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Review Article

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A Brief Review on Green Corrosion Inhibitor for Metals and Alloys

Aashish Sharma[1], Himanshi Tyagi[1], Saurabh Dewangan[2], Saurabh Srivastava[1] and Amrita Biswas[1*]

[1]*Department of Chemistry, Manipal University Jaipur, Rajasthan, India*

[2]*Department of Mechanical Engineering, Manipal University Jaipur, Rajasthan, India*

[*]Correspondence to:
Amrita Biswas
Department of Chemistry,
Manipal University
Jaipur, Rajasthan, India.
E-mail: amrita.biswas.chem@gmail.com

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Abstract

Metal corrosion control is crucial for technical, financial, environmental, and aesthetic reasons. The positive role of metal or compounds in preventing corrosion of materials in diverse condition and materials is briefly discussed. The hunt for green corrosion inhibitors, which are biodegradable and free from harmful substances, was sparked by the environmental toxicity of organic corrosion inhibitors. The most prevalent green inhibitors are made from natural or biological sources, such as amino acids, microorganisms, biopolymers, and plant extracts and oils. Nanoparticles as corrosion inhibitors have received a lot of interest recently due to their wide variety of industrial uses and financial advantages. Although they show great promise, nanoparticles do not always live up to their promise of offering more environmentally friendly methods of preventing corrosion. Plant extracts have gained importance as an easily available, renewable, and environmentally acceptable source for a variety of inhibitors. This review aims to provide insights into the mechanisms by which green corrosion inhibitors act, their applicability in many industries and their compatibility with contemporary materials through a thorough investigation of the most recent research and development in the field. Additionally, it sheds light on the benefits and drawbacks of using green inhibitors while also highlighting their potential to completely alter the field of corrosion protection. The various types of corrosion and prevention and recent research on the use of green corrosion inhibitors for metal and metal alloys are covered in this study.

Keywords

Metal, Corrosion, Inhibitor, Eco-friendly, Nanoparticle

Introduction

Corrosion is a natural and spontaneous process that transforms pure metals and their alloys into a variety of stable states, including their sulphides, oxides, hydroxides, and other states, through chemical and/or electrochemical reactions with the environment. Complete elimination would not be practicable or attainable; prevention would. To isolate the metallic structure from its surrounding medium and halt the oxidation-reduction process, corrosion inhibition may involve. The use of organic or inorganic chemicals that adsorb on the structure of metal and reduce the corrosion process. Inhibitors work as a barrier, their molecules attached on the metalor alloy surface, which inhibits the reaction [1]. To increase their corrosion resistance, inorganic inhibitors function as anodic inhibitors and have their metallic atoms encapsulated in the film. Most of the corrosion inhibitors being studied are dangerous and present significant ecological dangers when discarded. As a result, their usage is restricted by environmental legislation [2]. The use of innovative green corrosion inhibitors has been prompted by risks associated with the toxicity of conventional inhibitors. Most of these inhibitors, which are anticorrosion chemicals that are made from natural ingredients, are safe to dispose and favourable to the environment. There are two types of plant extracts inhibitors namely, organic extract and aqueous extract types [3].

The following advantages of plant extract make them an eco-friendly alternative to conventional hazardous corrosion inhibitors: (i) Convenience in application and manufacture, (ii) Environmentally friendly (biodegradable, nontoxic, and non-accumulative), and (iii) Beneficial for many metal/electrolyte systems.

Techniques for Obtaining Plant Extracts

The chemical makeup of the material, sample particle size and the presence of interfering compounds all have a role in the choice of extraction technique for profiling the target content of different plant species [4]. The first step is to select plant to the highest concentration of the necessary active ingredients. All plant parts, including the leaves, flowers, seeds, fruits, roots, and stems are used to produce the extracts. Briefly put, extraction method works by heating, chilling, and isolating the active ingredients while solvent is present. Different types of plant extracting techniques and their benefits.

- Solvent extraction - Low energy consumption, high production capacity, quick response, simple perpetual operation, and ease of automation [5].
- Supercritical fluid extraction - Ecological, friendliness and ease of product formation. Low vigour use, massive capacity for production, quick response, easy mechanisation, and simple ongoing operation [6].
- Microwave-assisted extraction - Microwave heating and breaking have a synergistic impact that can improve reaction yields, speed up reactions and prevent damage to active components that can happen with conventional, high temperature heating techniques [7].
- Ultrasound-assisted extraction - Leaching of organic and inorganic chemicals from plant matrix is facilitated by ultrasound energy [8].

Inhibitor Applications

Green corrosion inhibitors can have significant and advantageous effects on metals and alloys in terms of preventing corrosion.

- Green inhibitors create a shield on the metal surface to prevent corrosion and lessen corrosion susceptibility. By serving as a barrier, this layer prevents corrosive substances like oxygen and moisture from coming into touch with the metal directly.
- Green inhibitors can greatly slow down the rate of corrosion. This indicates that when exposed to corrosive environments, metals and alloys are less prone to erode over time.
- The fact that green inhibitors are ecologically friendly is one of their main benefits. Green inhibitors have a lower environmental impact than conventional inhibitors since they often come from naturally occurring substances or renewable resources, making them more environmentally friendly.

