Heliyon 10 (2024) e33748

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Review article

Plant extracts as green corrosion inhibitors for different kinds of steel: A review

Bhoomika R. Holla [a], R. Mahesh [b,**], H.R. Manjunath [c], V. Raghu Anjanapura [d,*]

[a] *Department of Chemical Engineering, RV College of Engineering, Bangalore, 560059, India*
[b] *Department of Chemistry, RV College of Engineering, Bangalore, 560059, India*
[c] *Department of Physics, Faculty of Engineering and Technology, JAIN (Deemed-to-be University), 562112, Bengaluru, India*
[d] *Department of Basic Sciences, Faculty of Engineering and Technology, CMR University, 562149, Bengaluru, India*

ARTICLE INFO

Keywords:
Corrosion inhibitors
Plant extracts
Adsorption
Steel
Adsorption isotherm

ABSTRACT

Corrosion significantly threatens the structural integrity of steel-based constructions like buildings and industrial units. Traditional corrosion inhibitors, such as chromates, are associated with environmental and health risks. This has led to a growing interest in environmentally sustainable alternatives, with plant extracts emerging as promising candidates. These extracts are widely available, sustainable, and eco-friendly. This review aims to explore the potential of plant extracts as corrosion inhibitors for various types of steel. After examining current scientific literature, over 40 plant extracts have been identified that exhibit corrosion inhibition properties. These extracts have been thoroughly analyzed to understand their effectiveness in preventing corrosion. The review elucidates the mechanisms by which these extracts interact with metal surfaces to form protective layers, effectively hindering the corrosion process. In this review, we focus on the challenges associated with utilizing plant extracts as inhibitors, including optimal extract concentration and temperature considerations.

1. Introduction

The International Union of Pure and Applied Chemistry (IUPAC) has defined corrosion as an environment-dependent, irreversible interfacial material interaction that leads to the consumption or dissolution of materials [1]. Metals are purified before entering commercial use, but they naturally tend to revert to their original ore form through corrosion [2]. Industries, such as oil and gas, petrochemical, and automotive sectors, suffer significant economic losses due to corrosion. To mitigate corrosion, inhibitors are commonly used, but many of them are often toxic and pose environmental risks.

A comprehensive study conducted by the National Association of Corrosion Engineers (NACE) across various nations revealed that the annual worldwide economic impact of corrosion is approximately 5 % of the global Gross Domestic Product (GDP) [3]. Corrosion also causes the collapse of metallic structures such as bridges, buildings, and overpasses, as well as explosions in chemical industries. In India, corrosion is estimated to cause losses of Rs. 2 lakh crore (Rs. 2 trillion) annually [2]. Therefore, there is a need to explore corrosion mitigation techniques. Green corrosion inhibitors made from organic materials like plant extracts have been developed as a sustainable and environmentally friendly alternative. Thiophene, hydrazine, inorganic compounds such as phosphates, chromates, and

* Corresponding author.
** Corresponding author.
E-mail addresses: maheshr@rvce.edu.in (R. Mahesh), avraghu23@gmail.com (V.R. Anjanapura).

https://doi.org/10.1016/j.heliyon.2024.e33748
Received 9 November 2023; Received in revised form 26 June 2024; Accepted 26 June 2024
Available online 27 June 2024
2405-8440/

dichromates, as well as silicates, borates, tungstates, molybdates, pyrrole compounds, arsenates, and chromium (VI), are among the most potent corrosion inhibitors currently in use. Due to their toxicity and lack of environmental friendliness, they threaten the environment and public health [4]. Plant extracts contain various organic compounds, such as alkaloids, flavonoids, and phenols, that possess good inhibitory properties. Utilizing plant extracts to prevent corrosion is a potential field of study that could lead to the development of corrosion inhibitors that are sustainable and environmentally friendly [5]. The non-toxic nature inherent in most plants makes them a viable substitute for toxic organic inhibitors. Additionally, they are biodegradable, simplifying the disposal process. Plant extracts can be derived from different parts of plants, including fruits, leaves, bark, roots, seeds, or peels [6].

Data are scarce on the use of plant extracts as green corrosion inhibitors for diverse types of steel. This scarcity of data has sparked interest in reviewing papers that delve into the use of plant extracts as corrosion inhibitors across various concentrations for different varieties of steel. By examining recent scientific literature, the paper assesses which plant extracts have proven to be effective in corrosion inhibition. The central objective of this review is to highlight the application of environmentally friendly alternatives, specifically plant extracts, as corrosion inhibitors, addressing the limited existing information in the field.

2. Corrosion inhibitors and their classification

Corrosion inhibitors are compounds that slow down the process of corrosion by forming a thin layer of molecules on the surface of the metal through adsorption. This layer reduces the metal's dissolution and prevents direct contact of the corrosive medium (the atmosphere) with the metal. They achieve this by modifying the reactions at the anode or cathode or by slowing down the pace at which reactants diffuse through the metal's surface, thereby reducing the rate of corrosion [7].

There are two types of corrosion inhibitors based on their molecular structure: inorganic and organic. Inorganic inhibitors (such as nitrites, arsenates, nitrates, phosphates, and chromate) create a passive film or coating on the metal anode, while organic inhibitors are mostly composed of heterocyclic substances (such as pyridine, amine, etc.) that either create a film to cover the metal's surface or adsorb on the metal due to the presence of various functional groups (e.g. nitro groups, cyanides, and isocyanides). These functional groups facilitate the transport of electrons from the inhibitor to the vacant *d*-orbital of the metal.

Inorganic inhibitors build brittle passive layers that can make the metal surface susceptible to local corrosion attacks, such as pitting and fissures. On the other hand, organic green corrosion inhibitors can evenly passivate metal surfaces, providing superior protection against aggressive media [8].

3. Adsorption and mechanism

Corrosion inhibition works by forming a protective film on the metal surface, which reduces the availability of active sites. This process involves adsorption, which can occur in three ways: physisorption, chemisorption, or combination. Each mode of adsorption affects corrosion inhibition in different ways. Physisorption occurs due to ionic interactions between the charged corrosion inhibitor and the metal surface, which reduces active sites [9]. Chemisorption involves the sharing of electrons, leading to coordination bonds between the metal surface and high electron density heteroatoms such as oxygen, sulfur, phosphorus, or nitrogen in the aromatic ring. The strength of the bond, conjugation in the aromatic ring, and the length of the carbon chain (affecting solubility) play an important role in inhibition. Mixed adsorption occurs when adsorption takes place at both the anodic and cathodic sites of the corroding metal. Fig. 1 shows the schematic representation of physisorption and chemisorption taking place in the same compound.

Anodic inhibitors are also known as passivation inhibitors, which work by slowing down the anodic reaction, preventing the anode reaction, and promoting natural passivation by creating a cohesive and insoluble film on the metal surface. On the other hand, cathodic corrosion inhibitors prevent the cathodic reaction by triggering a cathodic reaction through metal ions, leading to the formation of precipitates on cathodic sites. This results in a dense film that restricts the diffusion of reducible species. Both anodic and cathodic inhibitors need to be present in adequate concentrations to form protective films. If the amount of inhibitors is inappropriate, it may lead to incomplete coverage, resulting in localized corrosion [10].

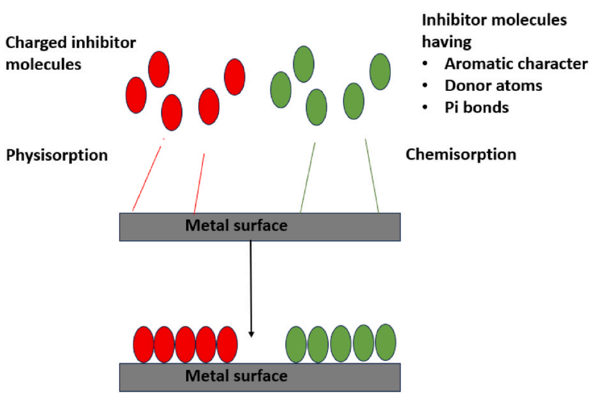


Fig. 1. Schematic representation of physisorption and chemisorption.

The cost associated with corrosion inhibitors is quite high, which has prompted researchers to focus on green corrosion inhibitors for their biodegradable and non-toxic properties. These inhibitors are made by extracting various plant extracts and using their complex phytochemicals to prevent corrosion. Phytochemicals include alkaloids, tannins, pectin, steroids, flavonoids, and glycosides, which contain nitrogen, sulfur, oxygen, or phosphorus. Various parts of plants such as stems, leaves, fruits, flowers, seeds, and roots can be used to extract desired phytochemicals. Leaves, being the main site of photosynthesis, exhibit heightened protective qualities even at low concentrations. Literature reviews indicate the feasibility of using plant extracts as effective corrosion inhibitors.

The process of extracting phytochemicals from plants involves selecting the plant portion (leaves, bark, stem, fruit, etc.) from which the phytochemicals are to be extracted. This plant component is then dried, ground, and sieved to create a powder. The desired phytochemical is then isolated and extracted using techniques such as solvent extraction, distillation, or sublimation processes. Solvent extraction is the most popular method and depends on extraction time, the ratio of solvent to solid, and a temperature that prevents active ingredients from being broken down. Ethanol is used as a solvent to extract alkaloids, flavonols, polyacetyles, tannins, sterols, and terpenoids. Methanol is used as a solvent to extract lactones, quassinoids, phenones, saponins, and total. Ether is used as a solvent to extract coumarins, fatty acids, and alkaloids, while acetone is used as a solvent to extract flavonols and tannins [11].

4. Corrosion inhibition of various kinds of steel

In a study conducted by Thapa et al., Khasianine alkaloid was extracted from Solanum xanthocarpum stem and found to be a highly effective corrosion inhibitor for mild steel in 1 M H_2SO_4. The inhibitor demonstrated a 98 % efficacy rate when tested using electrochemical measurements and was shown to be a mixed type of corrosion inhibitor. It was also found that the Khasianine alkaloid could withstand temperatures of up to 55 °C. The molecular structure of the Khasianine alkaloid is shown in Fig. 2 [12], and the mechanism of corrosion inhibition by the alkaloid is represented in Fig. 3.

Mwakalesi and their team have found a valuable use for waste by extracting an aqueous solution from it and using it as a corrosion inhibitor for mild steel in an acidic solution. Their research showed that an 81 % efficiency rate was achieved when the extract was used at a concentration of 0.5 g/L. Additionally, with elevated concentration levels, efficiency saw an increase. The inhibition arose from a homogeneous distribution of molecules adsorbed *via* physisorption, adhering to the Langmuir adsorption isotherm [13].

Khadom and his colleagues conducted a study to investigate the potential of *Cardaria darba leaves* combined with potassium iodide as a corrosion inhibitor for mild steel in a 1 M HCl environment. The inhibitor was found to form a monolayer film on the metal surface through chemisorption. The Langmuir isotherm confirmed this process, and the inhibitor showed an impressive 96 % effectiveness, especially at 60 °C. The weight-loss method revealed an inverse relationship between temperature and the extract concentration [14]. In another study, pomegranate aril extract was used as a corrosion inhibitor for mild steel exposed to 1 M HCl. This inhibitor was identified as a mixed-type anodic-cathodic inhibitor, achieving an efficiency of 74 % at 25 °C with an extract concentration of 400 g/L. However, its efficacy declined at higher temperatures. The inhibition mechanism was attributed to physical adsorption, as validated by adherence to the Langmuir adsorption isotherm [15]. El-Etre and his colleagues investigated the use of *Olea Europaea Sylvestris* (Olive leaves) as a corrosion inhibitor for steel in 1 M HCl. The inhibition mechanism was determined to be physical adsorption, in line with the Langmuir adsorption isotherm, resulting in an efficiency of 66 % at an extract concentration of 0.96 g/L [16]. Betle nutshell was discovered to avoid corrosion in Q235 steel by forming a film over the Q235 and HCl interface due to the presence of several active components like chrysophanic acid and emodin-3-methyl ether. The inhibition effect was calculated to be 93.1 % based on the corrosion current produced, which was found to be minimum i.e., 0.27 mA cm^{-2} at 0.5 g/L of extract concentration when compared to 0.05, 0.1, 0.3 g/L concentrations. This shows that inhibition efficacy is directly related to the concentration [17]. R. Karki and his team reported that alkaloids extracted from Acacia catechu have inhibitory effects on mild steel exposed to 1 M H_2SO_4. The plant extract exhibited physical adsorption and was effective up to 48 °C, displaying an efficiency of 84.4 % and had a maximum inhibitory efficiency of 93.9 % after 3 h of immersion, at 1000 ppm concentration, 28 °C [18]. Sweet yellow capsicum extract (SYCE) showed inhibitory capabilities towards steel bars in cement pore solution. The maximum degree of inhibition was 97.5 % at 300 ppm concentration. The adsorption mechanism was physisorption and obeyed the Freundlich adsorption isotherm. Gallic acid, caffeic acid, *p*-coumaric acid, ferulic acid, luteolin, and cinnamic acid are some of the most important components in the sweet yellow capsicum extract responsible for inhibiting corrosion [19]. The leaves of Fenugreek seed and Cape gooseberry were found to demonstrate

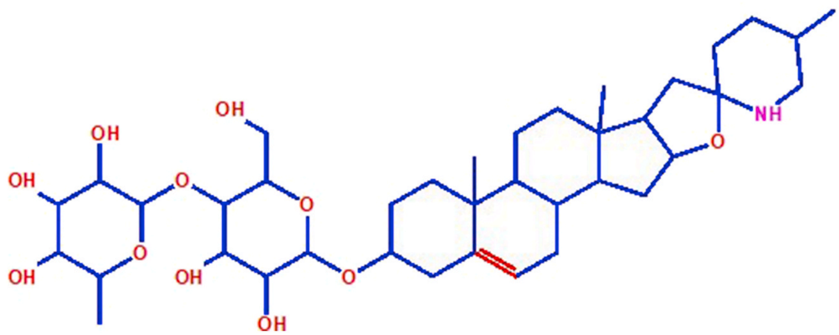


Fig. 2. Molecular structure of Khasainine alkaloid [12].

