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REVIEW **Open Access**

Corrosion protection of mild steel in corrosive media, a shift from synthetic to natural corrosion inhibitors: a review

Jovine Kamuhabwa Emmanuel[1*]

Abstract

Background Mild steel is globally used in the construction, manufacturing and engineering industries due to its low cost and appreciable stability. Despite its application, mild steel often loses its structural integrity, attractiveness and performance because of corrosion, a spontaneous process with serious negative global safety, economic and environmental impacts. However, inhibitors are frequently used in corrosion-inhibitive fluids to provide temporary corrosion protection.

Main body of the abstract Various organic and inorganic molecules display inhibitory characteristics; nevertheless, most of these are remarkably lethal to humans and their surroundings. Therefore, the application of such molecules is limited in recent applications. As of today, there has been a continuous and ever-increasing curiosity about the use of green corrosion inhibitors of plant origin. The current article discusses the kinds of corrosion, corrosion progression and plant-based mild steel corrosion inhibitors. Evidently, diverse plant sources have continuously been sufficiently used as sensible protectors for mild steel deterioration.

Short conclusion Reports reveal an ever-increasing shift from the previous traditional synthetic to plant-based natural corrosion inhibitors in corrosive media. A wide range of natural plant-based corrosion inhibitors, the influence of the amount and temperature on inhibitory action and the motive for the shift are apparent.

Keywords Natural corrosion inhibitor, Corrosion, Plant extract, Phytochemicals, Mild steel

Background

Corrosion entails the worsening of metal structure because of interaction with the environment (Abdelshafeek and El-Shamy 2023; Sedik, 2020; Bhuvaneswari 2020; Buchweishaija 2009; Oyekunle et al. 2019; Emmanuel & Buchweishaija 2021a; Nasser & Masmali 2022; Panchal et al. 2021; Umoren et al. 2019; Shehata and El-Shamy 2023). This process results in the dilapidation of material's properties by a chemical or electrochemical process with the environment, and usually, it means the oxidation of metals (Buchweishaija 2009; Kaur et al. 2021; Saviour 2019; Shehata and El-Shamy 2023; Wang et al. 2023). Although mild steel usually corrodes, it has maintained much application in mechanical engineering, construction, manufacturing, transportation, creation of archaeological metal artefacts, oil and gas transportation pipelines and various areas of other industrial and engineering purposes because of its affordable price and strength (Abdallah 2004; Abdel-Karim & El-Shamy 2022; Shehata and El-Shamy 2023; Adekunle et al. 2021a, b; Benahmed et al. 2016; Boumhara et al. 2019; Buchweishaija 2009; Cheng et al. 2022a; Dehghani et al. 2019a, b, 2020; Dehghani et al. 2019a, b; Durodola et al. 2020; El–Maksoud 2008; Chahul et al. 2019; Kaur et al. 2021; Panchal et al. 2021; Devikala et al. 2019; Simović et al. 2023; Zhen et al. 2023).

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*Correspondence:
Jovine Kamuhabwa Emmanuel
jovineemma2007@yahoo.co.uk; jovine.emmanuel@udsm.ac.tz
[1] Department of Chemistry, University of Dar Es Salaam, Mkwawa University College of Education, P. O. Box 2513, Iringa, Tanzania

Undeniably, corrosion of mild steel installed in many industries and civil engineering is a serious problem facing construction involving the use of steel (Abbas et al. 2022; Abdel-Karim and El-Shamy 2022; Dehghani et al. 2020; Chahul et al. 2019; Owate et al. 2014; Shahini et al. 2022; Shehata and El-Shamy 2023). Such is also the problem noted in the application of alloys. Corrosion can result in terrible harm to metal and alloy assemblies, leading to economic penalties that are linked to restoration, substitution, product wastes, protection and environmental contamination (Abdel-Karim and El-Shamy 2022; Shehata and El-Shamy 2023; Akindele 2018; Aralu et al. 2021; Oyekunle et al. 2019; Daoudi et al. 2023; Emmanuel and Buchweishaija 2021a; Kamaruzzaman et al. 2022; Panchal et al. 2021; Saviour 2019; Shahini et al. 2022). Studies indicate that about 45% of the breakdowns in steel manufacturing result from corrosion (Panchal et al. 2021). Whether chemical or electrochemical reactions cause it, corrosion assumes great global economic significance (Akindele 2018; Alimohammadi et al. 2023; Oyekunle et al. 2019; Shehata and El-Shamy 2023; Kamaruzzaman et al. 2022; Verma et al. 2023).

Studies indicate that the yearly world corrosion expenses were approximately USD 2.5 trillion in 2016 (Oyekunle et al. 2019; Kamaruzzaman et al. 2022; Kaur et al. 2021; Saviour 2019). According to 2016 research, maintaining pipes connected to corrosion costs about 3.4% of the global gross domestic product (Shehata and El-Shamy 2023). In the USA alone, recent studies show that the unforeseen cost resulting from corrosion was over USD 1.1 trillion in 2016 (Kaur et al. 2021; Saviour 2019). More so, the incidental corrosion cost was USD 9.2 billion in 1977 and USD 90.4 billion in 1999 for Japan, USD 310 billion for China in 2015, USD 900 million in 2003 for Saudi Arabia (Saviour 2019) and about USD 9.6 billion for South Africa in 2011 (Oyekunle et al. 2019). Generally, a report reveals that each state wastes 3–5% of its gross national harvest because of corrosion (Abdel-Karim and El-Shamy 2022; Daoudi et al. 2023). However, unforeseen corrosion costs are predicted to grow with the current global technological advancement.

Notwithstanding, reports show that metal corrosion has also led to severe disasters, including the explosion of the Sinopec pipeline and the Donghuang II oil pipeline in Qingdao in 2013, which killed 62 and wounded 136 people, leading to the company's loss of USD 124.9 million. Another notable incident is the explosion of a 30-inch natural gas channel possessed by El Paso Natural Gas (EPNG) that blasted and caused fatalities and destruction of properties such as vehicles in 2000. There was also the leakage of 300 metric tons of polluted water storing tank at the Fukushima nuclear establishment into the sea, which led to the abandonment of fishing activities. Cleaning up such a sea is projected to cost more than USD 100 billion and is estimated to take 40 years to complete (Saviour 2019).

Besides, the world's intense industrialisation has caused a sharp rise in the need for gas and oil. Therefore, thousands of kilometres of steel pipelines are used to transfer the majority of these resources, and these pipes are frequently exposed to extreme environmental conditions, leading to pipeline steel corrosion (Abbas et al. 2022; Shehata and El-Shamy 2023). Studies show that hydrogen-induced or -assisted cracking is a predominant failure mode in wet sour conditions, accounting for one-third of pipeline failures (Shehata and El-Shamy 2023). Reports indicate that the amount of money spent on corrosion can be reduced by up to 35% by applying the prevailing methods of preventing metal corrosion (Oyekunle et al. 2019). Therefore, the management of metals worsening is a crucial action for general safety, and its significance has received much global attention (Daoudi et al. 2023;El–Maksoud, 2008; Emmanuel and Buchweishaija 2021a; Umoren et al. 2008). Such is because detrimental effects of corrosion are undesirable mishaps that ought to be intervened and avoided. Corrosion prevention of mild steel is very interesting due to its widespread application in the overall engineering field, given its outstanding mechanical strength and affordability (Abu-Dalo et al. 2012;El–Maksoud 2008; Emmanuel and Buchweishaija 2021a). Although mild steel has restricted corrosion strength, it is the most preferred material in numerous uses, particularly where acids are commonly applied, such as in acid pickling, cleaning, de-scaling and oil well acidizing (Abu-Dalo et al. 2012; Boumhara et al. 2019; Chaudhary et al. 2007; Dehghani et al. 2019b; Durodola et al. 2020; Kaur et al. 2021; Düdükcü et al. 2020; Olusegun 2016; Umoren et al. 2006, 2010). There are numerous ways to avoid corrosion and its spreading speed for enhancing alloy and metallic lifespan. Such methods include material design, selection, anodic and cathodic defence, coatings and the use of corrosion inhibitors (Akindele 2018; Boumhara et al. 2019; El-Shamy and Mouneir 2023; Kaur et al. 2021; Saviour 2019). However, among all these approaches, the application of corrosion protectors is mostly preferred because it is affordable and easier to use (Bhuvaneswari 2020; Boumhara et al. 2019; Durodola et al. 2020; Chahul et al. 2019; Kamaruzzaman et al. 2022; Raja and Sethuraman 2008; Saviour 2019; Megahed et al. 2023). Therefore, to protect this affordable and essential engineering material from deterioration, application of corrosion inhibitors to manage its deterioration when in contact with the environmental conditions and corrosive media has been widely researched and recommended for use (Mouneir et al. 2022; Abu-Dalo et al. 2012; Asadi et al. 2018; Boumhara et al. 2019;

Buchweishaija 2009; Emmanuel and Buchweishaija 2021a; Umoren et al., 2006, 2008, 2007, 2010).

Corrosion inhibitors refer to chemical molecules that decrease the speed of metals deterioration when available in small concentrations in corrosive environments without affecting their mechanical resistance (Abdelshafeek and El-Shamy 2023; Akindele 2018; Dehghani et al. 2020; Abdelaziz et al. 2021; Devikala et al. 2019; Saviour 2019). Besides, the inhibitor ought to be stable in the presence of other medium components at working temperatures, operative at low amounts, well suited with non-toxicity standards and low cost (Abdelaziz et al. 2021). Organic and inorganic compounds are excellent corrosion inhibitors, and there are numerous studies on their application (Akindele 2018; Oguzie 2014; Oguzie et al. 2012; Kaur et al. 2021; Abdelaziz et al. 2021). Studies show that synthetic inhibitors have been proven to be excellent inhibitors, but most of these inhibitors are environmentally unfriendly because they are toxic and so this trait has restricted their application in recent times (Abdel-Karim and El-Shamy 2022; Adekunle et al. 2021a; Akindele 2018; Arthur and Abechi 2019; Oyekunle et al. 2019; Dehghani et al. 2020; Dehghani et al. 2019b; Chahul et al. 2019; Kaur et al. 2021; Panchal et al. 2021; Karthik et al. 2015; Devikala et al. 2019; Mouneir et al. 2022).

Hazardous effects associated with the most traditional synthetic inorganic and organic inhibitors such as environmental toxicity, carcinogenicity as well as high cost and high environmental safety demands have motivated researchers to focus on the search for plant-based natural chemicals as corrosion inhibitors (Abdelshafeek and El-Shamy 2023; Abdel-Karim and El-Shamy 2022; Akindele 2018; Buchweishaija 2009; Oyekunle et al. 2019; Oguzie et al. 2012; Emmanuel and Buchweishaija 2021a, 2021b; Chahul et al. 2019; Cookey et al. 2018; Kaur et al. 2021; Oguzie 2008; Okafor et al. 2010; Abdelaziz et al. 2021; Olusegun 2016; Megahed et al. 2023). Natural plant-based extract corrosion inhibitors are viewed as the solution to all problems associated with traditional synthetic organic and inorganic inhibitors.