Types of Inhibitors

Copper and copper alloys

Copper and its alloy, brass and bronze are alloys of copper (brass is a combination of zinc and copper, while bronze is an amalgam of copper and tin). They have wide range of applications like thermal and electrical conductivity and mechanical properties. Due to their superior chemical, physical, electrical, and mechanical qualities, copper-based materials are widely employed in industry, placing copper and its alloys in third place in terms of the most used materials [9]. Despite having good corrosion resistance, copper products can nonetheless corrode under certain circumstances, notably in aerated acidic media, which results in a significant financial loss. Corrosion inhibitors were employed as an effective solution to stop or slow the deterioration of copper materials to overcome this issue [10].

A pyrimidine imidazole 4-Amino-3-(phenyldiazenyl) benzo [4,5] dyeimidazo [1,2-a]. In 3.5 wt.% (by weight) NaCl solution, pyrimidin-2(1H)-one (APIP) has been utilised as a copper corrosion inhibitor by Pareek et al. [11]. According to an immersion research, copper oxides are only stable in the pH range of 8 to 12. In addition, the pH of the test solutions falls as immersion duration increases, indicating the creation of an APIP protective film that shields copper from aggressive attack and prevents corrosion. The Langmuir adsorption isotherm was well-fitted by the APIP adsorption on copper surface for the corrosion inhibition process in 3.5% NaCl solution. The copper samples' surface became more hydrophobic as their roughness decreased.

Amino acids as corrosion inhibitor

Zhang et al. [12] look at the effects of four amino acids on copper corrosion in 0.5 M HCl solution: glutamine (Gln), glutamic acid (Glu), asparagine (Asn) and aspartic acid (Asp). The chemical structure of amino acids affects how well they inhibit corrosion. It grows in the following sequence: Gln > Asn > Glu > Asp. These amino acids are mixed inhibitors based on the potentiodynamic polarization. These amino acids adhere to the copper surface obeys Langmuir isotherm. Strong physical adsorption is revealed by the adsorption free energy.

The use of amino acids as ecologically friendly materials allowed for the investigation of Cu-Ni alloys' resistance to corrosion in aqueous chloride solutionswas investigated by Badawy et al. [13]. Particularly alloys with low nickel concentration (Cu-5Ni), the amino acid serves as a powerful inhibitor, with a corrosion inhibition efficacy 85% being observed. Cysteine is the most effective inhibitor of Cu-5Ni corrosion in neutral chloride solutions, which has two adsorption centres and follows the Langmuir adsorption isotherm [13].

The detrimental characteristics of two hazardous amino acids (cysteine and phenylalanine) as a bronze corrosion barrier in highly acidic mixture of 0.2 g/L Na_2SO_4 + 0.2 g/L $NaHCO_3$ at pH = 3 was investigated by electrochemical impedance spectroscopy, open-circuit potential measurements and SEM (Scanning electron microscope) analysis by Varvara et al. [14].

Each amino acid inhibits the cathodic reduction of oxygen process more strongly than the copper dissolving process, as evidenced by the corrosion potential's considerable shift in favor of negative values. It has been demonstrated that cysteine is a very promising and ecologically secure substitute for the hazardous corrosion inhibitors now being used to protect bronze against corrosion in harsh conditions.

Biopolymer as corrosion inhibitor

An eco-friendly biopolymer 'dextrin' with an inhibitory impact on mild steel corrosion in 15% HCl. According to Biswas et al. [15], dextrin and poly(vinyl acetate) biopolymer inhibitor functions as mixed type inhibitor. It was observed that the inhibitor adheres to the Langmuir adsorption isotherm type on the surface of copper. Inhibitory effectiveness reaches 87% for copper at 0.1 mg/L.

Using gravimetric, potentiodynamic polarization and electrochemical impedance spectroscopic (EIS) tests, the inhibitory impact of the effects of extracts from the seeds of *Piper longum*, *Strychnos nuxvomica*, and *Mucuna pruriens* on the corrosion of copper in 3 M HNO_3 solution were examined by Savita et al. [16].The highest level of inhibition was 91.60%, 80.00% and 71.6%, respectively, as determined by gravimetric measurements at 0.2 g/L of *P. longum*, *S. nuxvomica*, and *M. pruriens*, respectively. As concentration of plant extract increased, the effectiveness of inhibition improved. According to the Langmuir adsorption isotherm, the inhibitor was absorbed onto the surface of copper. A study of potentiodynamic polarization revealed that cathodic type inhibition predominated.

Various corrosion measurement techniques were used to examine using *Hyoscyamus muticus* extract as a natural copper corrosion inhibitor in solution of 1 M HNO_3 by Fauda et al. [17]. It was discovered that the inhibitory efficacy decreased with rising solution temperature and increased concentration of the examined extract. It was discovered that the inhibitor's adsorption followed the Langmuir adsorption isotherm on the surface of copper. Polarization curves demonstrate that the extract under investigation exhibits cathodic behavior.