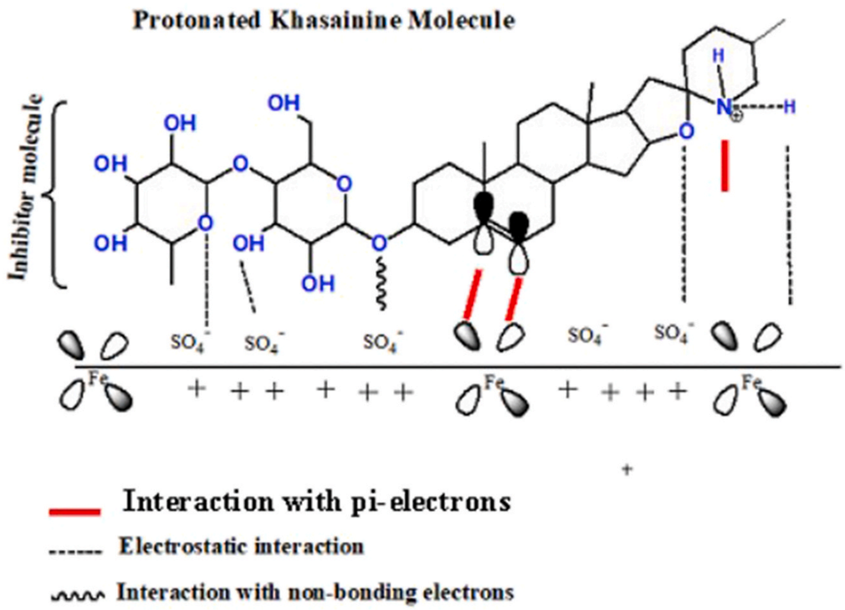


Fig. 3. Schematic representation of the mechanism of inhibition *via* interaction of alkaloid molecules with vacant *d*-orbitals of Fe. (MS – Mild Steel) [12].

corrosion inhibition for steel immersed in the H_3PO_4 for 1 h, with the formation of a coating on the surface due to L-tryptophan and Ferulic acid. The inhibition was accomplished through the physisorption mechanism. 0.4 g/L of Cape gooseberry extract and 1.2 g/L of fenugreek extracts had an 80 % inhibitory effectiveness for steel in a 20 % aqueous H_3PO_4 solution. Up to 55 °C, the inhibitory effectiveness was still strong, however as the temperature rose, the corrosion rate also increased. The structure of L-tryptophan and Ferulic acid is given in Fig. 4 [20].

Leaves extracted from *Lycoris radiata* and *Lycoris chinensis* were found to effectively inhibit the corrosion of carbon steel in acidic solutions of HF or HCl-containing chloride salt, due to a synergistic effect. Through a multi-compounding approach, it was discovered that the ideal ratio of the extracts that exhibit the strongest synergistic impact was 2:3. The maximum corrosion inhibition effectiveness of 91.5 % was observed for steel immersed in 5 % HCl at 35 °C [21]. Pineapple crown extract, which contains diverse phytochemicals and polyphenols, was utilized as a corrosion inhibitor for steel-39 in 1 M H_2SO_4 and 1 M HCl. The extract demonstrated great inhibitory efficacy due to the adsorption of phytochemicals on the surface of the steel. The greatest inhibitory efficacy of 76.8 % was achieved with 3 g/L of pineapple crown extract after 3 h of immersion. The inhibitory effectiveness increased with an increase in the concentration of the extract [22]. An extract from the *Trochodendron aralioides* plant is effective in inhibiting the corrosiveness of mild steel in 1 M HCl. The extract displayed the highest inhibitory efficacy of 96.4 % when used at a concentration of 250 ppm, although its effectiveness decreased with increasing temperature. The inhibitor worked by forming a protective oxide coating on the metal. Tafel polarization analysis indicated that it acted as a mixed-type inhibitor [23]. An extract from *Calopogonium mucunoides* was used to prevent mild steel from corroding in a solution of 0.5 M HCl. The highest level of efficiency, at 91.4 %, was achieved using an optimal concentration of 1.2 g/L at a temperature of 25 °C. Corrosion prevention efficiency decreased with increasing temperature. The most accurate description of the adsorption was provided by the Langmuir isotherm [24]. Kavitha and her team have documented their utilization of an aqueous Rosa damascena extract to mitigate mild steel corrosion within an oil-water environment. The maximum efficiency was found to be 96 % when using 0.1 M extract concentration, and the efficacy increased with extract concentration. This extract led to mixed-type inhibition, which caused the metal's surface to develop a protective barrier layer [25]. The corrosion of carbon steel in a 1 M H_2SO_4 solution was studied using an extract from *Azadiracta Indica leaves*, commonly known as Neem. The leaves were extracted using ethanol and tested for their effectiveness in preventing corrosion. It was found that the concentration of the extract had a significant impact on its ability to inhibit corrosion, with an increase in concentration resulting in an increase in corrosion inhibition efficiency from 41 % to 86 % [26]. An ethanolic extract of *Rumex* has been found to inhibit the C38 type of steel in a 1 M HCl

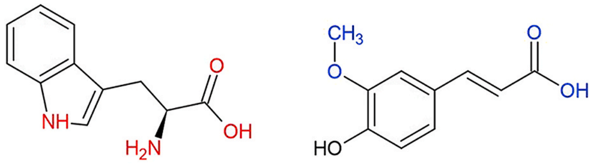


Fig. 4. (a) L-Tryptophan and (b) ferulic acid [20].

solution. The inhibition efficiency increased with the concentration of the extract but decreased at higher temperatures. The maximum inhibition efficiency of 94.6 % was achieved at 30 °C with an extract concentration of 2 g/L. At the same concentration, an inhibition efficiency of 91 % was achieved at 60 °C. Potentiodynamic polarization and impedance measurements confirmed that the inhibition mechanism was of a mixed type [27]. *Cucumber peel extract* (CPE) and *cucumber seed oil* (CSO) are effective in inhibiting the corrosion of AISI 1007 steel. The weight loss evaluation showed peak inhibitions of 94.4 % and 95.4 % respectively, when 1.0 g/L concentrations of CPE and CSO were used in seawater medium. The inhibitor showed mixed organic corrosion inhibitor behaviors and its effectiveness decreased over time. The inhibitor adhered to the Langmuir and Dubinin Radushkevich isotherms [28]. It has been reported that *Spinacia oleracea* extract can prevent carbon steel from corroding when immersed in 1.0 M HCl. To test its effectiveness, the extract was used at concentrations between 100 and 500 ppm and was found to be most effective at 500 ppm, with a maximum effectiveness of 93 %. Increasing the extract concentration also reduced the concentration of ferric ions, which in turn reduced the corrosion rate. The Langmuir isotherm was followed, indicating the formation of a protective film monolayer on the surface [29]. *Terminalia arjuna* is a plant that is commonly used in traditional medicine to treat a variety of illnesses, including diabetes mellitus, ulcers, and anemia. Recent studies have found that it also has potential as a corrosion inhibitor for mild steel in Hydrochloric acid (HCl) environments. It was found to be a mixed-type corrosion inhibitor with a maximum inhibitory effectiveness of 64.1 % when immersed in a 0.2 M HCl solution at 30 °C for 3 days [30]. *Rhus coriaria (RC),* a plant species found in Lebanon, is effective in preventing mild steel corrosion when dipped in acid solutions such as 0.5 M HCl and 0.5 M H_2SO_4. At a concentration of 0.75 g/L and a temperature of 30 °C, its corrosion inhibition efficiency was found to be 84 %. RC is considered to be a mixed-type inhibitor and follows the thermodynamic-kinetic model and the Flory-Huggins model, indicating the formation of a protective film. The inhibitory effect becomes less effective as the concentration of reactants or inhibitors increases and as the temperature rises [31]. The methanolic extract of *Equisetum hyemale* has been found to have corrosion resistance properties when applied to mild steel that has been immersed in 1 M H_2SO_4. As the temperature increased, the effectiveness of the inhibition increased for the first 6 h, demonstrating a maximum efficiency of 85 % at a 1000 ppm concentration and maintaining a steady-state value until 12 h of immersion. The surface adsorption was spontaneous, endothermic, and of mixed type. The inhibitory action followed the Langmuir isotherm, as the inhibitor adsorbed on the surface as a monolayer [32]. The anti-corrosion properties of *Date palm* leaves were studied when extracted using various organic solvents such as ethanol, acetone, and butanol. The study tested the leaves effectiveness against low-carbon steel that was dipped in a 1 M HCl solution at a temperature of 25 °C. The leaves extracted using butanol showed the highest inhibition rate of 82 % with a concentration of 400 ppm. It was observed that the efficiency of this inhibitor increased with concentration, and a concentration of 1000 ppm provided 97 % protection at a temperature between 25 °C and 40 °C. On the other hand, the inhibition performance slightly declined when the temperature was increased to 50 °C and 60 °C, demonstrating 86 % protection [33]. The extract from *Paederia Foetida* leaf has been found to inhibit the corrosion of mild-steel samples when immersed in 1 M HCl. The highest level of inhibitory efficiency, reaching 73.77 %, was observed after three days of exposure. The extract contains phytochemical compounds that physically adsorb to the steel surface, creating a barrier that prevents further corrosion. As the exposure time to the extract increased, it was also observed that the effectiveness of the inhibition decreased [34]. *Harmal* leaf extract is derived from a plant that predominantly grows in the desert of Saudi Arabia. A study reported that the extract can inhibit corrosion for carbon steel dipped in 0.25 M H_2SO_4. This property is attributed to phytochemicals like Harmine, Harmalol, Harmaline, Harmol, and Tetrahydroharmine. The study found that the highest inhibitory effectiveness was observed at an extract concentration of 283.4 ppm, which resulted in a 98 % inhibition. The extract mainly showed cathodic-type inhibition and followed the Langmuir isotherm [35]. Fekkar et al. conducted a study to determine the effectiveness of Chamaerops humilis L. fruit extracts in ethanol and hexane as inhibitors of corrosion for mild steel in a 1 M HCl solution. The study found that charge transfer regulates the corrosion mechanism as a mixed-type inhibitor. At 1 g/L concentrations of ethanol and methanol, the inhibition efficacy reaches 88 % and 80 % respectively. With higher inhibitor concentrations, the effectiveness of inhibition increases [36]. The study explored the effectiveness of using extracts from the fruit shells of *Hymenaea stigonocarpa* as a corrosion inhibitor for mild steel immersed in 0.5 mol/L H_2SO_4. The results showed that the extract was able to effectively inhibit corrosion, with a maximum efficiency of 87.2 % achieved at a concentration of 1233.4 mg/L. The extract was found to function as a corrosion inhibitor by slowing down the rate of hydrogen liberation. The inhibition process followed the Langmuir adsorption isotherm [37]. Corrosion inhibition on mild steel in 1 M H_2SO_4 by stem extract from Coriaria nepalenesis, attributed to the presence of 4-Pyrimindinecarboxylic acid and Dihydrocorynantheine, was evidenced by Fig. 5 [38]. At a temperature of 18 °C, a concentration of 1000 ppm of *Coriaria* nepalensis stem alkaloid (CNSA) solution resulted in over 96 % inhibition.