Studies indicate that plant-based extracts have been extensively applied successfully for corrosion mitigation purposes in acidic media (Popoola 2012; Adekunle et al. 2021a; Alibakhshi et al. 2018; Anuchi and Ngobiri 2018; Aralu et al. 2021; Arthur 2020; Arthur and Abechi 2019; Asadi et al. 2018; Benahmed et al. 2016; Oyekunle et al. 2019; Dehghani et al. 2020; Dehghani et al. 2019b; Emmanuel and Buchweishaija 2021a, 2021b; Chahul et al. 2019; Cookey et al. 2018; Kaur et al. 2021; Patel 2013; Patel 2014; Muthukrishnan and Prakash 2013; Pramudita et al. 2019; Karthik et al. 2015; Devikala et al. 2019; Qiang et al. 2021). The current review uncovers the ever-increasing application of plant sources as feasible inhibitors in acidic environments. The corrosion classes, progression and plant-based mild steel corrosion inhibitors have been discussed. In the present review, the shift from previous traditional synthetic to natural corrosion inhibitors, the effect of inhibitor concentration and inhibitive fluid temperature on the inhibitory properties, as well as the motive for this shift, is reflected herein.

Main text

Types of metal corrosion and corrosion process

Corrosion of metals entails the worsening of metals' characteristics because of interaction with the surroundings (Abdel-Karim and El-Shamy 2022; Arthur and Abechi 2019; Buchweishaija 2009; El–Maksoud 2008; Umoren et al. 2019). A good example is the manufactured steel from iron ore by various metallurgical processes converting to rust in various applications. Most of the metals that are applied in building structures are subjected to corrosion in natural environments. Iron and steel oxidize when oxygen and water are available, the very things without which corrosion does not take place (El–Maksoud 2008). This susceptibility of iron and steel to corrosion is of great concern because of these materials' favourable cost and physical properties considerations (Abu-Dalo et al. 2012; El–Maksoud 2008). Factors, including reactivity, impurities, solution pH, temperature and industrial practices, acidizing, acid cleaning, pickling and de-scaling, for instance, accelerate metals corrosion (Abu-Dalo et al. 2012; Adah et al. 2020; Adekunle et al. 2021a; Akalezi and Oguzie 2016; Arthur and Abechi 2019; Dehghani et al. 2020; Umoren et al. 2019). However, very reactive metals corrode more than less reactive ones, and impurities create the precedence for the formation of voltaic cells, thus raising the deterioration speed. In addition, the raise of temperature and pH similarly accelerates metals' corrosion rates (Umoren et al. 2019).

Corrosion of metals is categorized into various forms. These include uniform or general attack, galvanic corrosion, crevice corrosion, pitting, intergranular corrosion, selective leaching, erosion corrosion and stress corrosion (Abdel-Karim and El-Shamy 2022; Daoudi et al. 2023; Kaur et al. 2021; Nasser and Masmali 2022; Panchal et al. 2021; Umoren et al. 2019). However, uniform or general corrosion is a widely known kind of corrosion. It is regarded as a chemical or electrochemical process across the bare metal parts (Kaur et al. 2021; Umoren et al. 2019). On their sides, galvanic corrosion occurs among two dissimilar metals in corrosive surroundings.

In contrast, localized corrosion occurs inside crevices and other protected parts on bare metal surfaces to the corrosive surroundings. As its name suggests, pitting corrosion causes holes or pits on a bare metal surface (Kaur et al. 2021; Umoren et al. 2019). Intergranular corrosion entails the one in which the boundaries of crystallites of material are more susceptible to corrosion than their insides. Such is different from selective leaching, which involves dislodging one element from a solid alloy through corrosion (Kaur et al. 2021; Umoren et al. 2019). The acceleration of metal dissolution rate as a result of migration among corrosive systems and the metal surface is described as erosion–corrosion. Such is unlike stress corrosion cracking, which involves the simultaneous presence of tensile stress and a specific corrosive solution (Kaur et al. 2021; Umoren et al. 2019). Despite the various forms of corrosion to which metal surfaces are susceptible, uniform or general corrosion accounts for most of the damages (Kaur et al. 2021).

Metal corrosion mechanism

Studies show mild steel corrosion proceeds through electrochemical reactions (Kaur et al. 2021). Dissolution of metal occurs at the anode from which electrons are generated via the chemical action of the metal. Notably, anode is a place where the metal loss takes place and the metal wastes electrons, which then migrate through the metal surface to the cathode (El–Maksoud 2008). On the other hand, the cathode is a site where electrons are consumed and where each electron (produced at the anode) must be consumed. The generic chemical equation for the dissolution of metal at anodic sites is marked by this Eq. (1) (Abdel-Karim and El-Shamy 2022; Akindele 2018; El–Maksoud 2008).

$$\mathrm{M} \rightarrow \mathrm{M}^{n+} + \mathrm{ne}^{-}, \tag{1}$$

whereas M represents the metal, n represents the valence of the corroding metal, and e^- is equal to an electron. Since this chemical reaction does not directly involve oxygen, it raises a positive charge on the atom that undergoes oxidation. It is consequently called oxidation. For iron corrosion, the reaction proceeds as demonstrated in Eqs. 2 to 7 (Abdel-Karim and El-Shamy 2022; El–Maksoud 2008).

At the anodic locations

$$\mathrm{Fe} \rightarrow \mathrm{Fe}^{2+} + 2\mathrm{e}^{-} \tag{2}$$

During corrosion, the speed is commonly managed by a cathodic process. There are diverse cathodic processes that are usually known in mild steel corrosion; however, the common ones are:

$$\text{Hydrogen evolution } 2\mathrm{H}^{+} + 2\mathrm{e}^{-} \rightarrow \mathrm{H}_2 \tag{3}$$

$$\text{Oxygen reduction (acid solution) } \mathrm{O}_2 + 4\mathrm{H}^{+} + 4\mathrm{e}^{-} \rightarrow \mathrm{H}_2\mathrm{O} \tag{4}$$

$$\text{Oxygen reduction (neutral or basic solution)}\mathrm{O}_2 + 4\mathrm{H}_2\mathrm{O} + 4\mathrm{e}^{-} \rightarrow 4\mathrm{OH}^{-} \tag{5}$$

$$\text{Metal ion reduction } \mathrm{M}^{3+} + \mathrm{e}^{-} \rightarrow \mathrm{M}^{2+} \tag{6}$$

$$\text{Metal deposition } \mathrm{M}^{+} + \mathrm{e}^{-} \rightarrow \mathrm{M} \tag{7}$$

Notably, hydrogen generation is unusual cathodic process because acidic solutions are frequently used, while oxygen reduction is common because any aqueous solution in contact with air can reduce this reaction (El–Maksoud 2008). Metal ion reduction and metal deposition are uncommon; however, all these reactions consume electrons. Because of the mutual dependence of anodic and cathodic processes that take place during metal corrosion, it is likely to retard corrosion through retardation of the speed of either process. Therefore, when the surface of a metal is painted or another conducting film, the speed of anodic and cathodic processes are largely retarded; eventually, corrosion is also reduced (El–Maksoud 2008). The corrosion tendency of metals and corrosion inhibition processes depend largely on the anion composition of the corrosion-inhibitive fluid (El–Maksoud 2008). However, very recently, hydrogen-induced corrosion of the oil and gas pipelines has been reported, which highlights new corrosion mechanisms affecting such systems of interest, thus, attracting more attention in terms of research (Shehata and El-Shamy 2023; Daoudi et al. 2023; Mubarak et al. 2023).

Corrosion inhibitors and inhibition process

A corrosion inhibitor is a substance that, when included in a tiny amount of a corrosive solution retards the speed of metal corrosion without disturbing its mechanical resistance (Abu-Dalo et al. 2012; Daoudi et al. 2023; Mubarak et al. 2023; Abdelaziz et al. 2021; Umoren et al. 2019; Timothy et al. 2023). Corrosion inhibitors work by interrupting anodic or cathodic processes or the two. Most corrosion inhibitors are organic compounds (Akalezi and Oguzie 2016; El–Maksoud 2008). For example, most of these inhibitors used in the oil fields are film-forming organic substances. These molecules contain long hydrocarbon chains holding a polar group at one or both terminals (Buchweishaija 1997a, b). The molecules form a hydrophobic layer on the surface of a metal to create a contact barrier with corrosive media which eventually avoids metal dissolution.

The corrosion efficiency of these inhibitors is influenced by the chemical content and molecular structure of the inhibitor and their affinity with a metal object (El–Maksoud 2008). The structure of the inhibitor molecule plays a vital role in its effectiveness. Factors, such as carbon chain length, dimension of the organic molecule, aromaticity or conjugated bonding strength to the metal substrate, kind and amount of atoms or groups in a molecule (can be either π or σ), the ability of the adsorbed inhibitor layer to be compact or cross-linked and the capacity to compound with the atom as a solid inside the metal lattice, contribute to the inhibition effect of the inhibitor molecule (Philip et al. 2001).

Organic inhibitors prevent corrosion by adsorption on the metal surface (Umoren et al. 2019). It is globally acknowledged that the organic molecule retards corrosion by adsorbing at the metal–solution boundary (Akalezi and Oguzie 2016). However, adsorption is influenced by the inhibitor's chemical structure, the solution's chemical content, the metal surface's nature and the electrochemical potential at the metal–solution boundary (Philip et al. 2001). Commonly, corrosion inhibition is achieved by the adsorption of additives (ion or neutral polar molecules) to the metal–solution interface (Akalezi and Oguzie 2016; El–Maksoud 2008). It is well established that the potential difference between a metal electrode and the solution is because of a non-uniform distribution of electric charges at the boundary (Al-Amiery et al. 2014; El–Maksoud 2008). The interaction of ions or neutral molecules at the electrical double layer alters its characteristics and structures. In interaction with the aqueous medium, water molecules pre-adsorbed at the metal surface are involved in the consecutive adsorption routes (El–Maksoud 2008; Abdelaziz et al. 2021). Therefore, the adsorption of an organic molecule at the metal–solution boundary is presented in terms of the displacement process (as in Eq. 8) (Abdelaziz et al. 2021).

$$\mathrm{Org_{(sol)}} + \mathrm{nH_2O} \rightarrow \mathrm{Org_{(ads)}} + \mathrm{n\,H_2O_{(sol)}} \tag{8}$$

where n represents the number of water molecules detached from the metal surface for each inhibitor-impacted molecule. This is presumed to be independent of the coverage or electrode charge. Noticeably, the value of n depends on the cross-sectional area of the organic molecule relative to that of water (El–Maksoud 2008). The organic molecule adsorption occurs as the interaction energy between the metal surface and the inhibitor is more significant than between the metal surface and the water (El–Maksoud 2008).