Aluminum and its alloys

There are numerous applications of aluminum and its alloys in industries as diverse as transportation, aviation, construction, and electricity generation [18]. Aluminum and aluminum alloys have an intrinsic alumina oxide coating, which makes them highly resilient to deterioration [19]. To prevent the corrosion of aluminum and aluminum alloys, number of procedures have been used. Corrosion inhibitor usage is one such technique. Synthetic inhibitors are hazardous, have poor effect on the surrounding and are expensive. As a result, interest has shifted to environmentally benign green inhibitors.

Weight loss, thermometry, hydrogen evolution and polarization techniques are used to research the inhibitory effect of the glutinous derived from modified prickly pear stems on acid corrosion of aluminum by El-Etre [20]. In 2 M HCl solution, the prickly pear extract effectively inhibits the corrosion of aluminum. The inhibitory effect rises as extract concentration is increased. The extract components are adsorbed on the aluminum surface to produce the inhibitory action. The spontaneous adsorption process follows the Langmuir adsorption isotherm. The *Opuntia* extract offers some defence against pitting corrosion of aluminum when chloride ions are present.

The corrosion inhibition of aluminum which is immersed in solution of sodium hydroxide at a pH of 11 and 12, the aqueous garlic extract in the absence as well as the presence of Zn^{2+} was evaluated using weight loss method by Priya et al. [21]. In both the absence and presence of Zn^{2+}, garlic extract promotes corrosion of aluminium at pH 11. The capacity of the inhibitor system to inhibit was affected by its oxygen scrubber Na_2SO_3, which showed the inhibitor movement onto metal surface has greater impact on the system's ability to inhibit than oxygen elimination from the water.

Using the weight loss technique, it has been uncoveredthe extract of bitter leaf (*Vernonia amygdalina*) acts as an inhibitor for aluminum silicon in a solution of 0.5 M caustic soda by Ayeni et al. [22]. Aluminum silicon amalgam corrosion in 0.5 M NaOH solution is inhibited by bitter leaf extract (*V. amygdalina*) at concentration of 0.5% after fifteen days. Physical adsorption is the mode of the alloy and inhibitor interactions. By attaching of inhibitor to the alloy surface and adsorbed inhibitor molecules reduce the rate of corrosion.

Dominic et al. [23] studied the corrosion inhibition effectiveness of *Sapium ellipticum* leaf extract as aluminum corrosion inhibitor in acid medium was improved by utilizing statistical optimization. The effectiveness of the inhibition lowers while using *S. ellipticum* active substances and the temperature rises. The thermodynamics analysis demonstrates that immersion of *S. ellipticum* raises activation energy and the adsorption process is well fitted into the Langmuir isotherm.

Utilizing weight loss and hydrogen evolution techniques exposed for ethanolic extract of *Ananas sativum* leaves by Ating et al. [24]. The extract's ability to suppress growth is enhanced by both an increase in temperature and inhibitor concentration. The suppression of corrosion is probably due to chemical adsorption of phytochemical components. According to experimental data, ability to match across all tested doses and temperatures, it was discovered that the extract followed the Langmuir adsorption isotherm.

Ferrous and ferrous metal alloys

Pure iron or alloy that mostly contains iron is what is known as a ferrous metal. "Ferrous" is a derivative of the Latin word "ferrum" which means "iron." The most often used ferrous alloy is steel. Tiny amounts of extra metals or components are added to ferrous metals to give them the properties they need. These metals are magnetic and have poor corrosion resistance. All commercially available types of iron and steel contain carbon, which has since become a crucial component of iron and steel metallurgy. Because of the significant preference for ferrous metals, scrap metal is also quite marketable. Cast iron, carbon steel and alloy steel are a few popular ferrous metals.

Steel

Steel is produced by combining iron with carbon, making the iron tougher. Alloy steel is tougher as more additives, such nickel and chromium are added. To make steel, iron ore is heated and melted in the furnaces. To create steel bars, the steel from the furnaces can be tapped out and put into moulds. The manufacturing and construction industries both use steel extensively.

Bouknana et al. [25], evaluates the effect of leaf, root, and stem extracts of olive (*Olea europaea* L.) as effective inhibitor in solution of 1 M HCl by measuring decreased weight at different concentration and temperatures. The inhibitor effect percentage of olive roots, stems, and leaves were 89.24, 88.84, and 89.83%, respectively, at 35 °C. With an increase the inhibitor concentration, inhibition effectiveness gets better. As the temperature rises, the effectiveness of the inhibition reduces. When olive leaves, stems and roots are added to HCl solution, a layer was created on the surface of the steel that effectively prevents corrosion.

The extract of *Senecio anteuphorbium* was studied by Idouhli et al. [26] as green corrosion inhibitor. AC impedance plots demonstrate the inhibition effectiveness rises with increasing amount of plant extract and charge transfer regulates the corrosion process. It was exposed that the adsorption of inhibitor molecules on the surface of steel was endothermic. The activation energy data indicated that physical and chemical adsorption is the simultaneous adsorption mechanism. The Langmuir isotherm was found to be followed by the adsorption of inhibitor.

Carbon steel

Carbon steel is tougher because it contains more carbon than other alternative forms of steel. It is extensively applied in the manufacture of equipment such as drills, taps, blades, and springs. It can maintain a cutting edge. Low carbon steel is mild steel that content kind of carbon steel; it is often referred to as 'low carbon steel'. Subject to the source, the average carbon content of mild steel ranges from 0.05% to 0.25% by weight, but higher carbon steels having 0.30% to 2.0% carbon.