The presence of these alkaloids was confirmed using Mayer's and Dragendroff's tests reactions (Fig. 6), which show the reactions carried out to confirm the existence of 4-Pyrimidinecarboxylic acid [38]. The corrosion inhibition occurs because alkaloid molecules replace adsorbed H_2O molecules on the mild steel surface through the given reaction.

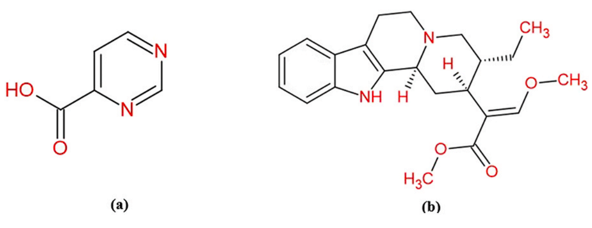


Fig. 5. Structure of 4-Pyrimindinecarboxylic acid (a) and Dihydrocorynantheine(b) [38].

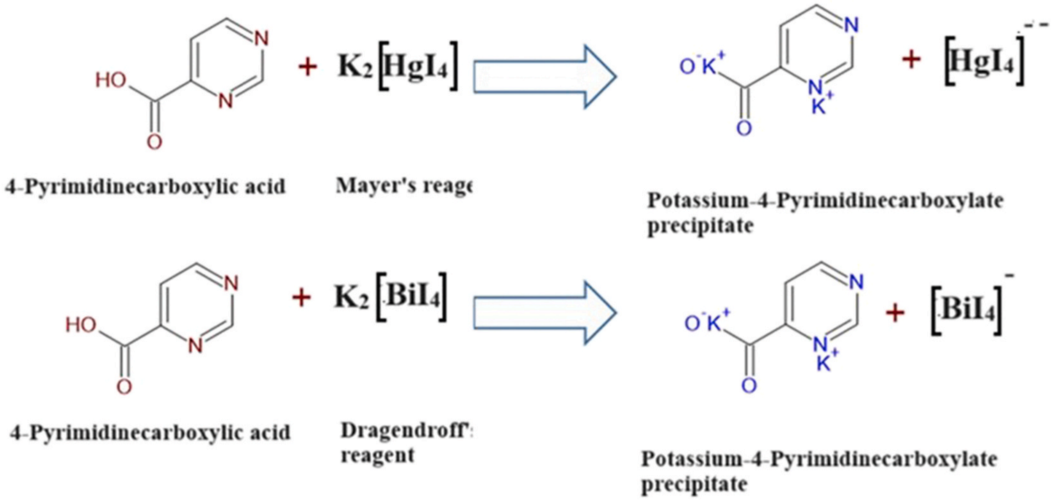


Fig. 6. Reaction during the alkaloid test [38].

Org(sol) refers to organic molecules that are dissolved in the aqueous phase, while Org(ad) represents organic molecules that are adsorbed onto a metallic surface. Similarly, H_2O (ad) represents water molecules that are adsorbed on the surface of the metal. When an alkaloid encounters H_2SO_4, it undergoes protonation, thereby reducing the availability of acid molecules to corrode mild steel. As sulphate ions move, a thin layer of sulphate is formed on mild steel. The protonated alkaloid molecules interface electrostatically with the sulphate layer to produce a second layer of the protective layer. As a result, the protonated alkaloids are transformed into neutral alkaloids by the evolution of H_2 gas. The highest inhibition efficacy was 96.4 % when mild steel was dipped in a 1000 ppm solution of the inhibitor for 6 h at 18 °C. A 97 % efficacy was reported when mild steel was immersed for 3 h. The corrosion inhibition was due to the physical adsorption of alkaloid molecules, which followed the Langmuir adsorption isotherm [38]. *Alnus nepalensis* extract was reported as inhibitor for mild steel immersed in 1 M H_2SO_4 due to 2-Amino-4-oxo-3,4-dihydro-pteridine-6-carboxylic acid, (3-nitro-pyridin-2-ylsulfanyl)-acetic acid, (6-cyano-5-methoxycarbonylmethyl-5,6-dimethyl-2-thioxo-piperidine-3-yl)-propionic acid methyl ester and camptothecin alkaloids. The molecular structure of these alkaloids is shown in Fig. 7 [38].

When alkaloid molecules are used to replace the adsorbed water molecules on mild steel, they can effectively inhibit corrosion. The alkaloids found in this extract are primarily composed of nitrogen, a heteroatom in the ring structure. When these molecules are dissolved in an acidic solution, they become protonated [39]. Due to the electrostatic force of attraction, the protonated alkaloid molecules interact with sulphate ions on the surface of mild steel and form a protective layer on the surface. An illustration of the interaction between camptothecin and the mild steel surface is provided in Fig. 8.

Berberine alkaloid extracted from *Mahonia nepalensis* was identified as an effective corrosion inhibitor for mild steel in a 1 M H_2SO_4

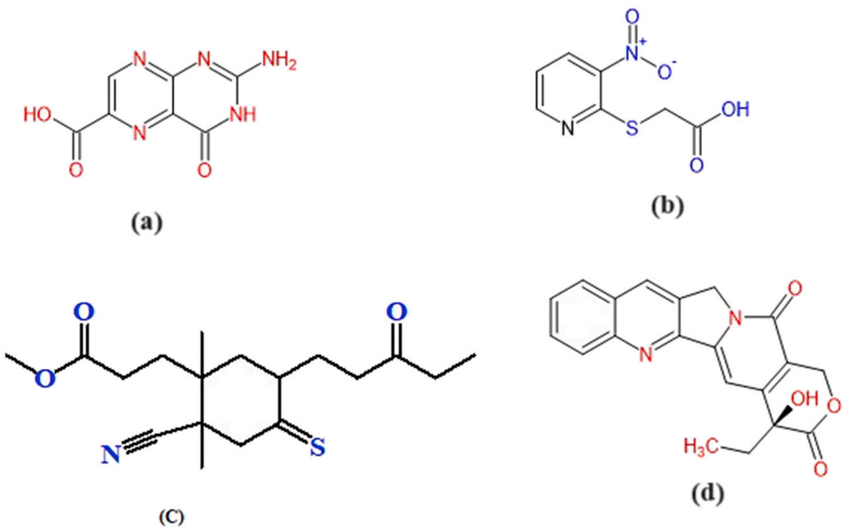


Fig. 7. (a) is 2-Amino-4-oxo-3,4-dihydro-pteridine-6-carboxylic acid, (b) is (3-nitropyridin-2-ylsulfanyl)-acetic acid, (c) is (6-cyano-5-methoxycarbonylmethyl-5,6-dimethyl-2-thioxo-piperidine-3-yl)-propionic acid methyl ester and (d) is camptothecin [38].

environment. Berberine alkaloid molecules were found to adhere to the metal surface, thereby obstructing the active sites on it, effectively safeguarding the metal against corrosion. This adsorption process of the inhibitor molecules was found to occur through the displacement of water molecules originally present on the metal surface, as represented below:

$$Org_{(sol)} + xH_2O_{(ad)} \rightarrow Org_{(ads)} + H_2O_{\ (sol)}$$

In the context of this study, $Org_{(sol)}$ pertains to organic molecules that are dissolved in the aqueous phase, while $Org_{(ads)}$ signifies the organic molecules that have adhered to the metallic surface. Similarly, $H_2O_{(ad)}$ denotes water molecules that have been adsorbed onto the metal surface. The schematic representation below illustrates the interaction between the Berberine alkaloid molecules and the surface of the mild steel (Fig. 9) [40].

An experiment was conducted to study the effect of Berberine on the inhibition of corrosion of mild steel. The results showed that a concentration of 1000 ppm of Berberine achieved a 91 % inhibition efficacy in just 0.25 h and around 94 % in 6 h. Furthermore, the inhibition efficacy increased with the concentration of the extract and the temperature, with the maximum inhibition efficacy of 97.2 % achieved at a temperature of 55 °C. These findings suggest that berberine facilitates chemical adsorption on the mild steel surface, which helps prevent corrosion. The alkaloid Berberine exhibited mixed-type inhibitory behavior and prevented corrosion by physical adsorption. Additionally, the bark and leaves extract from *Neolamarckia cadamba* showed inhibited corrosion on mild steel dipped in 1 M HCl. The primary alkaloid accountable for corrosion inhibition is 3 β-isodihydrocadambine, with its molecular structure provided in Fig. 10. These results provide insight into the nature and mechanism underlying the adsorption process facilitated by berberine, which is relevant for understanding corrosion inhibition [41].

3β -isodihydrocadambine reduces the extent of corrosion by controlling anodic and cathodic reactions. The protonation of the alkaloid in an acidic environment causes it to adsorb above the mild steel surface at the cathodic site, stopping the liberation of H_2 gas. The π-electrons of aromatic rings and the lone pair electrons of nitrogen and oxygen atoms, adsorb on anodic sites, thus reducing the anodic dissolution of mild steel [41]. The probable mode of the mechanism of inhibition is given in Fig. 11.

According to Langmuir isotherm, the corrosion inhibition rate was found to be approximately 80 % at 5 mg/L. *Annona squamosa's* extracted alkaloids Liriodenine and Oxoananlobine have been proven to be effective corrosion inhibitors on type C38 steel dipped in 1 M HCl [42]. The molecular structure of the Liriodenine and Oxoananlobine alkaloids is depicted in Fig. 12.

The observed inhibition mechanism was because physical adsorption of molecules onto the steel surface, resulting in a reduction in the availability of active sites on the surface. This adsorption behavior conformed to the Langmuir isotherm. Furthermore, the study findings revealed that the effectiveness of inhibition was temperature-dependent, exhibiting an upward trend as the concentration of the inhibitor increased [42]. An alkaloid extracted from the bark of the Cryptocarya nigra tree demonstrated corrosion inhibition properties when applied to mild steel immersed in a solution of 1 M HCl. The molecular structure of the alkaloids N-methyl-isococlaurine, N-methyllaurotetanine, and Atherosperminine present in Cryptocarya Nigeria is given below in Fig. 13 [43].

The Chemisorption facilitated the adsorption process, driven by the interaction between the unoccupied *d*-orbitals of iron and the available electron pairs from heteroatoms and multiple bonds. This type of adsorption was particularly pronounced due to the synergistic effect generated by the diverse components. The inhibitory action on mild steel was notably robust. In the case of pure alkaloids, their inhibitory mechanisms are dictated by their molecular structures and the spatial configuration of their functional groups. Fig. 14 illustrates the intricate interaction mechanism between these alkaloids and mild steel.

Leaves Persea americana leaves extract (PALE) demonstrated excellent inhibition for carbon steel in 1 M HCl, reaching 92 %, acting as a mixed-type inhibitor following the Langmuir adsorption isotherm. SEM analysis showed PALE adsorption on the metallic surface significantly decreased its dissolution rate, maintaining a clean and seamless surface. PALE exhibited antibacterial efficacy against *Staphylococcus aureus*, *Escherichia coli*, and Listeria monocytogenes, with in silico analysis suggesting apigenin and quercetin-3-

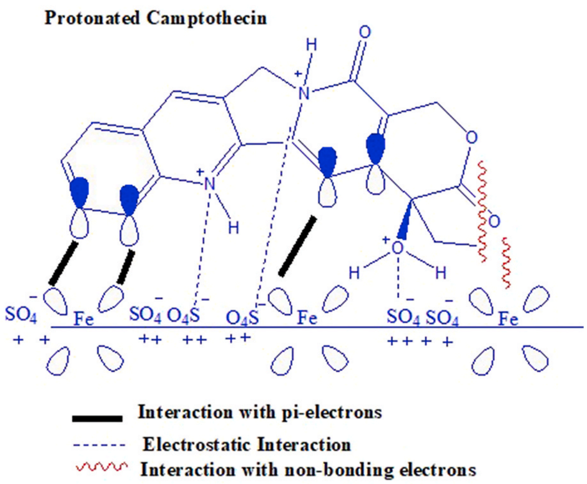


Fig. 8. Mechanism of inhibition by Camptothecin alkaloid on mild steel [39].