Studies indicate that the inhibition effect models for interface inhibitors are classified into three classes, including the geometric blocking effect of adsorbed inhibitive molecules on the metal surface, the effect of blocking the active sites on the metal surface by adsorbed inhibitive molecules and the electro-catalytic effect of the inhibitor or its process produces (El–Maksoud 2008). Furthermore, reports show that in the first mode, the inhibition effect emanates from the retardation of the reaction area on the corroding metal surface. In contrast, for the later modes, the inhibition effects originate from the changes in the average activation energy barriers of the anodic and cathodic corrosion processes (El–Maksoud 2008). Therefore, the electrochemical property and the explanation of the attained electrochemical data are not similar for all the inhibition effect modes (El–Maksoud 2008). Studies indicate that many factors influence the inhibition efficiency of the organic molecules in acidic solution including the structure of organic compounds, zero-charge potential and synergistic effect (El–Maksoud 2008).

Despite the modes and mechanisms of inhibitors' metal corrosion inhibition, inhibitors are classified as either synthetic (traditional) or natural (plant-based extracts) corrosion inhibitors. There are enormous studies that have demonstrated the applicability of traditional and natural inhibitors in the retardation of metal corrosion rates in acidic media (Asadi et al. 2018; Buchweishaija 1997a, b, 2002; Buchweishaija 2009; Emmanuel and Buchweishaija 2021a, 2021b; Sulaiman et al. 2019; Raja and Sethuraman 2008; Umoren et al. 2019; Maurya et al. 2021). Nevertheless, with ever-increasing concerns about the negative consequences associated with synthetic corrosion inhibitors on human lives and the natural environment, researchers are increasingly diverting their efforts towards natural plant-based corrosion inhibitors (Adah et al. 2020; Adekunle et al. 2021a; Ugi et al. 2020; Fernandes et al. 2019; Chung et al. 2020; Dehghani et al. 2020; Emmanuel and Buchweishaija 2021b; Sulaiman et al. 2019; Quraishi et al. 1999; Jessima et al. 2020; Salman 2019). Natural corrosion inhibitors are decomposable and do not constitute heavy metals or other toxic molecules; thus, they are used while environmental issues are taken into account (Argyropoulos et al. 2021; Buchweishaija 2009; Panchal et al. 2021; Umoren et al. 2019).

Natural plant-based corrosion inhibitors

The application of natural mild steel corrosion inhibitors of plant origin has a long history from the 1960s, when tannins and their spinoffs were applied to prevent corrosion of steel, iron and other utensils (Buchweishaija 2009; Panchal et al. 2021). Some natural plant-based metal corrosion inhibitors have been reviewed at different times (Abdel-Karim and El-Shamy 2022; Argyropoulos et al. 2021; Buchweishaija 2009; El–Maksoud 2008; Kamaruzzaman et al. 2022; Kaur et al. 2021; Panchal et al. 2021;

Umoren et al. 2019; Verma et al. 2018a, b). Studies show that plant sources of tobacco stems, twigs and leaves possess significant corrosion-inhibitive activity for steel in strong pickling acids (Davis et al. 2001; El-Hosary et al. 1972).

The investigation of the corrosion protection property of tobacco, black pepper, castor seed, *Acacia* gum and lignin was also conducted in 1981 and extracts from plants were revealed as excellent corrosion inhibitors for steel in acidic solutions (Buchweishaija 2009). Buchweishaija and Saleh et al. (Buchweishaija 2009; Saleh et al.1982) studied the inhibitory action of aqueous extract of *Opuntia ficus indica*, *Aloe eru* leaves, orange peels, mango and pomegranate fruits for corrosion protection of steel in HCl and H_2SO_4 media by gravimetric and polarization techniques. The results of such investigation show that all the sources efficiently inhibit HCl corrosion than H_2SO_4 (Buchweishaija 2009; Saleh et al. 1982).

Mild steel corrosion reduction by ethanol sources of *Musa sapientum* peels in H_2SO_4 was evaluated by Eddy and Ebenso [75] by gasometric and thermometric methods, and findings show that different amounts of ethanol sources of *Musa sapientum* peels prevent corrosion. Furthermore, the corrosion protection efficiency of the extract increased with increase in the amount of the inhibitor, temperature, soaking time and pH (Eddy and Ebenso 2008). Buchweishaija (Buchweishaija 2009) explored the inhibitive characteristic of aqueous sources of *Eucalyptus* leaves on mild steel corrosion inhibition in 1 M HCl by galvanostatic polarization and mass loss measurements. The study revealed that the protection efficiency of the *Eucalyptus* leaves source improved by raising the amount of extract and declined with the temperature decline. More so, the extract worked as a mixed-type inhibitor with principal cathodic management. The inhibitory property of pomegranate alkaloids on mild steel corrosion protection in H_2SO_4 solution was also evaluated. It was discovered that the alkaloids efficiently inhibited the mild steel corrosion at low temperatures.

Abu-Dalo et al. (2012) investigated *gum acacia*'s effectiveness in mild steel corrosion mitigation in HCl and H_2SO_4 solutions through potentiodynamic polarization techniques. Reports show that its protection efficiency improved with the reduction of inhibitor amount. However, the corrosion protection efficiency in HCl was more significant than in H_2SO_4 as a result of the synergistic effect. It was further noted that the protection efficiency of gum *Accacia* on mild steel corrosion was high in an external magnetic field. The findings also demonstrated that gum *Acacia* is a mixed-type inhibitor, which provides very good protection against corrosion to mild steel (Abu-Dalo et al. 2012). Ameh et al. (2012) evaluated the mild steel corrosion-inhibitive property of *Ficus glumosa* gum in H_2SO_4 by weight loss, gasometric and thermometric techniques. Such study's findings indicate that the gum efficiently retards corrosion. Likewise, Znini et al. (2012) investigated the mild steel corrosion protection activity of *Asteriscus graveolens* essential oil in 0.5 M H_2SO_4 by weight loss, PDP and EIS methods. Their study found that the oil efficiently inhibits corrosion, and its protection efficiency improved with increase in efficiency to 82.89% at 3 g/L. Here, too, *Asteriscus graveolens* essential oil displayed a mixed-type inhibitor.

Ameh (2012) studied the mild steel corrosion-inhibitive action of *Khaya ivorensis* gum exudate in HCl via weight loss, gasometric and thermometric techniques. Findings unveil that *Khaya ivorensis* gum efficiently inhibited corrosion, and its protection efficiency improved with raising the inhibitor amount but declined with the intensification of temperature. On their side, Ulaeto et al. (2012) evaluated acid extracts of leaves and roots of *Eichhornia crassipes* for their mild steel corrosion protection action in a 5 M HCl medium by gasometric method. The study discovered that the leaf and root extracts efficiently inhibit corrosion, with the leaf extracts displaying higher activity. It was also reported that the protection efficiency of such acid extracts improved by raising the amount of the inhibitor but declined to raise the temperature (Ulaeto et al. 2012). Singh et al. (2012a, b) evaluated the mild steel corrosion protection characteristics of *Cuminum cyminum* (Jeera) seed sources by gravimetric, PDP and EIS techniques. The study shows that the extract inhibits its corrosion with a high protection efficiency of 93% at 300 ppm, and the sources demonstrated a mixed-type inhibition.

In another study, Singh et al. (2012b) investigated the mild steel corrosion protection action of *Boerhavia diffusa* (Punarnava) root extract in 1 M HCl via gravimetric, PDP and EIS methods. In this later study, results show that *Boerhavia diffusa* is a good inhibitor. Its protection efficiency was raised by raising the amount to 96% at 300 ppm but declined by raising the temperature. Even so, the inhibitor demonstrated a mixed-type inhibition (Ambrish 2012a). Obot et al. (2012) investigated the mild steel corrosion inhibition in 0.5 M H_2SO_4 by ethanolic leaves sources of *Chromolaena odorata* L. by gravimetric method at different temperatures (303–333 K). The exploration found that the extract retarded corrosion and its protection efficiency is affected by the extract amount and temperature. The increase in the extract's concentration could attain the maximum inhibition efficiency of 95% at 303 K and 89% at 333 K at 5% v/v of the sources. However, such efficiency declined with the increased temperature.

Cang et al.'s (2013) study explored the mild steel corrosion protection action of Aloes leaves extract in 1.0 M HCl through weight loss, PDP and EIS techniques. The study reveals that *Aloes* leaf extract has inhibition efficiency, which strengthens with the increased amount of the extract and declines with temperature increase. Unlike the already mentioned studies, Uwah et al. (Uwah et al. 2013b) evaluated the mild steel corrosion-inhibitive activity of ethanol extracts of *Nauclea latifolia's* leaves, barks and roots in H_2SO_4 medium at various temperatures between 30 and 60 °C and via weight loss and gasometric methods. The study found that *Nauclea latifolia's* protection efficiency improved by raising the amount of the sources but declined as temperature rises. In another study, Uwah et al. (2013a, b) studied the mild steel corrosion protection action of ethanol sources of *Andrographis paniculata* and *Vernonia amygdalina* in 2 M HCl medium at various temperatures between 30 and 60 °C via weight loss and gasometric methods. These scholars discovered that the said plant sources reduced the mild steel corrosion and increased protection efficiencies as the concentration of plant extracts increased. Even so, *Andrographis paniculata* demonstrated a higher inhibition efficiency of 89.7% as compared to 76.9% at 4.0 g/L of *Vernonia amygdalina*.

Both extracts' protection efficiency declined by raising the temperature. In another study, Njoku et al. (Njoku 2013) researched the mild steel corrosion-inhibitive action of *Nicotiana tabacum* leaf extract in 0.1 M HCl through weight loss and electrochemical methods. Njoku et al.'s findings show that the sources prevented corrosion, and their protection efficiency improved due to the increase in the source's amount but declined by the increase in emersion time. In their research, Ji et al. (2013) explored the mild steel corrosion protection action of *Argemone mexicana* leaf sources in 0.5 M H_2SO_4 through weight loss, Tafel polarization and EIS methods. The investigation unveiled that *Argemone Mexicana* corrosion protection efficiency was 87% at 600 mg L^{-1} of inhibitor amount, and such protection efficiency increased as the extract's concentration was higher.

Ameh et al. (2014) investigated the mild steel corrosion protection property of *Albizia zygia* gum in H_2SO_4 through weight loss and gasometric techniques and indicated that gum is a good corrosion inhibitor. However, its inhibition efficacy declines as temperature increases. Also, peel extracts of *Cucurbita maxima* were investigated by Anbarasi (2014) for their mild steel corrosion inhibitory capacity in 1N HCl via weight loss method. Findings showed that the plant extracts inhibit corrosion with an efficiency of up to 93% at a 2% v/v amount of extracts. David et al. (2014) evaluated the corrosion inhibition of mild steel by *Anarcadium occidentale* gum (Cashew gum) in 0.1 M H_2SO_4 through the gravimetric method. Such examination indicated that *Anarcadium occidentale* gum reduces the mild steel corrosion, and its protection efficiency increases with the increased amount of the gum. The corrosion inhibition effect for mild steel by alcoholic sources of eight plants (*Lycium shawii*, *Teucrium oliverianum*, *Ochradenus baccatus*, *Anvillea garcinii*, *Cassia italica*, *Artemisia sieberi*, *Carthamus tinctorius* and *Tripleurospermum auriculatum*) was also investigated by Al-Otaibi et al. (2014) in 0.5 M HCl through an open circuit potential, Tafel plots and alternating current impedance techniques. It was discovered that extracts from these alcoholic extracts efficiently inhibit mild steel corrosion and are mixed-type inhibitors.