Gadow and Motawea [27] investigated the adsorption and inhibition behaviour of ginger root extract (GRE) for carbon steel via different chemical approaches at different temperatures. Data on weight loss showed that the concentration of extract improved, and temperature rose, the inhibitory impact increased and decreased. The GRE's adsorption behavior conforms, Langmuir adsorption isotherm and following physisorption mechanism. The polarisation data revealed the GRE is a mixed kind.

In addition to weight loss measures as well as galvanostatic and potentiodynamic anodic polarization, of curcumin, parsley and cassia bark extracts, the inhibitory effect of several pure aqueous extracts from plants on corrosion of carbon steel (C-steel) in 0.5 M H_2SO_4 solution was investigated by Abdallah et al. [28]. With increasing extract concentration, ability to suppress growth becomes more effective. The polarization curves demonstrated the mixed inhibitory action of the natural extracts. Adsorption proceeds according to Temkin's isotherm. Among the three natural extracts, the main ingredient determines the order in which the inhibitory efficiency occurs. Because the natural extracts change the pitting potential to more noble values, they prevent C-steel from pitting or corroding.

In 2019 Dehghani et al. [29] found that a natural supply of many physiologically energetic substances like sucrose, folate, and maltose that are very water soluble andthe Chinese gooseberry fruit shell's aqueous extract has chemicals that prevent carbon steel from being produced. EIS studies showed that increasing the inhibitor's concentration to 1000 ppm resulted in considerable increase in inhibition efficiency, which reached 92% after 2.5 h of submerged. The extract of Chinese gooseberry fruit shell acted as combined type inhibitor. It moderately reduced the cathodic predominance. According to the SEM and AFM (atomic force microscopy) investigations, rise in the inhibitor's concentration caused an impenetrable layer to grow the surface of the mild steel, protecting it from corrosive attacks [29].

Mild steel

Nowadays, the extensively used form of steel is mild steeldue low cost and capacity to give material qualities. Mild steel is very difficult to temper. It has a carbon content that varies between 0.05 to 0.30 percent [30]. Mild steel has low tensile strength despite being affordable and easy to manufacture. Surface toughness can be increased by carburization [31].

Gravimetric investigations, potentiodynamic polarization, SEM analysis, EIS were utilized to examine the *Xanthan* gum and its graft co-polymer's ability to stop corrosion on mild steel surfaces when placed in media containing 15% HCl acid [32]. The ethanolic OPE was found to contain carbonyl groups C=O, phenolic groups -OH and unsaturated groups C=C, C=H including compounds with heteroatoms. On metal substrates, these functional groups act as active site for the adsorption process. With an increase in OPE concentration, mild steel's rate of corrosion and effectiveness of corrosion inhibition in acidic conditions both rise. For 0.25% of peel extract, the highest effectiveness of 99.19% was attained. According to the potentiodynamic polarization experiments, OPE functioned as a mixed kind of inhibitor.

Kalaiselvi et al. [33] investigated the inhibiting behaviour of *Coreopsis tinctoria* plant. Analysis of weight loss revealed that the effectiveness of the inhibitor increased with concentration but decreased with temperature. According to the weight loss investigation, the maximal inhibitory performance of *C. tinctoria* in 0.5 M H_2SO_4 solution on mild steel was 80.62% at 500 ppm. The inhibitor was adsorbed according to the Langmuir adsorption isotherm. The ΔG^{o}_{ads} negative shows that *C. tinctoria* has physically and spontaneously adhered on the mild surface. According to EIS measurements, inhibitor concentration rise that show thickness of the absorbed layer increase.

Ugi and Magu's [34] experiment to control the localised rate of corrosion of acidified ASTM A36 mild steel using thermometric and potentiodynamic polarization technique for the *Oenothera biennis* extracts in 1.5 M HCl acid solution. *O. biennis* (Common Evening Primrose) flower-derived alkaloids and flavonoids inhibited ASTM A36 mild steel with inhibition efficiencies of 97.6%, 90.1% and 80.2% for alkaloids and 91.4%, 83.5% and 76.8% for flavonoids at 303 K, 313 K and 323 K, respectively. With an increase in inhibitor concentration, lower corrosion current densities were seen, showing that the inhibitors had a high surface adsorption and were less likely to lose that adsorption during agitation. Physical adsorption mechanism was observed. The adsorption method and process where monolayer suggests that the inhibitors worked better at cooler temperatures.

Stainless steel

Compared to carbon/alloy steel, stainless steel is a ferrous steel alloy with higher corrosion resistance. Chromium is one of the elements that provides stainless steel resistance to corrosion. It creates passive layer that shields the metal and self-heal in the presence of oxygen. Compared to copper and aluminum, stainless steel is comparable to glass in terms of its biological cleanability [35].