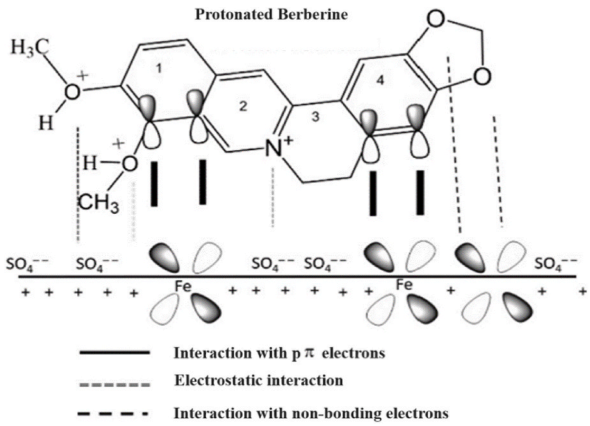


Fig. 9. Mechanism of inhibition by adsorption of the Berberine alkaloid in mild steel [40].

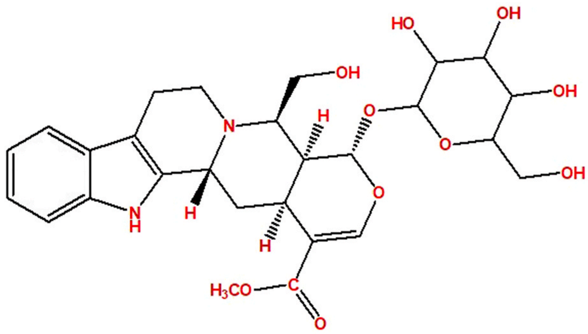


Fig. 10. Molecular structure of 3β-isodihydrocadambine [41].

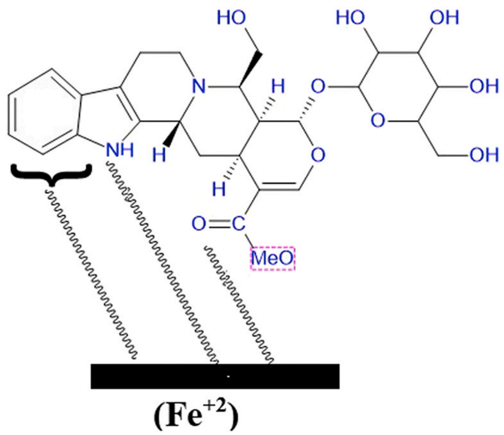
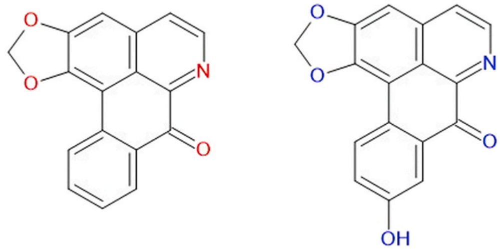


Fig. 11. Mechanism of inhibition by 3 β –iso-dihydrocadambine on mild steel [41].

glucoside as key compounds inhibiting bacterial proliferation [44]. The recently discovered plant extracts as inhibitors of corrosion as shown in Table 1.

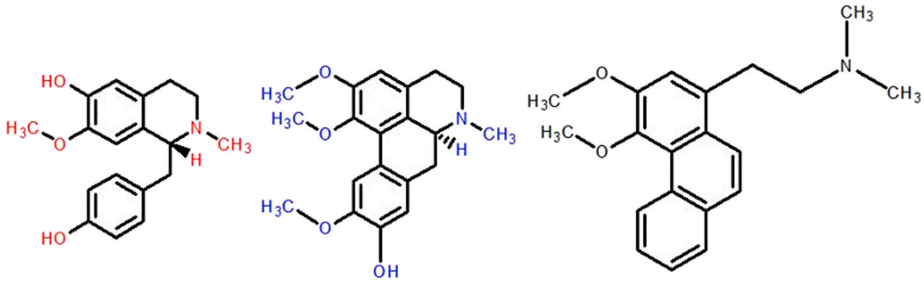
5. Drawbacks

Although plant extracts have shown potential as eco-friendly alternatives to traditional corrosion inhibitors, there are also several potential drawbacks associated with their use. The commonly used products as corrosion inhibitors as shown in Table 2. These include issues with stability and reproducibility, the effectiveness of plant extracts is subject to variation, and this variance can be attributed to



(a) (b)

Fig. 12. Molecular structure of (a) Liriodenine and (b) Oxoananlobine [42].



(1) (2) (3)

Fig. 13. Molecular structures of (1)-alkaloids N-methylisococlaurine (2) - N-methyllaurotetanine and (3)- Atherosperminine [43].

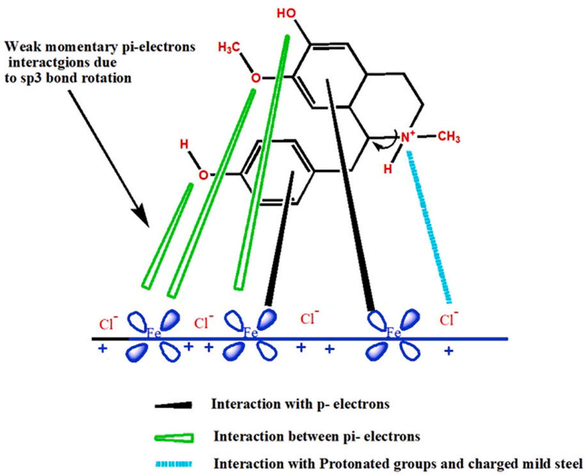


Fig. 14. Mechanism of interaction of alkaloids with mild steel [43].

factors such as the specific plant species, cultivation conditions, and the methods employed for extraction. There may also be challenges with standardization and quality control. In addition, plant extracts may be less effective or less durable than synthetic inhibitors under certain environmental conditions, and their performance can be influenced by factors such as pH, temperature, and the presence of competing ions. Other challenges associated with plant extracts as corrosion inhibitors include issues with toxicity, compatibility with other corrosion control measures, and cost-effectiveness. Climate, the vegetative cycle, geography, and rate of growth all have an impact on the concentrations of phytochemicals in plants. Although there is a plethora of literature on the utilization of plant extracts as green corrosion inhibitors, there is still a dearth of knowledge regarding their economic and commercial implications. Therefore, it is important to carefully evaluate the performance and limitations of plant extracts as corrosion inhibitors before using them in practical applications.

Table 1
Recently discovered Plant Extracts as inhibitors of corrosion.

Plant Extract	Metal	Medium With Conc.	Max Inhibition efficacy (MIE) (In %)	Testing Temp. (°C)	Duration of the test (In hr)	Remarks	Ref.
Camellia chrysantha flower	Q235 Steel	1 M HCl	65.1	30–60	4	Camellia chrysantha flower extract demonstrates corrosion inhibition for Q235 steel in 1 M HCl, with polar groups facilitating protonation and adsorption on metal surfaces, as confirmed by FTIR analysis.	[45]
Glebionis Coronaria	Carbon steel	1 M HCl 0.5 M H_2SO_4	79 86.6	20–40	4	Plant extract exhibits notable corrosion inhibition for carbon steel in 1 M HCl and 0.5 M H_2SO_4, demonstrating 79 % and 86.6 % efficiency at 20 °C, with a mixed-type action through Langmuir adsorption, enhanced efficiency at 40 °C (84.4 % and 92.2 %), synergistic interaction with KI, and the formation of a preventive coating confirmed by SEM–EDX examination.	[46]
Kleinhovia hospita	Q235 steel	1 M HCl	99	30	2.5	The corrosion inhibition efficiency of a plant extract on carbon steel in 1 M HCl is assessed by combining electrochemical corrosion test methods with in-situ quantification of H_2 evolution. The results are then correlated with SEM characterization of H_2	[47]
Maple leaves	Q235 steel	0.5 M H_2SO_4	93.4	30	48	Maple leaves extract (MLE) and potassium iodide (KI) exhibit synergistic corrosion inhibition on Q235 steel in 0.5 M H_2SO_4, achieving a superior combined protection effect with a corrosion inhibition efficiency (η) of 93.4 % at 200 mg/L MLE and 200 mg/L KI, surpassing the maximum η of 81.6 % with MLE alone.	[48]
Datura stramonium plant	Carbon steel	1 M HCl	94.2	30	6	Datura stramonium seed extracts, obtained with various solvents, exhibit significant corrosion inhibition for mild steel in 1 M HCl, with a maximum inhibition efficiency of 94.2 % observed for the methanolic extract at 200 mg/L concentration.	[49]
Lippia javanica leaf	Mild steel	1 M HCl	98	30	1	Lippia javanica leaf extract, primarily composed of verbascoside, exhibits significant potential as a mild steel corrosion inhibitor in 1 M HCl acidic media, assessed through weight loss measurements and thermodynamic parameter analysis.	[50]
Rheum ribes (RR) leaf	Mild steel	1 M HCl	94.9	25	1	Increasing RR leaf extract concentration resulted in a stronger inhibition effect, forming a stable and homogeneous protective film on the MS surface, with enhanced protection efficiency from 91.8 % to 94.9 % when 998.85 mg/L KI was added to the inhibited acid solution.	[51]
Feverfew root	Q235 Carbon steel	0.5 mol/L H_2SO_4	91	30	96	The research findings indicate a positive correlation between the concentrations of feverfew root (FRE) combined with potassium iodide (KI) and corrosion inhibition efficiency, reaching a remarkable 97.24 % at 400 mg/L FRE and 60 mg/L KI using the Electrochemical Impedance Spectroscopy (EIS) method.	[52]

(*continued on next page*)

Table 1 (*continued*)

Plant Extract	Metal	Medium With Conc.	Max Inhibition efficacy (MIE) (In %)	Testing Temp. (°C)	Duration of the test (In hr)	Remarks	Ref.
Fructus cannabis	Q235	1 M HCl	90	30	240	Fructus cannabis protein powder, extracted with water as a green solvent, serves as an environmentally friendly corrosion inhibitor for carbon steel in 1 M HCl. Electrochemical tests, including EIS and PDP, consistently reveal the FP inhibitor's remarkable corrosion inhibition efficiency, peaking at around 98 %.	[53]
Spinach	Mild steel	0.5 M HCl	90	30	8	Spinach extract (AESPE) is primarily chlorophyll-based, is stable in 0.5 M hydrochloric acid, and serves as a mixed-type corrosion inhibitor for Q235, markedly reducing corrosion rates through effective inhibition of both cathodic and anodic processes. This inhibition, surpassing 90 % inhibition at 30 °C with a 300 mg/L concentration, is attributed to Langmuir isothermal adsorption and charge transfer mechanisms, as validated by QCC analysis by experimental results.	[54]
Euphorbia prostrate	Mild steel	1 M H_2SO_4	96.2	20	6	The aqueous extract of Euphorbia prostrate plant, containing various phytochemicals, proves effective in reducing mild steel corrosion during acid cleaning, with a maximal inhibition efficiency of 96.23 % in 1 M H_2SO_4 at 1500 mg/L. Multiple bonds and heteroatoms in the phytochemicals contribute to the extract's anticorrosive properties, as confirmed by characterization techniques.	[55]
Brassica juncea stem	Mild steel	0.5 M H_2SO_4	90	20	6	The Brassica juncea stem extract exhibited significant corrosion inhibition for mild steel in 0.5 M H_2SO_4, reaching an optimal inhibition efficiency of 90 % at 20 °C with a concentration of 998.85 mg/L during a 6-hr immersion period, and polarization studies indicated a mixed-type inhibitor behavior.	[56]
Dracocephalum	Mild steel (st-37)	0.5 M H_2SO_4 1 M HCl	89 88	25	0.5	Dracocephalum extract, in both bulk and nano forms, exhibited substantial corrosion inhibition for mild steel in 0.5 M H_2SO_4 and 1.0 M HCl, with the highest efficiencies at 74.9 mg/L and 199.7 mg/L, respectively, underscoring its environmentally friendly and cost-effective potential as a green inhibitor.	[57]
Bougainvillea glabra petals	Mild steel	1 M H_2SO_4	93.1	20	5	The B. glabra petal extract displayed robust corrosion inhibition for mild steel in 1.0 M sulfuric acid, achieving an optimal efficiency of 93.13 % at 247.7 mg/L, validated through experimental, theoretical, and surface studies, contributing to sustainable development by reducing metal corrosion losses in acidic conditions.	[58]
Opuntia ficus-indica	Mild steel	1 M HCl	94.6	40	2	Corrosion inhibitory effects of prickly pear nopales-derived Pulp (PPUN) on mild steel in 1 M HCl solution, utilizing electrochemical studies, SEM, AFM, and XPS methods, revealing its	[59]

(continued on next page)

Table 1 (*continued*)