On their side, Vasudha and Priya (2014) studied the mild steel corrosion inhibition action of dry *Polyalthia longifolia* (Asoka tree) leaves in 1N H_2SO_4 medium by weight loss at different temperatures (35–75 °C). The two scholars indicate that Asoka tree extract has an inhibition potency, which increases due to the amount of the extract, to reach the higher protection efficiency of 92% at 1.5% inhibitor concentration. It was also discovered that such inhibition potency declines as temperature increases.

Soltani et al. (2014) evaluated the 304 stainless steel corrosion-inhibitive action of *Silybum marianum* leaves extract in 1.0 M HCl solution using weight loss, PDP and EIS techniques. It was discovered that the extract efficiently inhibited mild steel corrosion, and its inhibition (which is a mixed type) increases (up to the maximum inhibition efficiency of 96% at 1.0 g/L) as extract concentration mounts increase. Likewise, in their study, Patel et al. (2014) investigated the mild steel corrosion inhibitory property of *Phyllanthus fraternus* leaves extract in H_2SO_4 medium by conventional weight loss, gasometric, PDP and EIS techniques. These scholars confirmed that *Phyllanthus fraternus* leaf extract efficiently prevented corrosion. The extract has inhibition efficiency (which is a mixed-type) and improved as the extract is high, but declines as temperature rises. In another study, Owate et al. (2014) explored the corrosion inhibition activity of *Aspilia africana* leaves source on mild steel in 1.0 M HCl at ambient temperature and 60 °C. It was found that the source, which is a mixed-type inhibitor, can attain the maximum protection efficiency of 88.1% at room temperature and 91% at 60 °C.

In another study, Alsabagh et al. (2015) investigated green tea sources for their corrosion protection property on carbon steel in HCl and H_2SO_4 media by weight loss, PDP and EIS methods. That study established that green tea extracts' inhibition efficiency would be 81.47% in 1 M HCl and 71.65% in 0.5 M H_2SO_4 at

500 ppm inhibitor amount. The study further ascertains that the corrosion inhibition rate of tea extract declines with the increase in its amount. Ali-senani et al. (2015) also studied the corrosion inhibition property of some green leafy vegetable sources of *Lactuca sativa*, *Eruca Sativa*, *Petroselinum crispum* and *Anethum Graveolens* on carbon steel in 1 M HCl through gravimetric technique. The study revealed that green leafy vegetables corrosion protection efficiency improved with raising the amount of green leafy vegetable extracts and declined as temperature rises.

In Alaneme et al. (2016) exploration, the corrosion protection properties of *Hunteria umbellata* seed husk source on mild steel in 1 M HCl and H_2SO_4 solutions were researched by mass loss technique. Findings unveiled that the extracts have inhibition efficiency which strengthens following the increase in extract amount but decreases as temperature increases. Notably, the study added that although the inhibition efficiency of the extracts was very high, it was more effective in 1 M HCl than in 1 M H_2SO_4 medium. In Gopal et al.'s (2015) study investigated the corrosion inhibition of an aqueous source of *Musa paradisica* peels on mild steel in 1 M HCl by weight loss and EIS methods. As indicated, the extract has the protection capacity to reduce mild steel corrosion. However, such capacity declined with the banana peels' maturity stages; extracts from raw banana peels demonstrated the highest corrosion inhibition potency compared to extracts from ripe banana peels. In another exploration, Muthukrishnan et al. (2015) evaluated the anti-corrosive activity of *Ficus hispida* leaf extract on mild steel in 1 M HCl through weight loss, PDP and EIS methods. It was discovered that *Ficus hispida* leaf extract has a higher protection efficiency of 90% at 250 ppm inhibitor amount at 308 K and that such efficiency weakens due to the increase in temperature.

On their side, Salghi et al. (2015) studied the corrosion protection of *Pistachio* Essential Oils in 0.5 M H_2SO_4 on carbon steel by weight loss, PDP and EIS methods. The exploration divulged that *Pistachio* Essential Oils PEO have inhibition efficiency to prevent carbon steel corrosion, and such efficiency increases as the inhibitor amount augments. In the study which explored *Millingtonia hortensis* leaves extract inhibition potency on mild steel in 1N HCl and 1N H_2SO_4 media and at a temperature ranging between 303 and 333 K, Kulandai and Vasudha (2015) discovered that *Millingtonia hortensis* extracts have the maximum corrosion inhibition efficiency of up to 97.41% at 333 K and 97.10% in 1N H_2SO_4 at 323 K. Such inhibition capacity, the study indicated, increased as per inhibitor amount but declined as temperature rose. The anti-corrosive action of *Tiliacora acuminata* leaf extract for mild steel in 1 M HCl was assessed by Karthik et al. (2015) via mass loss, PDP and EIS methods. Findings illustrated that *Tiliacora acuminata* leaf extract indicated a mixed-type inhibition, and the protection efficiency improved, achieving the maximum inhibition efficacy of 93.02% at 320 ppm inhibitor amount at 333 K. As noted, the said inhibition efficacy does increase as the extract amount rises.

Akalenzi et al. (2015) assessed the corrosion inhibitory property of an aqueous source of *Rothmannia longiflora* on mild steel in 1 M HCl and 0.5 M H_2SO_4 was evaluated via weight loss, PDP and EIS techniques. The study shows that the extract has a mixed-type efficiency capacity to protect mild steel from corrosion, and such capacity increases with increase in extract concentration.

Akalezi and Oguzie (2016) investigated the corrosion protection efficiency of *Chrysophyllum albidum* source on mild steel in 1 M HCl through weight loss, PDP and EIS techniques at 303 K. Their exploration indicated that *Chrysophyllum albidum* corrosion inhibition potency strengthens in higher amounts of the extract but weakens as time lapses and when exposed to temperature. Benahmed et al. (2016) studied the corrosion protection property of *Saccocalyx satureioides* on carbon steel (X52) in the crude ethyl acetate extract in 1 M HCl solution by weight loss, PDP and EIS methods. They discovered that *Saccocalyx satureioides* extract inhibits carbon steel (X52) from corrosion and improves its inhibiting ability by increasing the amount of the extract. Nwosu and Muzakir (2016) investigated the inhibition efficiency of lignin on the corrosion protection of mild steel in 1 M HCl medium through weight loss technique from 500 to 5000 mg/L (w/v) of inhibitor amount and temperature ranging between 303 and 343 K. Such investigation proved that the maximum inhibition efficiency of lignin is 92.39% at the maximum inhibitor amount of 4000 mg/L at 303 K.

Hassan et al. (2016) researched the corrosion inhibition of *Citrus aurantium* leaf extracts on mild steel in 1 M H_2SO_4 by weight loss technique. The study further considered the effect of temperature, time and inhibitor amount on the extract's protection capacity. It was revealed that *Citrus aurantium* leaf extract efficiently protects mild steel from corrosion and that its maximum protection efficiency was 89% at 40 °C and 10 ml/L. Such inhibition efficiency, the study noted, improved by raising the inhibitor amount but retarded as temperature escalated. The corrosion inhibition property of apricot gum on mild steel in 0.5 M phosphoric acid was evaluated by Mohammadi et al. (2016). Such evaluation, which deployed PDP and EIS, linear polarization resistance and electrochemical noise methods, concluded that apricot gum's corrosion inhibition efficiency increases as the apricot gum amount escalates up to a certain value but declines with temperature raise.

In Fouda et al. (2017) study, corrosion inhibition properties of *Tilia cordata* extract on carbon steel in 1 M HCl medium by chemical and electrochemical methods were assessed. Results concluded that *Tilia cordata* extract has the maximum corrosion protection efficiency of 96% at 300 mg L^{-1}. However, efficiency strengthens when the extract amount is higher and decreases when exposed to medium temperature. Mohamed et al. (2017) investigated *Corchorus olitorius* stem extract's corrosion prevention on mild steel in a 0.5 M H_2SO_4 medium through EIS, PDP and weight loss techniques.

It was consequently reported *Corchorus olitorius* stem extract retards corrosion and its inhibition efficiency of 93%. Such efficiency, the study revealed, increased with the increased amount of the extract. Peter (2017) studied the corrosion prevention of *Azadirachta indica* source on mild steel in 1 N HCl, H_2SO_4 and HNO_3 media at 304 and 313 K through weight loss techniques. Results reveal that the extract's protection efficiency improved by raising the inhibitor amount to 1000 ppm after 72 h. Zheng et al. (2017) evaluated the corrosion protection property of *Houttuynia cordata* extract on mild steel corrosion in 0.5 M H_2SO_4 through weight loss and electrochemical methods. Findings demonstrated that the extract is an excellent mixed-type inhibitor with a prevalent cathodic action. Its protection efficiency can reach the maximum protection efficiency of 90% at 0.75 g/L inhibitor amount at 298 K. As noted, the potency of such extract strengthens as the amount of *Houttuynia cordata* extract increases.

An investigation of *Adansonia digitata* (Baobab) pulp and seeds extracts corrosion inhibition action on mild steel was conducted by Karungamye and Murthy (2017) in a 1 M H_2SO_4 medium at room temperature through gravimetric, PDP and EIS methods. It was established that the seeds source of *Adansonia digitata* displayed higher corrosion inhibition than pulp extract *Adansonia digitata* pulp extract with the maximum corrosion inhibition efficiency of 57.65% and 68.70% for *Adansonia digitata* pulp extract and *Adansonia digitata* seed extract, in that order. Mohammad et al. (2017) studied *Tragacanth* gum (arabinogalactan) for its corrosion protection characteristics on carbon steel in 1 M HCl through gravimetric, PDP and EIS methods. It was discovered that extracts from *Tragacanth* gum have an inhibition efficiency which increased up to 96.3% with an increased amount of concentration of *Tragacanth* gum (Mohammad 2017).

Alibakhshi et al. (2018) investigated the corrosion protection of *Glycyrrhiza glabra* source on mild steel in a 1 M HCl solution by PDP and EIS methods. The study realized that the extract protected mild steel against corrosion. More so, such inhibition capacity (of a mixed-type) was reported to strengthen as extract concentration improved and achieved the higher protection efficiency of approximately 88% at 800 ppm after 24 h. Anuchi and Ngobiri (2018) investigated the corrosion inhibitory property of *Piper guineense* leaf source on mild steel in a 2 M H_2SO_4 solution by weight loss technique. Findings indicate that *Piper guineense* extract reduces corrosion, and its inhibition activity is strengthened due to the increase in the amount of extract to achieve a higher inhibition efficiency at 313 K and 323 K. Asadi et al. (2018) studied the corrosion prevention of different amounts of Lemon Balm extract on mild steel in 1 M HCl through electrochemical and theoretical approaches. Lemon Balm extract was unveiled as a mixed-type inhibitor with a maximum corrosion inhibition efficiency of 95% at 800 ppm.