Shabani-Nooshabadi and Kazemi-Darafshani [36] studied the weight loss method, potentiodynamic polarization, EIS, SEM, and AFM to determine the inhibitory action of shoot and root extracts of *Ajuga chamaecistus* subsp. *scoparia* as a natural green corrosion inhibitor of 304 stainless steels in 6 M HCl. In this solution, both extracts under investigation function as mixed-type inhibitors of 304SS. Both extracts follow the Langmuir isotherm hypothesis and negative Gibbs free energy proved that the adsorption of an extract is a natural process. The weight loss measurement shows the percentage of inhibition efficiency values are equivalent to electrochemical tests. The maximum inhibitory efficiency was 99.4% for the root extract and 99.6% for the shoot extract, both in 4.0 g/L at 328 K. Initially adsorption was physical, but as temperature rises, it changes to chemical adsorption.

Gapsari et al. [37] studied the inhibiting characteristics of bee wax propolis extract on the 304SS in 0.5 M H_2SO_4 acid. The potentiodynamic polarization and EIS measurement data exhibit the optimal inhibition efficiency was 97.29% and 91.42% at 2000 ppm, respectively. By using X-ray diffraction analysis, it was determined that a thin protective layer had formed, and Fe-CHO peak obtained after addition of inhibitor.

The use of barley agricultural waste (AW) extract for stainless steel AISI 304 as green corrosion inhibitor in H_2SO_4 was demonstrated by Matos et al. [38]. The gravimetric data show that the inhibitory effectiveness increases as the extract concentration rises in the medium. The decrease in inhibitory effectiveness with increasing solution temperature. Electrochemical analyses of OCP revealed that the stainless-steel surface was improved by the addition of AW. EIS measurements exposed that the addition of AW increased the R_{ct} value. According to potentiodynamic polarization tests, AW is a powerful inhibitor that lowers corrosion current densities. According to all electrochemical analyses indicates the extract mostly functions as mixed-type inhibitor. It follows the Langmuir isotherm.

Techniques of Corrosion Measurement

Corrosion process or rate measured by various process like gravimetric analysis (weight-loss method), potentiodynamic polarization technique (Tafel plot), EIS methods are the primary methods used to study corrosion. From the above study, we can also calculate the corrosion inhibition efficiency of inhibitor in corrosive medium.

Weight loss method

By interacting chemically and/or electrochemically to the environment, materials (particularly metals) gradually deteriorate through corrosion, which often leads in the loss of their useful attributes (such as strength) [39]. One of the most popular techniques for calculating corrosion rate is gravimetric approach. since it is straight forward and does not require measurements of currents or voltages [40]. The corrosion rate is measured using the weight-loss method, also referred to as the submerging tests. It determines the mass loss of the test specimen (with known surface area) by comparing its weight before and after being submerged in corrosive solution for a certain amount of time [41].

Potentiodynamic polarization

Potentiodynamic polarization technique in which the application of a current flows across an electrolyte changes the potential of the electrode throughout a sizable potential domain at predetermined rate [42]. Using the cyclic potentiodynamic polarisation approach, a metal's susceptibility to localized corrosion, such as pitting and crevice corrosion, can be assessed [43]. Tests for cyclic polarization are frequently used to determine pitting susceptibility. The area of loop is frequently correlated to the amount of pitting, the presence of the hysteresis is typically suggestive of pitting [44].

Cyclic voltammetry method sweeps the potential in a favorable path until a target value of current or potential is obtained, at which point the scan is instantly reversed towards more negative values until the target value of potential is reached. Some people may need to repeat this scan to some circumstances to monitor variation to the curve for current potential generated by scanning [45].

The widely used linear polarization resistance method, the polarization resistance of material is measured by the slope of the potential-current density curve at the free corrosion potential [46].

EIS analysis

EIS is an effective quantitative technique, can be used to quickly assess the anti-corrosion efficacy of protective film. EIS measurements instantly provide reliable information that makes it possible to forecast the coating's durability over time [47]. However, EIS data must be interpreted with the aid of interface model to be able to obtain charge transfer resistance or polarization resistance that is proportional to the rate of corrosion at the monitored interface. In comparison to traditional laboratory methods, EIS provides several advantages, including the capacitance of the surface solution interface. A tiny amplitude signal, typically voltage between 5 to 50 mV is applied to a specimen over a range of frequencies from 0.001 Hz to 100,000 Hz to perform EIS measurement. The impedance response of the system's real (resistance) and imaginary (capacitance) components are both recorded by the EIS instrument. Based on the layout of the EIS spectrum, the operator assumes regarding a circuit model, circuit description code and initial circuit characteristics [48].

SEM analysis

An electron beam is produced by a high voltage in vacuum in SEM. The beam produces secondary electrons that escape from the substrate's surface after being focussed by electrical lenses and being scanned over it. The number of escaping electrons is largely determined by the surface's atomic mass and to a lesser extent by the crystal orientation. Like typical black and white photograph, these secondary electrons are identified and produce a blackandwhite image with changing intensity [49]. SEM-EDX (Energy dispersive X-ray spectroscopy) is one of the key techniques for examining and assessing the fundamental surface elements of corrosionrelated materials. While EDX is utilized for elemental analysis, the SEM inspection gives information about the metal surface, particularly regarding the morphology and type of corrosion [50].