Plant Extract	Metal	Medium With Conc.	Max Inhibition efficacy (MIE) (In %)	Testing Temp. (°C)	Duration of the test (In hr)	Remarks	Ref.
						potential as an eco-friendly inhibitor with adsorption capabilities on metal surfaces.	
Jacaranda mimosaefolia flower	1018 carbon steel.	Concrete pore solution having chlorine	28	25 + 2	21	The inhibitory behavior of Jacaranda mimosaefolia flower extract and its green copper nanoparticles (GCuJmNPs) on steel in an HCl medium was investigated, indicating the flower extract as a superior cathodic inhibitor, while GCuJmNPs demonstrated a 28 % green corrosion inhibition efficiency, paving the way for further exploration of green metallic nanoparticles as corrosion inhibitors.	[60]
Fatsia japonica leaves	Carbon steel	Concrete pour	89.6	20	12	Fatsia japonica leaf extract exhibited significant corrosion inhibition in chlorine-containing simulated concrete pore solution, reaching an 89.6 % inhibition rate at 1000 mg/L, stabilized at 91.2 % over time, and demonstrated effective adsorption on carbon steel substrate, proposing an eco-friendly and durable corrosion resistance solution for the building and construction industry.	[61]
Eupatorium adenophorum Spreng leaves	Cold rolled steel in citric acid ($H_3C_6H_5O_7$)	1 M	75	30	24	The Eupatorium adenophorum Spreng leaves extract (EASLE) and KI synergistically inhibit cold rolled steel corrosion in citric acid, with a combined efficiency exceeding 90 %, demonstrating a synergistic effect that significantly reduces surface corrosion and roughness, attributed to the presence of phenylpropanoids like chlorogenic acid, caffeic acid, and ferulic acid in EASLE.	[62]
Apple pomace	Mild steel	1 M HCl	90	25–55	8	The apple pomace extract demonstrated effective green corrosion inhibition for mild steel in 1 M HCl, achieving up to 90 % corrosion mitigation with a smooth surface and confirmed adsorption of biomolecules, suggesting its potential as an eco-friendly corrosion inhibitor for industrial applications.	[63]
Tomato pomace	Mild steel	0.5 M NaCl	98	25	48	Tomato pomace extract (TPE) exhibits notable green corrosion inhibition for mild steel in sodium chloride solution, reaching 98 % efficiency at 499.42 mg/L after 48 h, with strong metal bonding capabilities observed through various analyses, and adherence to the Langmuir isotherm.	[64]
Prosopis farcta	St37 steel	1 M HCl	91	25	72	Prosopis farcta extract exhibited significant corrosion inhibition (up to 91 % in the Tafel test, 94 % in the EIS test, and 82 % in the weight loss test) on St37 steel in 1 M hydrochloric acid, owing to its mixture of oily compounds, alkaloids, and flavonoids, demonstrating mixed-type behavior.	[65]
Eucalyptus leaves	Mild steel	0.5 M H_2SO_4 and 0.5 M H_3PO_4	>93	30	0.33	The extract was a mixed kind of inhibitor. Inhibition efficacy is lower in the H_3PO_4 solution as the active compounds (AC) of the extract are	[66]

(continued on next page)

Table 1 (*continued*)

Plant Extract	Metal	Medium With Conc.	Max Inhibition efficacy (MIE) (In %)	Testing Temp. (°C)	Duration of the test (In hr)	Remarks	Ref.
						adsorbed over an iron phosphate film whereas in the H_2SO_4 solution, there is direct adsorption of AC.	
Combretum indicum (CI)	Mild steel	1 M HCl	84	30	10	The experimental techniques consistently confirm the corrosion inhibition effect of CI leaf extract, revealing a sensitivity of the steel dissolution rate to the extract concentration, whereby an increase results in a reduced corrosion rate and achieves high protection efficiency.	[67]
Ranunculus arvensis	Steel	1 M HCl	>90	25	72	Examining Ranunculus arvensis (RA) and Glycine max (GM) extracts as eco-friendly corrosion inhibitors for mild steel in 1 M HCl unveils heightened inhibition efficiency with escalating concentrations. This is supported by electrochemical and theoretical analyses, highlighting RA's superior effectiveness over GM.	[68]
Nettle extract (NE)	X38 Mild steel	0.5 M H_2SO_4	95	30	3	At 4000 mg/L concentration, NE demonstrated 90 % maximum corrosion inhibition efficiency as a mixed-type inhibitor, evident from polarization studies, accompanied by increased charge transfer resistance and decreased double-layer capacitance values in EIS, with surface characterization confirming the formation of a protective NE layer on the steel surface.	[69]
Syzygium cumini Leaf extract	API 5L steel	1 M HCl	93	25	220	Thorough characterization using PDP, EIS, FTIR, and AFM revealed the novel cumini extract's excellent corrosion inhibition properties, achieving a remarkable 93 % inhibition efficiency.	[70]
Aerva lanata flowers(ALF)	Low carbon steel	1 M HCl	88	25	8	ALF demonstrates environmentally benign corrosion inhibition for low-carbon steel in 1 M HCl, with over 88 % efficiency at 599.34 mg/L, confirmed by mass loss, electrochemical measurements, and SEM, functioning as a mixed-type inhibitor following Langmuir adsorption isotherm on the steel surface.	[71]
Stachys scardica Hayek leaves	Mild steel	1 M HCl	92	30	6	Stachys scardica Hayek leaves extract from Eastern Kosovo effectively inhibits mild steel corrosion in 1 M HCl medium, demonstrating excellent protection with up to 92 % inhibition at 600 mg/L concentration.	[72]
Artemisia capillaris leaf	Q235 steel	1 M HCl	99	25–26	6	A study conducted by Zhang and coworkers suggests a potential alternative approach to metal corrosion inhibition by leveraging the synergistic effects of plant extracts in combination with other inhibitors.	[73]
Carissa macrocarpa	Copper	0.5 M HNO_3	91	25	4	Exploring Carissa macrocarpa leaf extract as an efficient and eco-friendly corrosion inhibitor for copper reveals over 91 % inhibition, broad temperature effectiveness, spontaneous adsorption, and a molecular preference for oxygen heteroatoms in adsorption.	[74]

(*continued on next page*)

Table 1 (*continued*)

Plant Extract	Metal	Medium With Conc.	Max Inhibition efficacy (MIE) (In %)	Testing Temp. (°C)	Duration of the test (In hr)	Remarks	Ref.
Peach pomace (PP)3-Amino propyltriethoxysilane (APTES) PP + APTES	Steel	Industrial water	99.2	25	750	The synergistic corrosion inhibition for steel in saline solution is achieved through a mix of peach pomace extract (PPE) and 3-Aminopropyl-triethoxysilane, providing over 750 h of protection with a 99.25 % efficiency at 449.42 mg/L, attributed to the synergism between PPE and APTES.	[75]
Cinchonain IIa	Q235 Steel	HCl	98	25	48	Cinchonain IIa, synthesized through straightforward recrystallization, acts as a mixed-type corrosion inhibitor, effectively impeding both anodic dissolution and cathodic hydrogen evolution of Q235 steel in an HCl medium by forming a robust protective film through physical/chemical adsorption.	[76]
Alternanthera philoxeroides	Cold rolled steel	0.1 M Cl_3CCOOH	94	25	6	Alternanthera philoxeroides extract (APE) exhibits excellent corrosion inhibition for cold rolled steel (CRS) in Cl_3CCOOH solution, with a 94 % inhibition efficiency at 200 mg/L, operating as a mixed-type inhibitor and forming a protective film, as validated by various analytical techniques.	[77]
Petroselinum crispum	Carbon Steel	1 M H_2SO_4	90.2	30	1	Petroselinum crispum (PC) extract effectively inhibits C-steel corrosion in 1 M sulfuric acid, exhibiting a mixed-type inhibition behavior, with enhanced effectiveness at higher extract doses and temperatures, as determined through mass loss, electrochemical, FT-IR, and XPS analyses.	[78]
Elettaria cardamomum pod	Mild steel	1 M HCl	60.6	30	1	The ethanolic extract of Elaeagnus umbellata leaves (ECPE) demonstrates effective corrosion inhibition of mild steel (MS) in 1 N HCl, as evidenced by gravimetric, electrochemical, spectroscopic, and surface morphological studies, achieving a maximum inhibition efficiency of 60.6 % at 249.7 mg/L ppm after 1 h of immersion.	[79]
Grapefruit and Lemongrass distillates	Carbon steel	0.5 M H_2SO_4 0.5 M HCl	96.3–98.3	25	240	The blend of grapefruit and lemongrass distillates proves effective in inhibiting corrosion of plain carbon steel in 0.5 M H_2SO_4 and HCl solutions, achieving inhibition values ranging from 96.31 % to 99.5 %, with strong chemisorption, covalent bonding, and passivation of the steel surface observed through weight loss analysis and optical macroscopy studies.	[80]
Uncaria laevigata	Q235 steel	1 M HCl	90	93	48	Derived from Uncaria laevigata, Cinchonain IIa proves to be a highly effective and sustainable green corrosion inhibitor for Q235 steel in 1 M HCl, with over 93 % inhibition efficiency lasting up to 28 days, showcasing low toxicity and industrial potential in oilfield acidification and acid pickling.	[81]
Ficus pumila Linn	XC38 steel	NaCl	90	20	2	Optimal corrosion inhibition for XC38 steel in NaCl solution is achieved	[82]

(*continued on next page*)

Table 1 (*continued*)

Plant Extract	Metal	Medium With Conc.	Max Inhibition efficacy (MIE) (In %)	Testing Temp. (°C)	Duration of the test (In hr)	Remarks	Ref.
						through the synergistic effect of Ficus pumila Linn. leaves hydroalcoholic extracts (HEFP) and zinc ions, demonstrating the formation of organometallic complexes and proposing a mechanism involving concerted reactions between steel oxidation products, zinc ions, and complexing agents present in the extract at concentrations of 199.7 mg/L HEFP and 49.94 or 99.98 mg/L zinc ions.	
Commiphora myrrha (CM)	Low Carbon steel	Dilute HCl Dilute H_2SO_4	>85	30	72–96	CM exhibited suboptimal corrosion inhibition at low concentrations, while Cymbopogon nardus demonstrated effective performance; their combined admixture displayed poor inhibition in H_2SO_4.	[83]
Xylocarpus Moluccensis	Mild steel	Dilute HCl	64	30–50	1	Xylocarpus moluccensis extract, rich in phenolic and flavonoid acids, demonstrated a maximum inhibition efficiency of 64 % as a mixed-type corrosion inhibitor in 1 M HCl at 40 °C, as revealed by electrochemical Tafel polarization analysis.	[84]
Rosa langevita	Copper	0.5 M H_2SO_4	89.8	*25*	10	The extract comprising 6,7-dimethoxy-coumarin, catechin, kaempferol, and loliolide, confirmed *via* HPLC-MS, 81exhibits excellent corrosion inhibition, especially as a mixed-type inhibitor in sulfuric acid solution, achieving 89.8 % efficiency at 300 mg/L, with efficacy increasing with concentration and maintaining stability within a temperature range.	[85]
Apium graveolens, Punica granatum, and Camellia sinensis, plants	Carbon steel	0.5 M H_2SO_4	60	25	240	Plant extracts demonstrate concentration-dependent corrosion inhibition of plain carbon steel in dilute acid, with cathodic inhibition effects, mitigating H_2 evolution and O_2 reduction reactions, and enhancing steel morphology in the corrosive medium.	[86]
Cumin essential oil	Mild steel	0.5 M HCl	>79	25	2	Rizi and coworkers reported establishes cumin essential oil is a robust and eco-friendly solution for effectively preventing corrosion in mild steel exposed to acidic environments, offering a significant contribution to corrosion science and sustainable protection for critical infrastructure.	[87]
Terminalia bellirica fruit	304 Stainless Steel	1 M HCl	95	25	6	Terminalia bellirica fruit extract significantly decreases corrosion current density, enhances pitting resistance, and exhibits a very high corrosion inhibition efficiency of 95 % at 300 mg/L in hydrochloric acid, with physical adsorption leading to inhibition, conforming to the Langmuir adsorption isotherm model.	[88]
Rosemary Extract	Carbon steel	1 M HCl	92	25	6	Exploring the anticorrosion impact of Rosemary extract in 1 M HCl media revealed a substantial reduction of steel corrosion by around 92 % at the optimal condition of 799.08 mg/L,	[89]

(*continued on next page*)

Table 1 (*continued*)

Plant Extract	Metal	Medium With Conc.	Max Inhibition efficacy (MIE) (In %)	Testing Temp. (°C)	Duration of the test (In hr)	Remarks	Ref.
						attributed to the presence of heteroatoms in the phytochemicals facilitating adsorption and corrosion inhibition.	
Glebionis Coronaria	Carbon steel	1 M HCl 0.5 M H_2SO_4	79 86.6	20	15	Glebionis Coronaria extract (GCE), rich in organic secondary metabolites, including flavonoids, tannins, polyphenols, and coumarin, proves effective as a green corrosion inhibitor for carbon steel in 1 M HCl and 0.5 M H_2SO_4, exhibiting a maximum efficiency of 79 % and 86.6 % 20 °C, with a mixed-type action through Langmuir adsorption and enhanced inhibition at higher temperatures, supported by characterization techniques.	[90]

6. Future work

Research into corrosion inhibitors shows promising potential, with ongoing efforts aimed at improving their effectiveness and aligning with environmental sustainability objectives, including sustainable development goals.