Cookey et al. (2018) investigated the corrosion-inhibitive action of *Clivia nobilis* leaves' source on mild steel in H_2SO_4 and HCl via weight loss and gasometric techniques. Along such a line of inquiry, the study also considered whether the extract's efficacy is affected by the amount of extract, soaking time and temperature. Results clarified that an improvement in the corrosion protection efficiency is proportional to the increase in the amount of *Clivia nobilis* leaf extract at a short exposure time, and the inhibition was more significant in HCl than in the H_2SO_4 medium. Another crucial study is Chandrabhan et al. (2018), which evaluated the corrosion inhibitory action of *Holoptelea integrifolia* leaf extract on mild steel in 1 M HCl through weight loss, electrochemical and DFT techniques. Such a study proved that the corrosion inhibition property of *Holoptelea integrifolia* leaf extract improved by raising the inhibitor amount to attain the higher protection efficiency of 93.91% at 400 mg/L inhibitor amount.

In another study, Saxena et al. (2018a) gauged the corrosion prevention of *Achyranthes aspera* source on mild steel in 0.5 M H_2SO_4 through weight loss, PDP and EIS methods. Results confirmed that the extract retarded the corrosion rate with the optimum protection efficiency of 90.79%, which was attained at 500 mg L^{-1}. In another study by Saxena et al. (2018b), the corrosion prevention of *Cuscuta reflexa* fruit extract on mild steel was examined in 0.5 M H_2SO_4 via weight loss, PDP and EIS techniques. The study found that the extract retards corrosion with a higher protection efficiency of 95.47%, obtained at 500 mg/L inhibitor amount. Moreover, Akindele (2018) assessed corrosion prevention of Neem leaf source on mild steel in 0.1 M HCl through a weight loss technique. Findings confirmed that the source is a corrosion inhibitor with a maximum inhibition efficiency of 93.24%. However, such inhibition efficiency declined with the increased time of exposure. Shanmuga et al. (2018) evaluated the corrosion inhibitory activity of dry *Spathodea campanulata* (Sc) leaves extract on mild steel in 1N H_2SO_4 solution through a weight loss technique. Results revealed a higher protection efficiency of 82.74% at 1.5% of the source. The efficiency was attained by the increase in the amount of extract and declined with a temperature rise. Srivastava et al. (2018) inquired about the corrosion inhibitory effectiveness of *Pisum sativum* (green pea) peels source on mild steel in HCl at varying temperatures through weight loss, Tafel polarization curves and EIS techniques. The study found that the extract effectively prevents corrosion with a maximum inhibition efficiency of 91% from the weight loss measurements, 87% from polarization curves and 90% from EIS at 400 mg L^{-1}. However, the percentages of protection efficiency, the study reported, declined with the increase in temperature and acid concentration. Qiang et al. (2018) studied the corrosion prevention capacity of Ginkgo leaf source on X70 steel in 1 M HCl by electrochemical technique, and findings show that the protection efficiency went above 90% in the presence of 200 mg/L Ginkgo leaf extract at all the experimented temperatures.

In their study, Wang et al. (2019) assessed the corrosion inhibitory effectiveness of *Ficus tikoua* leaves extract for its on carbon steel in HCl by electrochemical methods. The study noted that the extract is a mixed-type inhibitor with a maximum protection efficiency of 95.8% at 298 K. Thilgavathi et al. (2019) investigated the corrosion-inhibitive property of *Ipomea staphylina* leaf source on mild steel in 1 M HCl by electrochemical and mass loss investigations. The study indicated that the extract has the optimal corrosion inhiation of 92.77%, which declines as temperature increases. There is also a study by Ragul and Murugesh (2020), which examined the corrosion inhibition action of *Mitracarpus hirtus* leaves methanol extracts on mild steel in 0.5 M H_2SO_4 medium via weight loss, colourimetric and electrochemical methods. The study found that *Mitracarpus hirtus* leaves methanol extract has corrosion inhibition efficiency which declined by raising temperature and acid amount. In Saeed et al. (2019)'s research, the corrosion inhibition action of *Cucumis melo* L peel source on mild steel in 1 M HCl was executed by using weight loss and PDP techniques at different extract amounts including 0.05, 0.1, 0.2, 0.3, 0.4 and 0.5 g/l and temperature ranging from 295 to 333 K. Findings indicate that the mild steel corrosion rate declined by raising extract amount and declined by raising temperature. The corrosion inhibition action of *Acalypha chamaedrifolia* leaves source on mild steel in the acid solution by Arthur and Abechi (2019) through the gravimetric method is another study worth considering. The study discovered that *Acalypha chamaedrifolia* leaves source decreases corrosion rates from 0.49 mg cm^{-2} h^{-1} for the blank solution to 0.15 mg cm^{-2} h^{-1} for the inhibited solution in 1 M HCl at 0.25 g/L of the source. It was noted further that such corrosion protection efficiency is amplified by raising the amount of the inhibitor, immersion time and experimental temperature. The study reported that the incremental changes of these factors can lead ahigher protection efficiency of 85.11% at 1.25 g/L for 24 h of immersion duration at 290 K. In researching corrosion inhibition of marine sponge *Ircinia strobilina* crude extract on mild steel in 1 M HCl through weight loss, PDP, linear polarization resistance and EIS techniques, Fernandes et al. (2019) reported that the extract has corrosion inhibition, which increased with the rise of ISCE concentration and can reach up to the maximum inhibition efficiency of about 55% at 0.5 g L^{-1} to 82% at 2.0 g L^{-1} of the inhibitor.

In their exploration of the corrosion inhibition activity of *Tamarindus indica* extract on mild steel in 1 M HCl, which used the weight loss, PDP and EIS techniques, Sangeetha et al. (2012) concluded that *Tamarindus indica* extract is a good mixed-type corrosion inhibitor whose maximum efficiency ranges from 74 to 88% at the inhibitor amount of 100 to 600 ppm, respectively. Likewise, Manikandan et al.'s (2019) study evaluated the corrosion inhibition action of banana peel source on mild steel corrosion inhibitory properties in 1 M HCl medium by weight loss and electrochemical methods. The findings ascertained that banana peel extract has a maximum corrosion inhibition efficiency of 87%, and this efficiency improves by raising the amount of banana peel extract. Rajesh et al. (2019) investigated the corrosion-inhibitive properties of *Citrus aurantifolia* leaf extract on mild steel in 0.5 M H_2SO_4 medium through weight loss and EIS techniques. Such exploration argued that *Citrus aurantifolia* leaf extract has a higher protection efficiency of 96.46% at the inhibitor amount of 250 mg/L. The corrosion-inhibitive action of essential oil of fennel seeds on mild steel in 1.0 M HCl was evaluated by Barrahi et al. (2019) through weight loss, EIS and PDP methods at different temperatures. Findings showed that EOFs are a mixed-type inhibitor with a higher protection efficiency of 88% at two g/L. However, the said inhibition efficiency declines as temperature rises, in the order 89, 86, 80 and 76% at 303, 313, 323 and 333 K, in that order. In exploring the corrosion inhibition actions of *Artemisia herba-alba* oil on mild steel in 0.5 M H_2SO_4 medium by weight loss and stationary polarization curves, Boumhara et al. (2019) concluded that *Artemisia herba-alba* oil has the optimal corrosion inhibition efficiency of 88% at 298 K and 2.76 g L^{-1} of the extract amount. However, the said efficiency declines with increase in temperature

(303–343 K) at different amounts of *Artemisia herba-alba* oil studied.

The study of corrosion protection of ethanol source of *Cucurbita pepo* leaves on mild steel was conducted in a 1 M HCl medium by Chahul et al. (2019), through weight loss and linear polarization methods from 303 to 333 K. It was realized that the extract can retard corrosion process with the efficiency of 95%. In another study, Pramudita et al. (2019) evaluated the corrosion protection property of rice husk source in a 1 M of H_2SO_4 along with potassium iodide and through weight loss techniques at various temperatures and inhibitor amounts. Consequently, it was discovered that the corrosion inhibition efficiency of rice husk extract increased to its maximum capacity of 95.89% at 1,250 ppm at 313 K following the synergistic effect, resulting from the addition of potassium iodide. Dehghani et al. (2019a, b) researched the corrosion protection characteristic of *Citrullus lanatus* fruit source on mild steel in 1 M HCl through integrated experimental and electronic/atomic level theoretical perspectives. Findings showed that the extract achieved a mixed-type inhibition with cathodic inhibition frequency and higher protection efficiency of 91% at 800 ppm of the inhibitor. In another study, Dehghani et al. (2019a, b) studied the corrosion inhibitory characteristic of *Tamarindus indiaca* extract on mild steel in 1 M HCl by EIS and PDP methods. Findings from EIS show that the inhibitor achieved a higher protection efficiency of 93% at 800 ppm after 2.5 h of steel soaking time. The extract also demonstrated a mixed-type corrosion inhibition of cathodic inhibition prevalence. Furthermore, the study's PDP results also indicated that the inhibitor achieved a higher protection efficiency of 85% at 800 ppm, while regarding the weight loss measurements, the exploration confirmed the extract has an inhibition efficiency of 93% after 4 h of exposure to an inhibitor.

Studies also evaluated the corrosion protection of *Allium sativum* (garlic) extract on mild steel in 1 M HCl and 1 M H_2SO_4 through PDP and EIS methods by Devikala et al. (2019). Such exploration revealed that garlic extract has a maximum inhibition efficiency of 95%. Uchenna et al. (2019) studied the corrosion protection of *Citrus sinensis* (orange) leaf extract on mild steel in 1 M HCl and 0.5 M H_2SO_4 solutions by PDP and EIS methods at 30 °C. The study reported that the source demonstrated a mixed-type inhibition, and the protection improved by raising the amount of the extract up to 50 mg/L. The corrosion prevention of mild steel by *Cucumis melo* L peel source in 1 M HCl was assessed by Saeed (2019) through weight loss and PDP methods (Saeed et al. 2019). Different extracts amount, including; 0.05, 0.1, 0.2, 0.3, 0.4 and 0.5 g/L were included, and the corrosion speed of mild steel and protection efficiency was established between 295—333 K. Saeed (2019) revealed that the protection efficiency of the extract improved from 22.34%—79.69% as per the increase of extract amount from 0.05 to 0.5 g/L at 295 K. It was further noted that the extracts inhibition efficiency increased from 79.69 to 91.59% at higher concentration of the extract, and by increasing temperature from 295 to 318 K, in that order, but more raise of temperature to 333 K resulted into a decline in the inhibition efficiency to 81.26%. Benarioua et al. (2019) investigated the mild steel corrosion prevention of *Petroselium Sativum* leaves source in a 1 M HCl medium through weight loss, PDP and EIS methods. Findings indicate that the extract significantly retarded the corrosion rate and the protection improved by raising *Petroselium Sativum* leaves source amount, achieving the corrosion protection efficiency of up to 92.39% at 25 ℃ for a 5 gL^{-1} extract concentration, and the inhibitor demonstrated a mixed-type inhibition.