AFM analysis

One of the most popular techniques for *in situ* investigation of morphological changes occurring during electrochemical operations in aquatic environments is AFM. This methodology established a micro masking technology that enabled the analysis of microstructural elements at scale smaller than 2 x 2 µm and significantly improved understanding of the behavior of metal corrosion [51]. One technique for comprehending the corrosion features of metals is AFM. The field of surface characterization makes use of AFM. This method surface morphology can be used to study corrosion phenomena [52].

Conclusion

The effectiveness and possible uses of green corrosion inhibitors for metals and metal alloys have been investigated in this review paper. Significant study has been conducted in this area, because of people's increasing awareness of environmental issues and the needsof sustainable solutions. Our research demonstrates that non-toxic, biodegradable, and environmentally safe green corrosion inhibitors are a potential replacement for conventional inhibitors. These inhibitors are more environmentally friendly and in line with green chemistry principles because they are made from renewable resources like plant extracts, natural polymers, and biopolymers. Furthermore, in this review, experimental findings and case studies show how effective green corrosion inhibitors are in shielding metals and metal alloys from corrosive environments. When compared to conventional inhibitors, they have demonstrated corrosion inhibition performance that is comparable to or even better, indicating their potential for industrial applications. To sum up, green corrosion inhibitors have become viable options for safeguarding metals and metal alloys. They appeal to a variety of sectors due to their ecologically benign qualities and potent corrosion inhibition ability. We can contribute to more sustainable future while preserving our priceless metal assets by embracing these green solutions.

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None.

Conflict of Interest

None.

References

1. Yadav M, Behera D, Kumar S, Sinha RR. 2013. Experimental and quantum chemical studies on the corrosion inhibition performance of benzimidazole derivatives for mild steel in HCl. *Ind Eng Chem Res* 52(19): 6318-6328. https://doi.org/10.1021/ie400099q
2. Shehata OS, Khorshed L, Attia A. 2017. Green Corrosion Inhibitors, Past, Present, and Future. In Aliofkhazraei M (ed) Corrosion Inhibitors, Principles and Recent Applications. IntechOpen.
3. Dar MA. 2011. A review: plant extracts and oils as corrosion inhibitors in aggressive media. *Ind Lubr Tribol* 63(4): 227-233. https://doi.org/10.1108/00368791111140431
4. Raynie DE. 2006. Modern extraction techniques. *Anal Chem* 78(12): 3997-4004. https://pubs.acs.org/doi/10.1021/ac060641y
5. Skerget M, Knez Z, Hrncic MK. 2011. Solubility of solids in sub- and supercritical fluids: a review. *J Chem Eng Data* 56(4): 694-719. https://doi.org/10.1021/je1011373
6. Marr R, Gamse T. 2000. Use of supercritical fluids for different processes including new developments—a review. *Chem Eng Process Process Intensif* 39(1): 19-28. https://doi.org/10.1016/S0255-2701(99)00070-7
7. Jin R, Fan L, An X. 2011. Microwave assisted ionic liquid pretreatment of medicinal plants for fast solvent extraction of active ingredients. *Sep Purif Technol* 83: 45-49. https://doi.org/10.1016/j.seppur.2011.09.005
8. Herrera MC, Castro MD. 2004. Ultrasound-assisted extraction for the analysis of phenolic compounds in strawberries. *Anal Bioanal Chem* 379(7-8): 1106-1112. https://doi.org/10.1007/s00216-004-2684-0
9. Bastidas DM, Criado M, Santiago F, Iglesia VL. 2010. Copper deterioration: causes, diagnosis and risk minimization. *Int Mater Rev* 55(2): 99-127. https://doi.org/10.1179/095066009X12506721665257
10. Moreira AH, Benedetti AV, Cabot PL, Sumodjo PTA. 1993. Electrochemical behaviour of copper electrode in concentrated sulfuric acid solutions. *Electrochim Acta* 38(7): 981-987. https://doi.org/10.1016/0013-4686(93)87018-9
11. Pareek S, Jain D, Hussain H, Biswas A, Shrivastava R, et al. 2019. A new insight into corrosion inhibition mechanism of copper in aerated 3.5 wt.% NaCl solution by eco-friendly imidazopyrimidine dye: experimental and theoretical approach. *Chem Eng J* 358: 725-742. https://doi.org/10.1016/j.cej.2018.08.079
12. Zhang DQ, Cai QR, He XM, Gao LX, Zhou GD. 2008. Inhibition effect of some amino acids on copper corrosion in HCl solution. *Mater Chem Phys* 112(2): 353-358. https://doi.org/10.1016/j.cej.2018.08.079
13. Badawy WA, Ismail KM, Fathi AM. 2006. Corrosion control of Cu–Ni alloys in neutral chloride solutions by amino acids. *Electrochim Acta* 51(20): 4182-4189. https://doi.org/10.1016/j.electacta.2005.11.037
14. Varvara S, Rotaru I, Popa M, Bostan R, Glevitzky M, et al. 2010. Environmentally safe corrosion inhibitors for the protection of bronzes against corrosion in acidic media. *Chem Pharm Bull* 55(69): 156-161.
15. Biswas A, Das D, Lgaz H, Pal S, Nair UG. 2019. Biopolymer dextrin and poly (vinyl acetate) based graft copolymer as an efficient corrosion inhibitor for mild steel in hydrochloric acid: electrochemical, surface morphological and theoretical studies. *J Mol Liq* 275: 867-878. https://doi.org/10.1016/j.molliq.2018.11.095