6.1. Key research avenues include

Green corrosion inhibitors: Mother Nature's toolbox is unlocking new weapons in the fight against corrosion. Researchers are developing eco-friendly inhibitors derived from plants and biopolymers like chitosan and starch. These natural powerhouses are biodegradable, minimizing environmental impact while still offering impressive corrosion-fighting abilities.

Nanotechnology Applications: The utilization of metal oxide nanoparticles, including silver oxide and zinc oxide, synthesized *via* eco-friendly approaches such as plant extracts or bio-based reducing agents, is being explored. Additionally, there is a focus on developing nanocomposites by combining these nanoparticles with bio-based polymers like polylactic acid and polyhydroxyalkanoates, aiming to enhance corrosion protection while ensuring biodegradability.

Combination with other Functionalities: Integrating corrosion inhibitors into multifunctional coatings offers more than just anti-corrosion benefits; it extends to providing additional functionalities such as self-healing, antimicrobial effects, or anti-fouling capabilities. This approach not only enhances protective coatings but also enables diverse applications, thereby improving overall performance.

Advancing environmentally responsive inhibitors involves the development of corrosion inhibitors that react to environmental cues, such as fluctuations in pH, temperature, or humidity. This leads to the creation of a dynamic and adaptable corrosion protection mechanism capable of adjusting to diverse environmental conditions.

In summary, the future of corrosion inhibition involves a shift towards sustainable and eco-friendly solutions, incorporating nanotechnology for enhanced effectiveness, combining multiple functionalities in coatings, and developing inhibitors that respond to environmental changes. These approaches aim to improve the overall performance of corrosion protection while minimizing the environmental impact of the inhibitors themselves.

7. Conclusions

The fight against corrosion is complex, and it demands innovative preventive methods. Green corrosion inhibitors, particularly those derived from plants, are gaining significant interest due to their safety and environmental benefits. They are safer to handle, gentler on the environment, and offer a distinct advantage over traditional inhibitors. With their inherent chemical diversity, plant extracts create a synergistic effect that produces a more complete and effective corrosion inhibition mechanism. This review explores the various plant-based inhibitors and highlights the need to evaluate their efficacy. Careful selection and performance assessment are essential for maximizing the benefits of green corrosion inhibitors. By using green inhibitors, we can protect metals efficiently with minimal environmental and health impact, aligning perfectly with sustainability goals. Organic corrosion inhibitors are vital weapons in the battle against metal corrosion. Continued research is necessary to enhance their effectiveness and unlock the secrets behind their complex mechanisms. The pursuit of new and improved organic inhibitors holds the potential to reduce the toll corrosion takes on metal surfaces and extend the lifespan of countless metal structures. Therefore, the importance of organic corrosion inhibitors cannot be understated, and ongoing research is essential to unlock their full potential in preventing corrosion.

Table 2
Plant-based products as a corrosion inhibitor.

Commonly used product	Metal	Medium with conc.	Max Inhibition efficacy (MIE) in %	Temp. (°C)	Duration of the test	Remarks	Ref
Ginger and grapefruit oil	Mild Steel	0.5 M H_2SO_4	98.1	35	240	Terpenes present in the extract were responsible for the inhibition of corrosion. The following terpenes were found • Terpineol • Cineole Citronellal.	[91]
Mustard Seed	Mild steel	1 M HCl	97	2 25	3	MIE was found to be 97 % in 200 mgL-1 of HCl solution. Langmuir adsorption isotherm was followed and inhibition was mainly due to the presence of Alkaloid barberine.	[92]
Castor and Sesame oil	Mild steel	0.79 M brine solution	86.2	27	336	The extract behaved as a mixed kind of indicator and inhibition was mainly due to the presence of Alkaloid ricinine.	[93]
Garlic	AISI 304 stainless steel	0.5 M HCl	88	27	720	MIE was obtained as 88 % with 8 ccL^{-1} of solution. The extract behaved as a mixed kind of inhibitor and followed Langmuir adsorption isotherm and inhibition was mainly due to the presence of Allyl propyl disulphide.	[94]
Carrot peel	Mild steel	1 M HCl	88.1	50	6	The rate of corrosion increased with the temperature rise and decreased with a reduction in inhibitor concentration. Freundlich isotherm was followed and inhibition was mainly due to the presence of Pyrrolidine.	[95]
Citrus limetta - Mosambi	Mild steel	1 M HCl	93	30	24	MIE was found to be 93 % with an EC of 400 ppm. The extract behaved as a mixed kind of inhibitor. Increase in temperature reduced the efficacy of inhibitor and inhibition was mainly due to the presence of Limonene.	[96]
Orange peel	Stainless steel	1 M HCl	80 %	27	2	The efficacy decreases with increase in immersion time and inhibition was mainly due to the presence of Antioxidants -Neohesperidin, Naringin, Ascorbic acid.	[97]
Pomegranate extract	Carbon steel	NaCl	93.3	25	–	MIE was obtained to be 93.3 % with 300 ppm of EC. Inhibition efficacy increases with EC. The inhibitor molecules physically adsorbed on the metal and followed Temkin isotherm.	[98]
Black Pepper	C38 steel	1 M HCl	95.8	35	6	MIE was 95.8 % at 2 gL^{-1} of EC. Inhibition follows Langmuir isotherm and inhibition was mainly due to the presence of Alkaloid piperine.	[99]
Cashew nutshell	Thermo-mechanically treated steel	Seawater.	75	30	360	MIE was found to be 75 % at 30 °C with 500 ppm of EC.	[100]

Data availability statement

Data will be made available on request.

Additional information

No additional information is available for this paper.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

Bhoomika R. Holla: Validation, Funding acquisition, Formal analysis. **R. Mahesh:** Writing – original draft, Conceptualization. **H. R. Manjunath:** Visualization, Resources, Methodology. **V. Raghu Anjanapura:** Writing – review & editing, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Dr Anjanapura V Raghu.

References

[1] L.T. Popoola, Organic green corrosion inhibitors (OGCIs): a critical review, Corrosion Rev. 37 (2) (2019) 71–102, https://doi.org/10.1515/corrrev-2018-0058.

[2] D.S. Chauhan, C. Verma, M.A. Quraishi, Molecular structural aspects of organic corrosion inhibitors: experimental and computational insights, J. Mol. Struct. 1227 (2021). https://doi:10.1016/J.MOLSTRUC.2020.129374.

[3] C. Verma, Recent developments in sustainable corrosion inhibitors: design, performance and industrial scale applications), Mater. Adv. 2 (2021) 3806–3850, https://doi.org/10.1039/D0MA00681E.

[4] B.E. Amitha Rani, B.J. Bai Basu, Green inhibitors for corrosion protection of metals and alloys: an overview, Int. J. Corros 2012 (15) (2012), https://doi.org/10.1155/2012/380217.

[5] A. Zakeri, E. Bahmani, A.S.R. Aghdam, Plant extracts as sustainable and green corrosion inhibitors for protection of ferrous metals in corrosive media: a mini-review, Corros. Commun. 5 (2022) 25–38, https://doi.org/10.1016/j.corcom.2022.03.002.

[6] Taher Rabizadeh, Shahin Khameneh Asl, Casein as a natural protein to inhibit the corrosion of mild steel in HCl solution, J. Mol. Liq. 276 (2019) 694–704, https://doi.org/10.1016/j.molliq.2018.11.162 (ISSN 0167-7322.

[7] P.B. Raja, M.G. Sethuraman, Natural products as corrosion inhibitor for metals in corrosive media-A review, Mater. Lett. 62 (1) (2008) 113–116. https://doi:10.1016/j.matlet.2007.04.079.

[8] H. Wei, B. Heidarshenas, L. Zhou, G. Hussain, Q. Li, K. Ken, Ostrikov, Green inhibitors for steel corrosion in the acidic environment: state of art, Mater. Today Sustain. 10 (2020) 100044. https://doi:10.1016/J.MTSUST.2020.100044.

[9] M. Abdallah, Antibacterial drugs as corrosion inhibitors for corrosion of aluminum in hydrochloric solution, Corrosion Sci. 46 (8) (2004) 1981–1996. https://doi:10.1016/J.CORSCI.2003.09.031.

[10] K.K. Kennedy, K.J. Maseka, M. Mbulo, K.K. Kennedy, K.J. Maseka, M. Mbulo, Selected adsorbents for removal of contaminants from wastewater: towards engineering clay minerals, Open J. Appl. Sci. 8 (8) (2018) 355–369. https://doi:10.4236/OJAPPS.2018.88027.

[11] S.Z. Salleh, et al., Plant extracts as green corrosion inhibitor for ferrous metal alloys: a review, J. Clean. Prod. 304 (2021). https://doi:10.1016/j.jclepro.2021.127030.

[12] O. Thapa, et al., Alkaloids of Solanum xanthocarpum stem as green inhibitor for mild steel corrosion in one molar sulphuric acid solution, Electrochemistry (Tokyo, Jpn.) 3 (4) (2022) 820–842. https://doi:10.3390/electrochem3040054.

[13] A.J. Mwakalesi, M. Nyangi, Effective corrosion inhibition of mild steel in an acidic environment using an aqueous extract of macadamia nut green peel biowaste, Eng. Proc. 1 (1) (2023) 41, https://doi.org/10.3390/ASEC2022-13804.

[14] A.A. Khadom, A.N. Abd, N.A. Ahmed, Synergistic effect of iodide ions on the corrosion inhibition of mild steel in 1 M HCl by Cardaria Draba leaf extract, Results Chem 4 (2022) 100668. https://doi:10.1016/j.rechem.2022.100668.

[15] M. Shahsavari, A. Imani, E. Asselin, Pomegranate arils extract as a green corrosion inhibitor for mild steel: effect of concentration and temperature in hydrochloric acid, Mater. Res. Express 9 (11) (2022). https://doi:10.1088/2053-1591/aca06c.

[16] A.Y. El-Etre, Inhibition of acid corrosion of carbon steel using aqueous extract of olive leaves, J. Colloid Interface Sci. 314 (2) (2007) 578–583, https://doi.org/10.1016/j.jcis.2007.05.077.

[17] Z. Zipeng, Y. Yan, Z. Gao, Betel nut shell water extract as a green corrosion inhibitor for Q235 steel in 1 M HCl, Int. J. Electrochem. Sci. 17 (2022), https://doi.org/10.20964/2022.11.47.

[18] R. Karki, et al., Acacia catechu bark alkaloids as novel green inhibitors for mild steel corrosion in a one molar sulphuric acid solution, Electrochemistry (Tokyo, Jpn.) 3 (4) (2022) 668–687, https://doi.org/10.3390/electrochem3040044.

[19] M.A. Deyab, Q. Mohsen, Inhibitory capabilities of sweet yellow capsicum extract toward the rusting of steel rebars in cement pore solution, ACS Omega 8 (3) (2023) 3303–3309, https://doi.org/10.1021/acsomega.2c06639.

[20] A.M. Abdel-Gaber, A. Ezzat, M.E. Mohamed, Fenugreek seed and cape gooseberry leaf extracts as green corrosion inhibitors for steel in the phosphoric acid industry, Sci. Rep. 12 (2022) 22251, https://doi.org/10.1038/s41598-022-26757-z.

[21] Z. Xia, X. Zhang, Study on corrosion resistance of carbon steel in HF/HCl acid mixture in presence of Lycoris radiata and Lycoris chinensis leaf extract as environmentally friendly corrosion inhibitor, Int. J. Electrochem. Sci. 17 (9) (2022) 220921, https://doi.org/10.20964/2022.09.20.

[22] A. Jano, A. Lame, E. Kokalari, Pineapple crown extract as green inhibitor for steel 39 in acidic media, in: Proceedings of the 8th World Congress on Mechanical, Chemical, and Material Engineering, Avestia Publishing, Aug. 2022, https://doi.org/10.11159/iccpe22.114.

