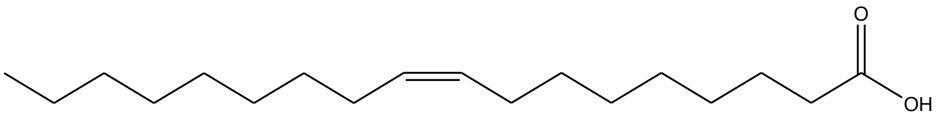
Palmitic acid



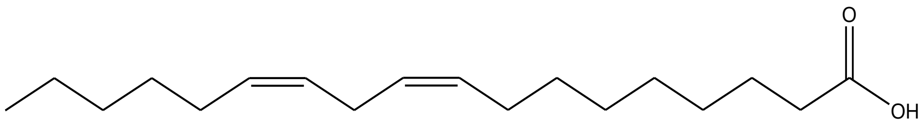
Stearic acid



Ricinoleic acid



Oleic acid



Linoleic acid

Figure 8. Structure of main constituents of Ricinus communis extract (Houbairi *et al*, 2014).

The inhibition of corrosion of metals by organic compounds (Tsuru *et al.*, 1978) is attributed to either the adsorption of inhibitor molecule or the formation of a layer of insoluble complex of the metal on the surface which acts as a barrier between the metal surface and the corrosive medium. It has been reported that the adsorption of the inhibitor molecules depends on a variety of factors, for example the presence of functional groups (or electron donor or withdrawal) steric factors, the distribution of load on the donor atom the π-orbital nature of electron donors, the nature of the metal substrate, and the type of interaction between the organic molecules and the metal surface (Hasanov *et al*., 2010). The literature suggests that the presence of negative ions in acidic medium enables the existence of organic constituents of inhibitor in the protonated form as well as neutral molecules, and the adsorption of inhibitor molecules due to excess of negative charge on the metal surface, enhancing the electrostatic interactions between protonated inhibitor molecules and the negatively charged metal surface (Prabakaran *et al*., 2016, Santos *et al*., 2017, Nazeer *et al*., 2015). On the other hand, neutral molecules reduce the metal dissolution by its adsorption through lone pair of electrons over heteroatoms (Sastri *et al*., 1959). The inhibiting molecules adsorbed at the metal surface block the active sites probably due to the displacement of water molecules through hydrogen bonding with hydroxyl groups of the inhibitor. This results in the formation of a protective barrier that contributes to retard the ionic flow on the metal surface thus reducing the corrosion rate (Verma *et al*., 2016, Loto *et al*., 2019, Negam *et al*., 2013). Given that the natural extract contains an infinity of compounds at different contents, the inhibitory action is generally interpreted by the phenomenon of intermolecular synergy (Benali *et al*., 2013, Khadom *et al*., 2022, Lrhoul *et al*., 2023).

Conclusion

This review paper has summarized the research works carried out by various researchers on corrosion of various metals and alloys in different acidic, neutral and alkaline media by Ricinus communis as eco-friendly inhibitor was presented. The percentage I.E of inhibitors was calculated using WL, PDP and EIS methods. Other methods like SEM, FT-IR and EDS were also used to study the nature of surface film produce on metals. Langmuir, Temkin, Frundlich, El-Awady and Frumkin isotherms were found in the present review. RC behaved as anodic, cathodic and mixed-type of inhibitor. Ricinus communis obtained corrosion IE (%) above 56.0%, most of them around 72.0 to 99.47%. Results obtained from WL data were in good agreement with results obtained from PDP and EIS methods.

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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