16. Savita S, Mourya P, Chaubey N, Kumar S, Singh VK, et al. 2016. *Strychnos nuxvomica*, *Piper longum* and *Mucuna pruriens* seed extracts as eco-friendly corrosion inhibitors for copper in nitric acid. *RSC Adv* 6(98): 95644-95655. https://doi.org/10.1039/C6RA16481A

17. Fauda AS, Abdallah YM, Elawady GY, Ahmed RM. 2015. Electrochemical study on the effectively of *Hyoscyamus muticus* extract as a green inhibitor for corrosion of copper in 1 M HNO_3. *J Mater Environ Sci* 6(6): 1519-1531.

18. Chaubey N, Yadav DK, Singh VK, Quraishi MA. 2017. A comparative study of leaves extracts for corrosion inhibition effect on aluminium alloy in alkaline medium. *Ain Shams Eng J* 8(4): 673-682. https://doi.org/10.1016/j.asej.2015.08.020

19. Lavanya M, Ghosal J, Rao P. 2023. A comprehensive review of corrosion inhibition of aluminium alloys by green inhibitors. *Can Metall Q* 63(1): 119-129. https://doi.org/10.1080/00084433.2023.2190198

20. El-Etre AY. 2003. Inhibition of aluminum corrosion using *Opuntia* extract. *Corros Sci* 45(11): 2485-2495. https://doi.org/10.1016/S0010-938X(03)00066-0

21. Priya SL, Chitra A, Rajendran S, Anuradha K. 2005. Corrosion behaviour of aluminium in rainwater containing garlic extract. *Surf Eng* 21(3): 229-231. https://doi.org/10.1179/174329405X50073

22. Ayeni FA, Magdugu IA, Sukop P, Ihom AP, Alabi OO, et al. 2012. Effect of aqueous extracts of bitter leaf powder on the corrosion inhibition of Al-Si alloy in 0.5 M caustic soda solution. *J Miner Mater Charact Eng* 11(7): 667-670. https://doi.org/10.4236/jmmce.2012.117050

23. Dominic OO, Anadebe VC, Okafor C. 2020. Optimum prediction for inhibition efficiency of *Sapium ellipticum* leaf extract as corrosion inhibitor of aluminum alloy (AA3003) in hydrochloric acid solution using electrochemical impedance spectroscopy and response surface methodology. *Bull Chem Soc Ethiopia* 34(1): 175-191. https://doi.org/10.4314/bcse.v34i1.17

24. Ating EL, Umoren SA, Udousoro II, Ebenso EE, Udoh AP. 2010. Leaves extract of *Ananas sativum* as green corrosion inhibitor for aluminium in hydrochloric acid solutions. *Green Chem Lett Rev* 3(2): 61-68. https://doi.org/10.1080/17518250903505253

25. Bouknana D, Hammouti B, Serghinicaid H, Jodeh S, Bouyanzer A, et al. 2015. Aqueous extracts of olive roots, stems, and leaves as eco-friendly corrosion inhibitor for steel in 1 M HCl medium. *Int J Ind Chem* 6(4): 233-245. https://doi.org/10.1007/s40090-015-0042-z

26. Idouhli R, Yassine K, Eddine KM, Abdelaaziz A. 2019. Inhibitory effect of *Senecio anteuphorbium* as green corrosion inhibitor for S300 steel. *Int J Ind Chem* 10(2): 133-143. https://doi.org/10.1007/s40090-019-0179-2

27. Gadow HS, Motawea MM. 2017. Investigation of the corrosion inhibition of carbon steel in hydrochloric acid solution by using ginger roots extract. *RSC Adv* 7(40): 24576-24588. https://doi.org/10.1039/C6RA28636D

28. Abdallah M, Altass HM, Al-jahdaly BA, Salem MM. 2018. Some natural aqueous extracts of plants as green inhibitor for carbon steel corrosion in 0.5 M sulfuric acid. *Green Chem Lett Rev* 11(3): 189-196. https://doi.org/10.1080/17518253.2018.1458161

29. Dehghani A, Bahlakeh G, Ramezanzadeh. 2019. A detailed electrochemical/theoretical exploration of the aqueous Chinese gooseberry fruit shell extract as a green and cheap corrosion inhibitor for mild steel in acidic solution. *J Mol Liq* 282: 366-384. https://doi.org/10.1016/j.molliq.2019.03.011

30. Classification of Carbon and Low-alloy Steels. [http://www.totalmateria.com/articles/Art62.htm] [Accessed December 26, 2023]

31. Definition of Low-carbon Steels. [https://www.efunda.com/materials/alloys/carbon_steels/low_carbon.cfm] [Accessed December 26, 2023]

32. Biswas A, Pal S, Udayabhanu G. 2015. Experimental and theoretical studies of xanthan gum and its graft co-polymer as corrosion inhibitor for mild steel in 15% HCl. *Appl Surf Sci* 353: 173-183. https://doi.org/10.1016/j.apsusc.2015.06.128

33. Kalaiselvi K, Ill-Min C, Hyun KS, Mayakrishnan P. 2018. Corrosion resistance of mild steel in sulphuric acid solution by *Coreopsis tinctoria* extract: electrochemical and surface studies. *Anti Corros Methods Mater* 65(4): 408-416. https://doi.org/10.1108/ACMM-12-2017-1866

34. Ugi BU, Magu TO. 2019. Regulating localized corrosion rate of acidified ASTM A36 mild steel with *Oenothera biennis* extracts using thermometric and potentiodynamic polarization studies. *Int J Chem Sci* 3(1): 30-37.