[23] P. Baskar, P. Rathinapriya, M.P.- Processes, Use of Trochodendron aralioides extract as green corrosion inhibitor for mild steel in 1M HCl solutions, Processes 10 (8) (2022) 1480, https://doi.org/10.3390/pr10081480, 2022.

[24] O. Kelvin Amadi, S. Mbanyeaku Ufearoh, I. Ajah Okoro, P. Adaeze Ibezim, Mitigation of the corrosion of mild steel in acidic solutions using an aqueous extract of Calopogonium muconoide (cm) as a green corrosion inhibitor, Commun. Phys. 8 (3) (2022) 364–377. https://journalcps.com/index.php/volumes/article/view/295/255.

[25] K. Kavitha, H. Sherine, S.R.-Int J. Corros S. Inhib, Rosa damascena (Damask Rose) as corrosion inhibitor for mild steel in simulated oil well water medium, Int. J. Corros. Scale Inhib. 11 (2) (2022) 851–861, https://doi.org/10.17675/2305-6894-2022-11-2-26.

[26] R. Mahesh, et al., Removal of pollutants from wastewater using alumina based nanomaterials: a review, Kor. J. Chem. Eng. 40 (9) (2023), https://doi.org/10.1007/s11814-023-1419-x.

[27] H.A. Al-Sharabi, et al., Electrochemical and thermodynamic evaluation on corrosion inhibition of C38 steel in 1 M HCl by Rumex ethanolic extract, Int. J. Corros. Scale Inhib. 11 (1) (2022) 382–401, https://doi.org/10.17675/2305-6894-2022-11-1-23.

[28] H.G. Luo, et al., Modified nano-lignin as a novel biomass-derived corrosion inhibitor for enhanced corrosion resistance of carbon steel, Corrosion Sci. 227 (2024) 111705, https://doi.org/10.1016/j.corsci.2023.111705.

[29] R.S.A. Hameed, et al., Spinacia oleracea extract as green corrosion inhibitor for carbon steel in hydrochloric acid solution, Int. J. Electrochem. Sci. 17 (2022), https://doi.org/10.20964/2022.10.31.

[30] N. Hossain, M.A. Chowdhury, M. Rana, M. Hassan, S. Islam, Terminalia arjuna leaves extract as green corrosion inhibitor for mild steel in HCl solution, Results Eng 14 (2022) 100438, https://doi.org/10.1016/j.rineng.2022.100438.

[31] K.M. Hijazi, A.M. Abdel-Gaber, G.O. Younes, R. Habchi, Comparative study of the effect of an acidic anion on the mild steel corrosion inhibition using rhus coriaria plant extract and its quercetin component, Port. Electrochim. Acta 9 (4) (2021) 237–252, https://doi.org/10.4152/pea.2021390402.

[32] N. Karki, et al., Equisetum hyemale: a new candidate for green corrosion inhibitor family, Int. J. Corros. Scale Inhib. 10 (1) (2021) 206–227, https://doi.org/10.17675/2305-6894-2021-10-1-12.

[33] S.A. Umoren, M.M. Solomon, I.B. Obot, R.K. Suleiman, Date palm leaves extract as a green and sustainable corrosion inhibitor for low carbon steel in 15 wt.% HCl solution: the role of extraction solvent on inhibition effect, Environ. Sci. Pollut. Res. 28 (30) (2021) 40879–40894, https://doi.org/10.1007/s11356-021-13567-5.

[34] N. Hossain, M.A. Chowdhury, A.K.M.P. Iqbal, M.S. Islam, N.Y. Sheikh Omar, A.Z.A. Saifullah, Paederia Foetida leaves extract as a green corrosion inhibitor for mild steel in hydrochloric acid solution, Curr. Opin. Green Sustainable Chem. 4 (4) (2021) 100191, https://doi.org/10.1016/J.CRGSC.2021.100191.

[35] N. Al Otaibi, H.H. Hammud, Corrosion inhibition using harmal leaf extract as an eco-friendly corrosion inhibitor, Molecules 26 (22) (2021) 7024, https://doi.org/10.3390/molecules26227024.
[36] G. Fekkar, et al., Eco-friendly chamaerops humilis l. Fruit extract corrosion inhibitor for mild steel in 1 M HCL, Int. J. Corros. Scale Inhib. 9 (2) (2020) 446–459, https://doi.org/10.17675/2305-6894-2020-9-2-4.
[37] E. de B. Policarpi, A. Spinelli, Application of Hymenaea stigonocarpa fruit shell extract as eco-friendly corrosion inhibitor for steel in sulfuric acid, J. Taiwan Inst. Chem. Eng. 116 (2020) (2020) 215–222, https://doi.org/10.1016/j.jtice.2020.10.024.
[38] H.B. Oli, J. Thapa Magar, N. Khadka, A. Subedee, D.P. Bhattarai, B. Pant, Coriaria nepalensis stem alkaloid as a green inhibitor for mild steel corrosion in 1 M H_2SO_4 solution, Electrochemistry (Tokyo, Jpn.) 3 (4) (2022) 713–727, https://doi.org/10.3390/electrochem3040047.
[39] C. Monticelli, Corrosion inhibitors, encycl, Interfacial Chem. (2018) 164–171, https://doi.org/10.1016/B978-0-12-409547-2.13443-2.
[40] N. Karki, et al., Berberine isolated from Mahonia nepalensis as an eco-friendly and thermally stable corrosion inhibitor for mild steel in acid medium, Arab. J. Chem. 14 (12) (2021) 103423, https://doi.org/10.1016/J.ARABJC.2021.103423.
[41] B. Raja, A. Qureshi, A. Rahim, H. Osman, K, Neolamarckia cadamba alkaloids as eco-friendly corrosion inhibitors for mild steel in 1 M HCl media, Corrosion Sci. 69 (2013) 292–301, https://doi.org/10.1016/j.corsci.2012.11.042.
[42] M. Lebrini, F. Robert, C. Roos, T. Biran, F. Guiana, Inhibition Effect of Alkaloids Extract from Annona Squamosa Plant on the Corrosion of C38 Steel in Normal Hydrochloric Acid Medium, vol. 5, 2010, pp. 1698–1712, https://doi.org/10.1016/S1452-3981(23)15422-8.
[43] M. Faiz, A. Zahari, K. Awang, H. Hussin, Corrosion inhibition on mild steel in 1 M HCl solution by Cryptocarya nigra extracts and three of its constituents (alkaloids), RSC Adv. 10 (11) (2020) 6547–6562, https://doi.org/10.1039/C9RA05654H.
[44] A. Thoume, et al., In vitro and silico antibacterial and anti-corrosive properties of Persea americana leaves extract as an environmentally friendly corrosion inhibitor for carbon steel in a hydrochloric acid medium, Colloids Surf. A Physicochem. Eng. Asp. 674 (2023) 131848, https://doi.org/10.1016/j.colsurfa.2023.131848.
[45] J. Dai, X. An, Corrosion inhibition properties of Camellia chrysantha flower extract for Q235 in 1 M HCl solution, Int. J. Electrochem. Sci. 18 (4) (2023) 100080, https://doi.org/10.1016/j.ijoes.2023.100080.
[46] Yuanyuan Meng, Shuangxi Li, Zhi Zhang, Inhibition performance of uniconazole on steel corrosion in simulated concrete pore solution: an eco-friendly way for steel protection, Heliyon 10 (2024) e24688, https://doi.org/10.1016/j.heliyon.2024.e24688.
[47] F. Gapsari, et al., Analysis of corrosion inhibition of Kleinhovia hospita plant extract aided by quantification of hydrogen evolution using a GLCM/SVM method, Int. J. Hydrogen Energy 48 (41) (2023) 15392–15405, https://doi.org/10.1016/j.ijhydene.2023.01.067.
[48] Y. Wang, Y. Qiang, H. Zhi, B. Ran, D. Zhang, Evaluating the synergistic effect of maple leaves extract and iodide ions on corrosion inhibition of Q235 steel in H_2SO_4 solution, J. Ind. Eng. Chem. 117 (2023) 422–433, https://doi.org/10.1016/j.jiec.2022.10.030.
[49] K. Hjouji, et al., Datura stramonium plant seed extracts as a new green corrosion inhibitor for mild steel in 1M HCl solution: experimental and surface characterization studies, Sustain Chem Pharm 34 (2023) 101170, https://doi.org/10.1016/j.scp.2023.101170.
[50] T. Nesane, N.E. Madala, M.M. Kabanda, L.C. Murulana, I. Bahadur, Lippia javanic, leaf extract as an effective anti-corrosion agent against mild steel corrosion in 1 M HCl and its characterization by UHPLC/Q-TOF-MS spectroscopy and quantum chemical evaluation of its adsorption process on Fe(110), Colloids Surf. A Physicochem. Eng. Asp. 667 (2023) 131405, https://doi.org/10.1016/j.colsurfa.2023.131405.
[51] F. Kaya, R. Solmaz, İ.H. Geçibesler, Investigation of adsorption, corrosion inhibition, synergistic inhibition effect and stability studies of Rheum ribes leaf extract on mild steel in 1 M HCl solution, J. Taiwan Inst. Chem. Eng. 143 (2023) 104712, https://doi.org/10.1016/j.jtice.2023.104712.
[52] Z. Zhou, X. Min, S. Wan, J. Liu, B. Liao, X. Guo, A novel green corrosion inhibitor extracted from waste feverfew root for carbon steel in H_2SO_4 solution, Results Eng 17 (2023) 100971, https://doi.org/10.1016/j.rineng.2023.100971.
[53] B. Liao, et al., Fructus cannabis protein extract powder as a green and high effective corrosion inhibitor for Q235 carbon steel in 1 M HCl solution, Int. J. Biol. Macromol. 239 (2023) 124358, https://doi.org/10.1016/j.ijbiomac.2023.124358.
[54] X. Liu, et al., Corrosion inhibition properties of spinach extract on Q235 steel in a hydrochloric acid medium, Arab. J. Chem. 16 (9) (2023) 105066, https://doi.org/10.1016/j.arabjc.2023.105066.
[55] J. Kaur, A. Saxena, E. Berdimurodov, D.K. Verma, Euphorbia prostrata as an eco-friendly corrosion inhibitor for steel: electrochemical and DFT studies, Chem. Pap. 77 (2) (2023) 957–976, https://doi.org/10.1007/s11696-022-02533-1.
[56] J. Sharma, S. Gandash, Brassica juncea stem extract as corrosion inhibitor for mild steel in 0.5 M sulphuric acid, J. Surv Fish Sci 10 (2S) (2023) 2357–2369, https://doi.org/10.17762/SFS.V10I2S.1243.
[57] Z. Golshani, F. Arjmand, M. Amiri, S.M.A. Hosseini, S.J. Fatemi, Investigation of Dracocephalum extract based on bulk and nanometer size as green corrosion inhibitor for mild steel in different corrosive media, Sci. Rep. 13 (1) (2023) 1–18, https://doi.org/10.1038/s41598-023-27891-y.
[58] H. Kumar, et al., Highly efficient green corrosion inhibitor for mild steel in sulfuric acid: experimental and DFT approach, Colloids Surf. A Physicochem. Eng. Asp. 675 (2023) 132039, https://doi.org/10.1016/j.colsurfa.2023.132039.
[59] A. Madaci, et al., Experimental and theoretical study of polysaccharides extracted from prickly pear nopales Pulp (PPUN) of Opuntia ficus-indica as corrosion inhibitors, J. Mol. Liq. 384 (2023) 122272, https://doi.org/10.1016/j.molliq.2023.122272.
[60] J. Bhawsar, G. Chavez Diaz, M.A. Rodriguez Rivera, J. Uruchurtu-Chavarin, M. Jani, M.G. Valladares-Cisneros, Green corrosion inhibition and DFT studies of phytoextract and green synthesis of copper nanoparticles of Jacaranda mimosaefolia, Mater. Today: Proc. 89 (2) (2023) 56–64, https://doi.org/10.1016/j.matpr.2023.05.695.
[61] Q. Wang, et al., Evaluation for Fatsia japonica leaves extract (FJLE) as green corrosion inhibitor for carbon steel in simulated concrete pore solutions, J. Build. Eng. 63 (2023) 105568, https://doi.org/10.1016/J.JOBE.2022.105568.
[62] H. Yang, S. Deng, D. Shao, R. Lei, G. Du, X. Li, Eupatorium adenophorum Spreng leaves extract/potassium iodide as a highly sustainable inhibitor for the corrosion protection of steel in citric acid solution, J. Mol. Liq. 387 (2023) 122614, https://doi.org/10.1016/j.molliq.2023.122614.
[63] P. Ghahremani, A.H. Mostafatabr, A. Dehghani, G. Bahlakeh, B. Ramezanzadeh, Apple pomace extract: a potent renewable source of active biomolecules for suppressing mild steel aggression in aquatic solution, Biomass Convers Bioref 12 (2022) 1–18, https://doi.org/10.1007/s13399-022-03581-z.
[64] V. Vorobyova, M. Skiba, K. Andrey, Tomato pomace extract as a novel corrosion inhibitor for the steel in industrial media: the role of chemical transformation of the extract and proinhibition effect, J. Mol. Struct. 1264 (2022) 133155, https://doi.org/10.1016/j.molstruc.2022.133155.
[65] M. Ferdosi Heragh, H. Tavakoli, Electrochemical properties of a new green corrosion inhibitor derived from prosopis farcta for St37 steel in 1 M hydrochloric acid, Acid. Met. Mater. Int. 26 (2020) 1654–1663, https://doi.org/10.1007/s12540-019-00453-6.
[66] A.M. Abdel-Gaber, H.T. Rahal, F.T. Beqai, Eucalyptus leaf extract as a eco-friendly corrosion inhibitor for mild steel in sulfuric and phosphoric acid solutions, Int J Ind Chem. 11 (2) (2020) 123–132, https://doi.org/10.1007/s40090-020-00207-z.
[67] P.S. Neriyana, V.D.P. Alva, A green approach: evaluation of combretum indicum (CI) leaf extract as an eco-friendly corrosion inhibitor for mild steel in 1M HCl, Chemistry Africa 3 (4) (2020) 1087–1098, https://doi.org/10.1007/s42250-020-00190-z.
[68] G.S. Sajadi, R. Naghizade, L. Zeidabadinejad, Z. Golshani, Ma Amiri, S.M.A. Hosseini, Experimental and theoretical investigation of mild steel corrosion control in acidic solution by Ranunculus arvensis and Glycine max extracts as novel green inhibitors, Heliyon 8 (10) (2022) e10983, https://doi.org/10.1016/j.heliyon.2022.e10983.
[69] R. Maizia, et al., Experimental assessment and molecular-level exploration of the mechanism of action of Nettle (Urtica dioica L.) plant extract as an eco-friendly corrosion inhibitor for X38 mild steel in sulfuric acidic medium, Arab. J. Chem. 16 (8) (2023) 104988, https://doi.org/10.1016/j.arabjc.2023.104988. Aug. 2023.
[70] R. Riastuti, et al., Effect of syzygium cumini leaf extract as a green corrosion inhibitor on API 5l carbon steel in 1M HCL, East.-Eur. J. Enterp. Technol. 6 (6) (2022) 30–41, https://doi.org/10.15587/1729-4061.2022.267232.
[71] N.R.J. Hynes, R.M. Selvaraj, T. Mohamed, A.M. Mukesh, K. Olfa, M.P. Nikolova, Aerva lanata flowers extract as green corrosion inhibitor of low-carbon steel in HCl solution: an in vitro study, Chem. Pap. 75 (3) (2021) 1165–1174, https://doi.org/10.1007/s11696-020-01361-5.