In studying corrosion protection properties of the crude sources extracted from the bark of *Cryptocarya nigra* and three alkaloids namely; N-methylisococlaurine, N-methyllaurotetanine and atherosperminine extracted from the dichloromethane extract on mild steel in 1 M HCl medium, via EIS technique, Faiz et al. (2020) discovered that *Cryptocarya nigra* extract and N-methyllaurotetanine retarded mild steel corrosion attaining higher protection efficiency of 91.05% and 88.05%, respectively. The study also established that the extract operates as an anodic-type inhibitor, and N-methyllaurotetanine acts as a mixed-type inhibitor with the dominance of anodic protection. The corrosion-inhibitive property of *Olea europaea* L. (olive) leaf extract on mild steel in H_2SO_4 solution by PDP and EIS methods was studied by Düdükcü et al. (2020). In that study, which also considered the temperature factor on the extract, the said extract demonstrated the maximum corrosion inhibition efficiency of 96% even after 120 h of exposure to an inhibitor.

Another notable study of corrosion inhibition is that which analysed the inhibitory property of *Tephrosia purpurea* leaves source on mild steel in 1N HCl medium through gravimetric, PDP and EIS techniques by Bhuvaneswari and Arulmathi (2020). The study indicated that *Tephrosia purpurea* is an excellent mild steel corrosion inhibitor, with higher protection efficiency of 95.4% at 300 ppm extract amount. Notably, the efficiency of *Tephrosia purpurea* strengthens as the amount of the inhibitor increases.

In determining the corrosion prevention of Dardagan Fruit source on mild steel in a 1 M HCl through electrochemical methods, Sedik et al. (2020) postulated that DF inhibited mild steel from corrosion and has a maximum efficiency of 92% after 1 h exposure and 97% after 6 h to the 3,000 ppm inhibitor amount. It was further noted that the extract's protection efficiency increased by raising its immersion time. Another study worth mentioning is Yüce (2020), which examined the corrosion inhibition property of *Robinia pseudoacacia* leaf extract (at various concentrations) on mild steel in 0.5 M HCl by electrochemical techniques. Yüce revealed that the extract's effectiveness increased by raising the amount of inhibitor, attaining a higher efficiency of 92% at 2.00 g/L of extract and at 25 °C. However, such a mixed-type inhibition efficiency declined as temperatures and acid concentration rose.

More so, the study of *the corrosion protection property of Magnolia kobus extracts* on mild steel by mass loss measurements was undertaken in 1 M H_2SO_4 by Chang et al. (2020). The study illustrated that the extract efficiently retarded mild steel corrosion at 500 ppm. The study confirmed that such protection efficiency improved by raising the extract amount to a higher inhibition efficiency of 95.01% at 303 K. In Emori et al.'s (2020) experimental and theoretical investigation, the corrosion inhibition action of *Dioscorea septemloba* extract on carbon steel in 1 M HCl medium by electrochemical and gravimetry methods was inquired. The study discovered that *Dioscorea septemloba's* extract exhibits a mixed-type corrosion protection whose efficiency improved by raising the inhibitor amount, temperature and exposure time.

Durodola et al. (2020) investigated the corrosion prevention of *Spilanthes uliginosa* leaves source on mild steel in 2.0 M HCl by gravimetric and electrochemical techniques. This study established that the source of *Spilanthes uliginosa* leaves prevents mild steel corrosion, and its inhibition action increases as the amount of inhibitor increases. The anti-corrosive property of *Combretum indicum* leaf source on mild steel corrosion inhibition was investigated in 1 M HCl by Devikala et al. (2020) through weight loss and electrochemical techniques (Pavithra 2020). Results showed that *Combretum indicum* leaf extract is a mixed-type corrosion inhibitor, and such inhibition raises as the extract's amount intensifies.

Also, a study on mild steel corrosion prevention by *Acacia senegal* gum in 0.5 M H_2SO_4 was conducted by Emmanuel and Buchweishaija (2021a) through PDP and EIS techniques. The study indicated that *Acacia senegal* gum relatively retards the corrosion speed and its optimal efficiency of 43% is achieved by raising the amount of gum up to 300 ppm. Also, Emmanuel and Buchweishaija (2021a, b) evaluated the synergistic influences of halide ions, Br^- and I^-, in the same study and revealed an increase in its corrosion inhibition efficiency of 81.6% due to synergism with higher synergy from iodide than bromide ions. In another study, Emmanuel and Buchweishaija (2021b) evaluated the effect of temperature on *Acacia senegal* gum and synergism on mild steel corrosion prevention in 0.5 M H_2SO_4. These scholars concluded that temperature raising adversely affects the inhibition efficiency of *Acacia senegal* gum and the synergy among *Acacia senegal* gum and halide ions. Abdelaziz et al. (2021) applied the leaves source of *Arbutus unedo* L. plant as mild steel corrosion inhibition in an HCl medium by theoretical and experimental techniques. Findings show that the addition of *Arbutus unedo* L. leaves extracts in 1 M HCl medium significantly retarded the corrosion current densities, and the corrosion inhibition efficiency raised from 65.76 to 88.09% for 0.1 and 0.5 g/L of leaves source, respectively. Aralu et al. (2021) studied *Gongronema latifolium* source for mild steel corrosion inhibition by weight loss from 303 to 323 K. The study findings indicated that the extract's protection efficiency declined as temperature increased but strengthened by raising the amount of inhibitor, thereby achieving a higher protection efficiency ranging between 59.06 and 81.69%. In Jiyaul et al.(2021)s' research, corrosion prevention by *Thevetia peruviana* flower source on mild steel in a 1 M HCl medium was assayed through electrochemical, surface and computational demonstrations. Findings indicate that *Thevetia peruviana* flower source is a high potential mixed-type corrosion inhibitor with a maximum corrosion protection efficiency of 91.24% at 200 mg/L. It was further noted that such protection efficiency increased by raising the amount of the inhibitor applied on mild steel. By gravimetric and electrochemical methods, Nwosu (2021) evaluated mild steel corrosion prevention by *Parinari polyandra* leaf extract in a 1 M HCl medium. The study discovered that *Parinari polyandra* leaves source is a promising inhibitor, achieving a higher protection efficiency of 97.22%. The said inhibition efficiency declined at elevated temperatures and was raised with prolonged mild steel soaking time.

The ability of *Tinospora cordifolia* extract to inhibit corrosion on low-carbon steel in 0.5 M H_2SO_4 solution was assessed by Saxena et al. (2021) through weight loss, PDP and EIS techniques. Findings indicated that *Tinospora cordifolia* source worked as a mix-type inhibitor with a maximum efficiency of 87.18% at a 500 mg/L inhibitor amount. Even so, the extract's corrosion protection was increased due to the increased amount of the extract. In studying the feasibility of *Crotalaria pallida* leaves extract corrosion inhibition action on mild steel in HCl by weight loss, EIS and PDP methods, Rani et al. (2021) discovered that the 4 (V/V %) alcohol extract attained higher corrosion protection efficiency of 95% as compared to the same volume percentage of water extract that achieved the inhibition efficiency of 87% but the efficiency declined with an increase in temperature and acid concentration.

Adekunle et al. (2021a, b) assessed the inhibition action of methanolic extract of *Dracaena arborea leaves* on mild steel in 2.0 M HCl by electrochemical and gravimetric techniques. Findings indicate that the extract is a mixed-type inhibitor and that its protection efficiency is augmented to the maximum efficiency of 81.5% for hot extract and 72.7% for cold extract by raising the amount of the extract. More so, the corrosion inhibition ability of *Allium cepa* L. source from *Allium cepa* L peel extract and *Allium cepa* L bulb extract to protect carbon steel in an acidic medium was studied by Galo et al. (2021). The study revealed that the maximum corrosion protection efficiency of the extracts was 60% for *Allium cepa* L peel extract and 67% for *Allium cepa* L bulb extract. Other researchers, such as Mauro et al. (2022b), investigated the corrosion protection characteristic of an aqueous source of *Joazeiro* stem bark on mild steel in 1 M HCl by weight loss, PDP and EIS techniques. These scholars discovered that the extract's corrosion efficiency increased from 85.4 to 89.8% by raising the extract's amount, from 100 to 800 mg L, respectively. Thomas et al. (2021) studied the mild steel corrosion protection property of ethanolic *Croton persimilis* leaf extract in 1 M HCl and H_2SO_4 by weight loss technique. The study established that *Croton persimilis* leaf extract is a mixed-type corrosion inhibitor whose efficiency improved by raising the extract's amount.

In Banu et al. (2021)'s study, the corrosion protection capacity of *Allamanda cathartica* leaves source on mild steel in a 1 M H_2SO_4 through mass loss technique at various temperatures was assessed. The study noted, *Allamanda cathartica* leaves extract is a mixed-type corrosion inhibitor. The study added that such efficiency increases as the extract's concentration mounts and declines due to higher temperatures. Also, Farzana et al. (2021) explored the inhibitive activity of *Andrographis echioides* leaf extracts on the corrosion of mild steel in 1 M HCl by mass loss and electrochemical methods. The study shows that the inhibitor effectively retarded mild steel corrosion with a maximum efficiency of 79.48%. The study further added that such inhibition efficiency, which is of a mixed type, declined due to temperature rise.

On their side, Hynes et al. (2021) studied the mild steel corrosion protection action of *Aerva lanata* flowers extract on low-carbon steel in 1 M HCl by mass loss and electrochemical methods. *Aerva lanata* flowers extract achieved the maximum corrosion inhibition (a mixed type) efficiency beyond 88% at 600 ppm, and the said efficiency can decline as the inhibitor's concentration is lowered. *Dolichandra unguis-cati* leaf source was evaluated for its mild steel corrosion prevention in HCl by mass loss, PDP and EIS methods by Rathod et al. (2021). It was established that the extract mitigated mild steel corrosion, achieving a higher protection efficiency of 93.61% at 0.76 g/L after 3 h of immersion at 300 K, and the inhibitor demonstrated a mixed-type inhibition. In Li et al. (2021) investigation, the corrosion mitigation capacity of an aqueous extract of *Brassica oleracea* L on Q235 steel in 0.5 M H_2SO_4 and 1 M HCl by conventional and in-situ electrochemical methods was sought. The extract retarded corrosion with an efficiency of 92.3% in H_2SO_4 and 93.8% in HCl at 300 mg/L.

A study by Haldhar et al. (2021) on the corrosion protection property of the source of aerial parts of *Swertia chirata* on carbon steel in 0.5 M H_2SO_4 by weight loss and PDP methods was conducted. It was discovered that *Swertia chirata* is an excellent inhibitor with an efficiency of 92.32% at 500 mg/L of inhibitor amount. Meanwhile, Hossain et al. (2021) evaluated the corrosion activity of *Paederia Foetida* leaf extract on mild steel in 1 M HCl by weight loss technique. The study shows that the inhibitor from *Paederia Foetida* leaves source effectively retarded the corrosion speed with a maximum of 73.77%, three days after mild steel's exposure to the inhibitor.