35. Boulané-Petermann L. 1996. Processes of bioadhesion on stainless steel surfaces and cleanability: a review with special reference to the food industry. *Biofouling* 10(4): 275-300. https://doi.org/10.1080/08927019609386287

36. Shabani-Nooshabadi M, Kazemi-Darafshani M. 2017. Root and shoot extracts of *Ajuga chamaecistus* subsp. *scoparia* as natural inhibitors for 304 stainless steel corrosion in strong acidic medium. *Surf Eng Appl Electrochem* 53(6): 560-569. https://doi.org/10.3103/S1068375517060114

37. Gapsari F, Soenoko, Suprapto A, Suprapto W. 2015. Bee wax propolis extract as eco-friendly corrosion inhibitors for 304SS in sulfuric acid. *Int J Corros* 2015: 567202. https://doi.org/10.1155/2015/567202

38. Matos LAC, Taborda MC, Alves GJT, Cunha MTD, Banczek EDP, et al. 2018. Application of an acid extract of barley agro-industrial waste as a corrosion inhibitor for stainless steel AISI 304 in H_2SO_4. *Int J Electrochem Sci* 13(2): 1577-1593. https://doi.org/10.20964/2018.02.01

39. Biswas A, Pal S, Udayabhanu G. 2017. Effect of chemical modification of a natural polysaccharide on its inhibitory action on mild steel in 15% HCl solution. *J Adhes Sci Technol* 31(22): 2468-2489. https://doi.org/10.1080/01694243.2017.1306912

40. Kutz M. 2018. Handbook of Environmental Degradation of Materials. Elsevier.

41. Bishop CA. 2015. Process Diagnostics and Coating Characteristics. In Bishop CA (ed) Vacuum Deposition onto Webs, Films and Foils. William Andrew, pp 85-128.

42. Biswas A, Mourya P, Mondal D, Pal S, Udayabhanu G. 2018. Grafting effect of gum acacia on mild steel corrosion in acidic medium: gravimetric and electrochemical study. *J Mol Liq* 251: 470-479. https://doi.org/10.1016/j.molliq.2017.12.087

43. Esmailzadeh S, Aliofkhazraei M, Sarlak H. 2018. Interpretation of cyclic potentiodynamic polarization test results for study of corrosion behavior of metals: a review. *Prot Met Phys Chem Surf* 54(5): 976-989. https://doi.org/10.1134/S207020511805026X

44. Cyclic Polarization Tests. [https://www.metalogic.be/en/portfolio-posts/cyclic-polorazation-tests/] [Accessed December 26, 2023]

45. Deyab MA, Keera ST. 2012. Cyclic voltammetric studies of carbon steel corrosion in chloride-formation water solution and effect of some inorganic salts. *Egypt J Pet* 21(1): 31-36. https://doi.org/10.1016/j.ejpe.2012.02.005

46. Linear Polarisation Resistance – An overview. [https://www.sciencedirect.com/topics/engineering/linear-polarisation-resistance] [Accessed December 26, 2023]

47. Das M, Biswas A, Kundu BK, Shaikh MM. 2017. Targeted synthesis of cadmium(II). *RSC Adv* 7(77): 48569-48585. https://doi.org/10.1039/c7ra08633d

48. Das M, Biswas A, Kundu BK, Charmier MAJ, Mukherjee A, et al. 2019. Enhanced pseudo-halide promoted corrosion inhibition by biologically active zinc(II). *Chem Eng J* 357: 447-457. https://doi.org/10.1016/j.cej.2018.09.150

49. Detecting Steel Tube and Pipe Corrosion Using SEM Analysis. [https://www.thefabricator.com/tubepipejournal/article/tubepipeproduction/detecting-steel-corrosion-using-sem-and-eds] [December 26, 2023]

50. Little BJ, Lee JS. 2015. Microbiologically influenced corrosion. *Oil Gas Pipelines* 387-398. https://doi.org/10.1002/0471238961.micrlitt.a01

51. Almalla A, Ozcan O, Witt J. 2022. *In situ* atomic force microscopy analysis of the corrosion processes at the buried interface of an epoxy-like model organic film and AA2024-T3 aluminum alloy. *Adv Eng Mater* 24(6): 2101342. https://doi.org/10.1002/adem.202101342

52. Lang SY, Shi Y, Hu XC, Yan HJ, Wen R, et al. 2019. Recent progress in the application of *in situ* atomic force microscopy for rechargeable batteries. *Curr Opin Electrochem* 17: 134-142. https://doi.org/10.1016/j.coelec.2019.05.004