[72] A. Berisha, et al., Going green: stachys scardica H. leaves extract derived from supercritical CO_2 extraction as an effective corrosion inhibitor for mild steel in 1 M HCl media, Chem. Pap. 77 (2023) 6567–6582, https://doi.org/10.1007/s11696-023-02959-1.
[73] M. Zhang, Y. Chen, L. Liu, K. Zhuo, Artemisia capillaris leaf extract as corrosion inhibitor for Q235 steel in HCl solution and its synergistic inhibition effect with L-cysteine, Chemelectrochem 10 (10) (2023) e202300008, https://doi.org/10.1002/celc.202300008.
[74] A. El-Asri, et al., Carissa macrocarpa extract (ECM) as a new efficient and ecologically friendly corrosion inhibitor for copper in nitric acid: experimental and theoretical approach, J. Taiwan Inst. Chem. Eng. 142 (2023) 104633, https://doi.org/10.1016/j.jtice.2022.104633.
[75] V. Vorobyova, M. Skiba, V. Dzhyndzhoian, O. Linucheva, Evaluating the synergistic effect of peach pomace extract and organosilane on corrosion inhibition of steel in industrial water media, Inorg. Chem. Commun. 153 (2023) 110773, https://doi.org/10.1016/j.inoche.2023.110773.
[76] L. Huang, H.J. Li, Y.C. Wu, Comprehensive evaluation of corrosion inhibition performance and ecotoxicological effect of cinchona IIa as a green corrosion inhibitor for pickling of Q235 steel, J. Environ. Manag. 335 (2023) 117531, https://doi.org/10.1016/j.jenvman.2023.117531.
[77] F. Zhang, S. Deng, G. Wei, X. Li, Alternanthera philoxeroides extract as a corrosion inhibitor for steel in Cl_3CCOOH solution, Int. J. Electrochem. Sci. 18 (3) (2023) 100057, https://doi.org/10.1016/j.ijoes.2023.100057.
[78] H.M. Elabbasy, M.E. Elnagar, A.S. Fouda, Surface interaction and corrosion inhibition of carbon steel in sulfuric acid using Petroselinum crispum extract, J. Indian Chem. Soc. 100 (5) (2023) 100988, https://doi.org/10.1016/j.jics.2023.100988.
[79] R. Shanmugapriya, M. Ravi, S. Ravi, M. Ramasamy, A. Maruthapillai, A. S. J, Electrochemical and Morphological investigations of Elettaria cardamomum pod extract as a green corrosion inhibitor for Mild steel corrosion in 1 N HCl, Inorg. Chem. Commun. 154 (2023) 110958, https://doi.org/10.1016/j.inoche.2023.110958.
[80] R.T. Loto, P.C. Okpaleke, U. Udoh, Inhibition reaction behaviour of combined grapefruit and lemongrass plant distillates on plain carbon steel degradation, Solid State Phenom. 338 (2022) 41–48, https://doi.org/10.4028/p-s135ee.
[81] L. Huang, Z. Wang, S. Wang, Y. Wang, H. L.-E., and undefined 2022, Environmentally benign cinchonain IIa from Uncaria laevigata for corrosion inhibition of Q235 steel in HCl corrosive medium: experimental and theoretical investigation, Environ. Res. 215 (2) (2022) 114376, https://doi.org/10.1016/j.envres.2022.114376.
[82] O.R. Wamba-Tchio, et al., Electrochemical study and experimental simulation of the synergistic effect of a formulation based on Ficus pumila Linn. Leaves extract and zinc sulfate on the XC38 steel corrosion inhibition in NaCl solution, J. Electroanal. Chem. 919 (3) (2022) 116553, https://doi.org/10.1016/j.jelechem.2022.116553.
[83] V. David, C. Iroanyanwu, B. Suleiman Atane, R. Tolulope Loto, Numerical analysis of the inhibition effect of Commiphora myrrha and Cymbopogon nardus plant extracts on low carbon steel corrosion in simulated industrial environment, Mater. Today: Proc. 65 (3) (2022) 2144–2150, https://doi.org/10.1016/j.matpr.2022.05.215.
[84] S. Prifiharni, et al., Extract sarampa wood (Xylocarpus Moluccensis) as an eco-friendly corrosion inhibitor for mild steel in HCl 1M, J. Indian Chem. Soc. 99 (7) (2022) 100520, https://doi.org/10.1016/j.jics.2022.100520.
[85] X. Zhang, L. Yang, Y. Zhang, B. Tan, X. Zheng, W. Li, Combined electrochemical/surface and theoretical assessments of Rosa laevigata extract as an eco-friendly corrosion inhibitor for copper in acidic medium, J. Taiwan Inst. Chem. Eng. 136 (2022) 104408, https://doi.org/10.1016/j.jtice.2022.104408.
[86] R. Tolulope, et al., Inhibition effect of apium graveolens, punica granatum, and camellia sinensis extracts on plain carbon steel, Cogent Eng 7 (1) (2020) 1798579, https://doi.org/10.1080/23311916.2020.1798579.
[87] Ai Rizi, A. Sedik, et al., Sustainable and green corrosion inhibition of mild steel: insights from electrochemical and computational approaches, ACS Omega 8 (49) (2023) 47224–47238, https://doi.org/10.1021/acsomega.3c06548.
[88] S. Sutthiruangwong, C. Wongpaiboon, N. Sritha, N. Anukulkich, Pitting potential improvement of 304 stainless steel in hydrochloric acid solution by Terminalia bellirica fruit extract, Metals 13 (2) (2023) 262, https://doi.org/10.3390/met13020262.
[89] A. Dehghani, B. Ramezanzadeh, Rosemary extract inhibitive behavior against mild steel corrosion in tempered 1 M HCl media, Ind. Crops Prod. 93 (2023) 116183, https://doi.org/10.1016/j.indcrop.2022.116183.
[90] R. Kellal, D.B. Left, M. Azzi, M. Zertoubi, Insight on the corrosion inhibition performance of Glebionis coronaria plant extract in various acidic mediums, J. Appl. Electrochem. 53 (7) (2023) 811–832, https://doi.org/10.1007/s10800-022-01813-8.
[91] G. Bahlakeh, A. Dehghani, B. R.-J, Highly effective mild steel corrosion inhibition in 1 M HCl solution by novel green aqueous Mustard seed extract: experimental, electronic-scale DFT and atomic-scale, J. Mol. Liq. 293 (2023), https://doi.org/10.1016/j.molliq.2019.111559.
[92] D.T. Oyekunle, T.I. Oguntade, C.S. Ita, T. Ojo, O.D. Orodu, Corrosion inhibition of mild steel using binary mixture of sesame and castor oil in brine solution, Mater. Today Commun. 21 (2019) 100691, https://doi.org/10.1016/j.mtcomm.2019.100691.
[93] M.P. Asfia, M. Rezaei, G. Bahlakeh, Corrosion prevention of AISI 304 stainless steel in hydrochloric acid medium using garlic extract as a green corrosion inhibitor: electrochemical and theoretical studies, J. Mol. Liq. 315 (2020) 113679, https://doi.org/10.1016/j.molliq.2020.113679.
[94] M. Tariq Saeed, M. Saleem, A. Hussain Niyazi, F. Ahmad Al-Shamrani, N. Abdulelah Jazzar, M. Ali, Carrot (Daucus carota L.) peels extract as an herbal corrosion inhibitor for mild steel in 1 M HCl solution, Mod. Appl. Sci. 14 (2) (2020), https://doi.org/10.5539/mas.v14n2p97.
[95] A.S. Sowmyashree, et al., Potential sustainable electrochemical corrosion inhibition study of Citrus limetta on mild steel surface in aggressive acidic media, J. Mater. Res. Technol. 24 (2023) 984–994, https://doi.org/10.1016/j.jmrt.2023.02.039.
[96] N.A. Barghout, A. El Nemr, B.A. Abd-El-Nabey, H.A. Fetouh, S. Ragab, N.O. Eddy, Use of orange peel extract as an inhibitor of stainless-steel corrosion during acid washing in a multistage flash desalination plant, J. Appl. Electrochem. 53 (2023) 379–399, https://doi.org/10.1007/s10800-022-01772-0.
[97] A.S. Fouda, M. Eissa, M. Fakih, Pomegranate aqueous extract (PAE) as an eco-friendly inhibitor for carbon steel used in sanitation plants: kinetics and bacteria effect, J Bio Tribocorros 5 (5) (2019) 1–13, https://doi.org/10.1007/s40735-018-0197.
[98] M. Dahmani, et al., Investigation of piperanine as HCl ecofriendly corrosion inhibitors for C38 steel, Int. J. Electrochem. Sci. 7 (3) (2012) 2513–2522, https://doi.org/10.1016/S1452-3981(23)13897-1.
[99] D.O. Enabulele, G.O. Bamigboye, M.M. Solomon, B. Durodola, Exploration of the corrosion inhibition potential of cashew nutshell on thermo-mechanically treated steel in seawater, Arabian J. Sci. Eng. 48 (1) (2023) 223–237, https://doi.org/10.1007/s13369-022-06981-5.
[100] J. Ghoshal, L. M, Inhibition of microbial corrosion by green inhibitors: an overview, Iran. J. Chem. Chem. Eng. 42 (2) (2022) 684–703, https://doi.org/10.30492/ijcce.2022.539832.4950. Aug.