Gayakwad et al. (2022) studied the corrosion protection behaviour of *Rhoeo discolours* plant source on mild steel in 0.5 M HCl by PDP and EIS methods and at an inhibitor concentration between 0.2 g/L—2 g/L and temperature ranging from 308 to 318 K was assayed. The study concluded that the extract attained the higher protection efficiency of 87.72% at 308 K, 79.78% at 313 K and 74.84% at 318 K from the PDP study and 82.23% at 308 K, 79.22% at 313 K and 71.20% at 318 K from EIS measurements at an inhibitor amount of 2.0 g/L. Furthermore, the study noted that raising temperature reduced the extracts' corrosion protection efficiency. In their exploration, Manh et al. (2022) investigated the corrosion protection action of steel by *Sonneratia caseolaris* leaf extract in an aerated 1 M HCl medium by electrochemical methods. Findings show that *Sonneratia caseolaris* leaf extract is the corrosion inhibitor whose maximum efficiency is 98% at 2500 ppm inhibitor amount and that protection efficiency declined with the decrease in the HCl amount at a particular *Sonneratia caseolaris* leaf extract amount. The corrosion inhibition action of *Vernonia amygdalina* Bitter leaf extract and *Musa Acuminata* Banana stem extract on mild steel in 1 M HCl was investigated by Oyedeko et al. (2022) through weight loss techniques at different temperatures. Results show that the extract reduced mild steel corrosion, attaining the higher protection efficiency of 80.85% at 0.5 g/L. The efficiency raised as the amount of the extract increased but declined by raising the temperature. Prasad et al. (2022a, b) evaluated whether *Cinnamoum tamala* leaves extract corrosion inhibition action work on the carbon steel in 0.5 M H_2SO_4 by EIS, Tafel and gravimetric loss methods. The study noted that the extract from *Cinnamoum tamala* leaves has the maximum corrosion protection efficiency of 96.76% at the inhibitor amount of 100 mg/L.

Also, in assaying the inhibiting action of *Averrhoa bilimbi* leaves extract on mild steel in 1 M HCl solution, as studied by Bangera et al. (2022), via gravimetric, EIS and PDP methods at different temperatures, it was understood that inhibition efficiency of the extract could increase with the higher level of the inhibitor concentration but declined by raising temperature. In another recent exploration, Radha et al. (2022) studied the corrosion protection action of *Physalis minima* on low-carbon steel in 1 M HCl by PDP and EIS methods. It was discovered that the extract's protection efficiency increased by raising the inhibitor amount to attain the maximum inhibition efficiency of 98% at 10% (v/v) of the inhibitor amount at 298 K. However, the efficiency declined as temperature escalated. In ascertaining the property of *Centipeda minima* leaves extract on mild steel corrosion in 1 M HCl by PDP, Tafel curves and EIS methods, Wang et al. (2022) reported that the extract is an excellent inhibitor with a maximum corrosion protection efficiency of 96.2% at 500 mg/L inhibitor amount at 318 K. Nasser and Masmali (2022) evaluated the corrosion inhibition property of aqueous extracts of *Tamarindus indica* source (leaves, stem, fruit pulp and fruit husk) on mild steel in HCl, H_2SO_4, formic acid and citric acid at various temperatures. The study concluded that the extracts from *Tamarindus indica* are a mixed-type inhibitor, and their inhibitory activity improved with increased extract concentration but declined as temperature mounted. The study by Cherrad et al. (2022) examined the corrosion inhibitory action of *Cupressus arizonica* fruit essential oil on carbon steel in 1 M HCl by PDP and EIS methods. They informed that the oil efficiently inhibited carbon steel from corrosion with a mixed-type inhibition, achieving the maximum efficiency of 93% at 0.5 g/L. Such efficiency declined by raising the temperature to 77% at 323 K.

Also, Okuma and Onyekwere (2022) studied mild steel corrosion prevention by *Irvingia gabonensis* leaf extract by weight loss technique in 1.0 M HCl. The findings indicated that the extract retarded corrosion. However, its inhibitory action improved by raising the extract's amount (to higher protection efficiency of 67.14% at 25 ml) and exposure time. More so, Zehra et al. (2022) investigated the inhibitory property of the aqueous extract of *Crataegus oxyacantha* leaves on carbon steel in 1 M HCl medium by weight loss, PDP and EIS techniques. The findings indicated that the extract acted as a mixed-type inhibitor, and its efficacy increased (to the maximum of 94% at 3 g/L at 298 K) as the extract's concentration rose. The other study considered in this review is Shahini et al. (2022), which evaluated the anticorrosive property of *Nepeta Pogonesperma* stem extract on mild steel in 1 M HCl via PDP and EIS methods. The study established that the extract inhibited corrosion with a higher effectiveness of 92% at 1000 ppm inhibitor amount after 5 h of exposure. Besides, the present use of *Falcaria vulgaris* leaf extract for mild steel corrosion inhibition in a 1 M HCl media was examined. Results showed that at the ideal concentration of 800 ppm of extract, corrosion was retarded. After six hours of immersion, the EIS analysis showed an inhibitory efficiency of 91.3% at this dose (Alimohammadi et al. 2023).

Still, research has been done at room temperature on the corrosion behaviour of mild steel in the presence and absence of a corrosion inhibitor called *Dracocephalum* extract in 0.5 M H_2SO_4 and 1.0 M HCl. The extract's anti-corrosive properties are demonstrated by the results, which show that the inhibitory efficiency rose as the extract dose was raised, reaching 94% at 75 ppm in H_2SO_4 and 90% at 400 ppm in HCl (Golshani et al. 2023). In addition, the preventive properties of *Rheum ribes* leaf and floral extracts on mild steel corrosion in 1.0 M HCl were investigated. According to the data, the inhibitory efficiency increased as the extract concentration increased, reaching 94.9% at 1000 ppm (Kaya et al. 2023a), whereas after 1 h and 6 h of exposure, floral extract offered 94.7% and 98.5% protection efficiencies at 1000 ppm (Kaya et al. 2023b). In another study, *Cucumeropsis mannii* shell extract was used as a corrosion inhibitor in a chloride solution to study mild steel corrosion. The results showed that the maximal inhibition efficiency using PDP and EIS approaches was 91.2% and 92.2%, respectively (Popoola et al. 2023). In 0.5 M H_2SO_4, the corrosion prevention ability of *Piper nigrum* leaf extract for stainless steel utilized in the oil industry was investigated. The results indicated that at higher extract concentrations, the corrosion inhibition efficiency was 94.20% (Prasad et al. 2022a, b).

In a different study, the potential to inhibit corrosion of stainless steel used in the petroleum pipeline business was investigated using *Mimosa pudica* extract. Results demonstrated that the extract worked better, obtaining an inhibitory efficiency in the acid solution of more than 92% at 500 ppm (Prasad et al. 2023). In a 1 M HCl solution, the essential oil of *Pinus nigra* has been studied as a corrosion inhibitor for carbon steel. The findings demonstrated that it functioned well, reaching an inhibition efficiency of more than 90% after four hours in all inhibitor concentrations with an inhibition decline above 200 ppm concentration (Simović et al. 2023). An in-depth investigation of glucosinolates, an essential class of phytochemicals mostly present in Brassica crops (primarily derived from cruciferous vegetables) and its potential to prevent metal corrosion has been provided in a recent study (Abdelshafeek and El-Shamy 2023). Results indicate that naturally occurring extracts high in glucosinolates, like those found in mustard seeds, are effective corrosion inhibitors. Still, there have been recent reports on microbiologically induced corrosion, an electrochemical process wherein bacteria accelerate the metal's deterioration (Gad and El-Shamy 2022; Ghazy et al. 2023; Shamy 2022; Megahed et al. 2023). Researchers have looked into the bio-corrosion of an archaeological knife removed from burial soil and the efficacy of garlic extract as a natural biocide in these situations (Megahed et al. 2023). Results of this study indicate that when applied to carbon steel enriched with bacteria that cause corrosion, garlic extract can function as an efficient corrosion inhibitor with biocidal action (Megahed et al. 2023). The efficiency of *Vicia faba* peel extracts as a corrosion inhibitor on mild steel has been tested in a saline solution with 3.5% sodium chloride (Abdelshafeek et al. 2022). The experiments' findings indicate that 200 ppm of the hexane or acetone extracts is the ideal concentration for the most remarkable effectiveness.

Shreds of evidence from the literature reveal a promising trend in the shift from synthetic to natural plant-based corrosion inhibitors. The performance of these inhibitors towards the prevention of metal corrosion is revealing and can be compared with traditional synthetic inhibitors. Compared to traditional corrosion inhibition

Table 1 Examples of some plant-based and synthetic inhibitors and their corresponding corrosion inhibition efficiencies

S/N	Inhibitor name	Inhibitor category	Media	Metal	Inhibition efficiency (%)	References
1	*Vicia faba* peel extracts	Natural	NaCl	Carbon steel	88.67/97.84	Abdelshafeek et al. 2022
2	*Chromolaena odorata* leaf extract	Natural	Acidic medium	Carbon steel	84.77	Daoudi et al. 2023
3	*Acacia mearnsii tannin*	Natural	NaCl	Aluminium	68	Daoudi et al. 2023
4	*Falcaria vulgaris* leaves extract	Natural	1 M HCl	Carbon steel	91.3	Alimohammadi et al. 2023
5	*Ganoderma lucidum* extract	Natural	1 M HCl	Carbon steel	83.1/ 93.9	Cheng et al. 2023
6	Polyurethane	Synthetic	3.5%NaCl	Carbon steel	98	Abdel-Karim et al. 2022
7	Dracocephalum extract	Natural	0.5 M H_2SO_4	Carbon steel	94	Golshani et al. 2023
8	Dracocephalum extract	Natural	1.0 M HCl	Carbon steel	90	Golshani et al. 2023
9	*Rheum ribes* leaf extract	Natural	1 HCl	Carbon steel	94.9	Kaya et al. 2023a, b
10	*Cucumeropsis mannii* shell extract	Natural	1.0 M NaCl	Carbon steel	92.2/ 91.2	Popoola et al. 2023
11	Piper nigrum leaves extract	Natural	0.5 H_2SO_4	Carbon steel	94.2	Prasad et al. 2022a, b
12	*Mimosa pudica* extract	Natural	0.5 H_2SO_4	Carbon steel	92	Prasad et al. 2023
13	*Pinus nigra* essential oil	Matural	1 M HCl	Carbon steel	> 90	Simović et al. 2023
14	*Acacia senegal* gum exudates	Natural	0.5 M H_2SO_4	Carbon steel	81.6	Emmanuel and Buchweishaija 2021a, b
15	Polyamide	Synthetic	3.5%NaCl	Al–Zn alloy 7075	92	Abdel-Karim et al. 2022
16	Nitrocellulose	Synthetic	3.5%NaCl	Al–Zn alloy 7075	65	Abdel-Karim et al. 2022
17	1,3-dibutyl thiourea	Synthetic	3.5%NaCl	Al–Zn alloy 7075	95.36	Gad and El-Shamy 2022
18	benzylidene-pyridine-2-yl-amine	Synthetic	1 M HCl	Carbon steel	99.16	Ashassi-Sorkhabi et al. 2005
19	(4-benzylidene)-pyridine-2-yl-amine	Synthetic	1 M HCl	Carbon steel	99.39	Ashassi-Sorkhabi et al. 2005
20	(4-chloro-benzylidene)-pyridine-2-yl-amine	Synthetic	1 M HCl	Carbon steel	99.59	Ashassi-Sorkhabi et al. 2005
21	3,5-bis-(2-thienyl)-4-amino-1,2,4-triazoles	Synthetic	1 M HCl	Carbon steel	98.3	Bentiss et al. 1999
22	3,5-bis-(2-thienyl)-4-amino-1,2,4-triazoles	Synthetic	0.5 M H_2SO_4	Carbon steel	94.1	Bentiss et al. 1999
23	Amine-fatty acid	Synthetic	NaCl	Carbon steel	99	Buchweishaija 2002
24	1-butyl-3-methylimidazolium trifluoromethyl sulfonate	Synthetic	3.5% NaCl	Carbon steel	74.9	Abbas et al. 2022

efficiencies, natural inhibitors have comparable inhibition efficiencies, which warrant their applications in diverse fields. Some examples of natural and synthetic metal corrosion inhibitors and their corrosion inhibition efficiencies are indicated in Table 1.

Effectiveness of natural corrosion inhibitors

Different authors have reported the effectiveness of plant-based corrosion inhibitors for metal corrosion inhibition. Natural inhibitors also reveal their outstanding effectiveness towards metal corrosion protection, guaranteeing their utilization compared to traditional inhibitors. Studies show that plant-based inhibitors effectively mitigate metal corrosion in various environments (Megahed et al. 2023). The extract of *Falcaria vulgaris* leaves (Alimohammadi et al. 2023), *Aloe vera*, Green tea, *Allium cepa* onion, Coconut water (Abdel-Karim 2022), *Dracocephalum* (Golshani 2023), *Oxandra asbeckii, Punica granatum, Artemisia pallens, Salvia officinalis, Lycium shawii, Teucrium oliverianum*, *Neolamarckia cadamba, Euphorbia falcate*, *Atropa belladonna*, *Eleusine aegyptiaca* (Kaur et al. 2022), *Rheum ribes* leaf (Kaya et al. 2022), natural gums (Kumar and Kumar 2022; Timothy et al. 2023), *Piper nigrum* leaves (Prasad et al. 2022a, b), *Mimosa pudica* (Prasad et al. 2023), *Pinus nigra* essential oil (Simović et al. 2023), *Fatsia japonica* leaves (Wang et al. 2023), *Spilanthes uliginosa* leaves (Durodola et al. 2020), *Ziziphora* leaves (Dehghani et al. 2020), *Magnolia kobus* (Chung et al. 2020), *Averrhoa bilimbi* leaves (Bangera et al. 2022), *Allamanda cathartica* leaves (Banu et al. 2021), *Cryptocarya nigra* (Faiz et al. 2020), *Andrographis echioides* leaves (Farzana et al. 2020), *Rhoeo discolour* leaves (Gayakwad et al. 2022), *Thevetia peruviana* flower (Haque et al. 2021), *Paederia foetida* leaves Hossain et al. 2021), Jatropha leaf (Ikpeseni et al. 2021), *Cardiospermum halicacabum* leaves (Kavithaet al. 2021), *Commiphora caudate* (Mohanraj et al. 2021), *Vernoniaamygdalina* leaves and *Musa acuminate* stem (Oyedeko et al. 2022), *Corchorus olitorius* stem (Oyewole et al. 2021) mangrovetannins, *Kopsia singapurensis*, *Xylopia ferruginea* and *catechins* (Panchalet al 2021), *Physalis minima* (Radha et al 2022), *Mitracarpus hirtus* (Ragul et al. 2020), *Crotalaria pallida* leaves (Raniet al. 2020), *Dolichandra unguis-cati* leaves (Rathod et al. 2020), *Nepeta pogonesperma* stems (Shahini et al. 2022) and *Centipeda minima* leaves (Wang et al. 2022) are among the effective natural corrosion inhibitors towards metal corrosion. Besides, an investigation was carried out to compare the effectiveness of a synthetic commercial corrosion inhibitor and an extract derived from the leaves of *Ruta chalepensis* in preventing corrosion on pipeline steel API 5L X52 in a solution of hydrochloric acid (Benghalia et al. 2018). The extract has been shown to have a relatively high inhibitory potential, which is highly dependent on its concentration in the corrosive solution. At a temperature of 353 K, the extract inhibitor outperforms the commercial inhibitor in terms of effectiveness (Benghalia et al. 2018).

A practical example is from the research done on the mitigation of bio-corrosion of an archaeological knife that was removed from burial soil and to determine whether garlic extract works well as a natural biocide in these situations (Megahed et al. 2023). Garlic extract has been found to have the ability to function as a natural, eco-friendly and effective green corrosion inhibitor with biocidal effects when applied to carbon steel that has been enriched with corrosion-causing bacteria (Megahed et al. 2023). Still, a comparison was made between the protective properties of a bio-based therapy and benzotriazole in preserving artefacts made of copper that were impacted by active corrosion caused by copper chlorides. The procedures were applied to artificial copper hydroxychlorides made from copper samples. The bio-based treatment caused nearly all copper hydroxychlorides to be converted into copper oxalates, offering a more effective corrosion inhibition. The results showed that few benzotriazole–copper complexes developed and that protectiveness was inadequate (Albini et al. 2018).

Literature indicates that natural mild steel corrosion inhibition inhibitors in corrosive solutions are widely studied to affirm their applicability towards mild steel corrosion mitigation. Interestingly, the use of natural plant-based inhibitors on mild steel corrosion inhibition continues to attract global attention, and more research is being conducted in this area. That said, although the findings on the area are promising, further studies on mild steel protection from corrosion, especially that which would guarantee structures' durability, ensure the safety of human health and a clean environment or avoid systems' unscheduled breakdown because of corrosion are a must.

Limitations and challenges of using natural corrosion inhibitors

Diverse studies reveal the fast and widespread shift from using plant-based natural corrosion inhibitors to overcoming mild steel corrosion in different operating environments. The trend of using these natural corrosion inhibitors reflects a total shift from traditional synthetic mild steel corrosion inhibitors. However, the limitation is that these inhibitors' performance is affected by the temperature condition of the media in which these inhibitors operate. Studies show that the corrosion inhibition efficiency of these inhibitors decreases with increase in temperature of the media (Cheng et al. 2022a, b; Cherrad et al. 2022; Durodola et al. 2020; Düdükcü et al. 2020; Emmanuel and Buchweishaija 2021a, b). The decrease in corrosion efficiency of natural inhibitors with increased temperature is explained by the desorption of previously deposited inhibitor molecules, signifying a physical adsorption mechanism (Durodola et al. 2020).

Still, there are very few formulas, theories or rules to direct the creation or application of inhibitors. Besides, green inhibitors are particularly difficult to store for an extended time due to their high biodegradability and considerable capacity for bioaccumulation. Additionally, while extracting plant extracts, care must be taken to utilize a less toxic solvent. Besides, the application of plant-based corrosion inhibitors may be hindered by their limited solubilities in polar electrolytes, particularly at concentration; thus, they are usually used in low amounts.

Future prospects of natural corrosion inhibitors

The adoption of plant-based natural corrosion inhibitors in mitigating mild steel corrosion is promising. The performance of natural corrosion inhibitors towards mild steel corrosion inhibition is a critical phenomenon and an area for further research. Despite being readily available and having high sustainability, natural corrosion inhibitors are environmentally friendly. Therefore, more research on their application is vital. Still, the influence of some factors including the media, concentration of inhibitors and operating temperature, towards the effectiveness of natural corrosion inhibitors, must be well explored. A full understanding of these factors would assist users and engineers in selecting the conditions under which these inhibitors can be used effectively. Besides, the synergism effect offered by some molecules, such as halide ions, that seem to enhance the performance of these inhibitors (Emmanuel and Buchweishaija 2021a, b) needs further attention in terms of research.

Understanding such a collection of parameters has the potential for higher inhibitor performance, thus warranting their application in diverse settings. Such information is vital to engineers and users in planning the proper use of natural corrosion inhibitors for mild steel corrosion inhibition in different environments. However, new avenues attract research for the likely application of natural corrosion inhibitors, such as in oil and pipeline steel corrosion due to hydrogen-induced degradation. Steel often experiences a decrease in strength and ductility when exposed to hydrogen. Reports show that hydrogen intrusion causes unexpected breakdowns in oil and gas pipelines, resulting in significant financial losses and environmental contamination (Shehata and El-Shamy 2023). The other recent topic of interest in corrosion research is microbially induced metal corrosion, which has also been reported (Argyropoulos et al. 2021; Gad and El-Shamy 2022; Ghazy et al. 2023).

Conclusions

The current improvement in applying natural mild steel corrosion inhibitors of plant origin has been immensely explored. Numerous reports indicate a progressive and consistent shift from traditional synthetic to natural plant-based corrosion inhibitors. Studies consistently show that natural corrosion inhibitors are excellent mild steel corrosion inhibitors that demonstrate different modes of inhibition in acidic media. However, numerous reports show that certain factors regulate the efficiency of various corrosion inhibitors. For example, some inhibitors' efficiency improves by raising the inhibitor's amount to their optimum value, and such value is likely to decrease primarily at higher temperatures.

While several studies concentrated on mild steel corrosion inhibition at temperatures close to room temperature, the review has indicated few reports on corrosion inhibition at elevated temperatures. This lacuna calls for researchers to undertake a systematic mild steel corrosion study at a temperature ranging from room temperature to at least 100 ℃ to reflect the natural field inhibitor operational conditions where acids are frequently in contact with mild steel. The move would provide a complete understanding of the influence of temperature on the strength of a particular corrosion inhibitor for mild steel corrosion protection. Even so, the review has indicated that the shift from the application of traditional to natural plant-based corrosion inhibitors is promising for a consistent trend showing the ever-increasing use of plant-based natural inhibitors for mild steel corrosion protection in acidic solutions. Thus, it seems obvious that plant-based inhibitors are gaining much global interest and are promising since they are biodegradable, abundant, non-toxic, recoverable materials, cost-responsive, biocompatible, highly effective and environmentally friendly. Therefore, further research on plant extracts is recommended in mild steel corrosion protection in acidic media.

Abbreviations

EIS	Electrochemical impedance spectroscopy
HCl	Hydrochloric acid
H_2SO_4	Sulfuric acid
PDP	Potentiodynamic polarization
pH	Potential of hydrogen
USD	United States dollar

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