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Application of Herbal Extracts in Corrosion Inhibition of Valuable Metals: A Review

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Abstract: Corrosion is a natural chemical or electrochemical process that results in the deterioration of metals and other materials due to their interaction with the surrounding environment. The most common contribution to the acceleration of corrosion is oxygen, although other atmospheric gases including sulphur oxides, nitrogen oxides, halogens, and hydrogen sulphide also play a significant impact. Inorganic and synthetic organic inhibitors have historically been used to prevent corrosion, however many of these substances are costly, hazardous, and non-biodegradable. Green and sustainable corrosion inhibitors are becoming the subject of more study due to growing environmental concerns. In harsh acidic environments, plant extracts that are abundant in phytochemicals including alkaloids, flavonoids, terpenoids, phenolics, and other compounds that include oxygen, nitrogen, and sulphur have shown encouraging adsorption capabilities and corrosion prevention effectiveness.
Comprehensive analysis of surface shape, adsorption processes, and inhibitor performance has been made possible by sophisticated analytical and electrochemical methods, including as SEM, EDX, XRD, FTIR, XPS, AFM, UV–Visible spectroscopy, and Electrochemical Impedance Spectroscopy (EIS). Phytochemical adsorption on metal surfaces, which is frequently explained using isotherm models like Langmuir adsorption, is essential for creating protective coatings that lower corrosion rates. This study underscores the significance of environmentally friendly corrosion inhibitors and the possibility of herbal extracts as sustainable substitutes for traditional inhibitors.
Keywords: Corrosion, hazardous, phytochemicals, electrochemical methods.

I. INTRODUCTION

Latin words "redre" (which means "to grow") and "corroder" (which means "to grow to pieces") are the origins of the word corrosion. Corrosion is a chemical or electrochemical reaction process that deteriorates a material and its qualities. It often affects metal and its surroundings. A major issue that arises on a daily basis is the corrosion reaction, which turns the original metal into a less attractive substance and reduces the functionality of a system or component (El Faydy *et al.*, 2025). All materials, including ceramics, plastics, rubber, and wood, degrade at the surface to some degree when exposed to specific combinations of liquids and/or gases, even though the term "corrosion" is typically used to refer to metals. Metal surface corrosion results from direct reactions between metals and ambient gases such as oxygen, halogens, sulphur oxides, nitrogen oxides, hydrogen sulphide, and chemical fumes. The degree to which a given metal corrodes is determined by its chemical affinity for reactive gases. Compared to other gases and chemicals, oxygen is mostly to blame for the corrosion of the majority of metallic materials (Abdel-Gaber *et al*., 2023).

Corrosion has a huge financial impact; annual global expenses are projected to be in the trillions of dollars. These hazards have made the development and application of effective corrosion inhibitors crucial for safeguarding industrial assets and prolonging material life. As a result, it is evident how important it is to comprehend corrosion, particularly when it comes to systems that use metal as a primary component material that is exposed to corrosive conditions (Dahmani *et al*., 2024).

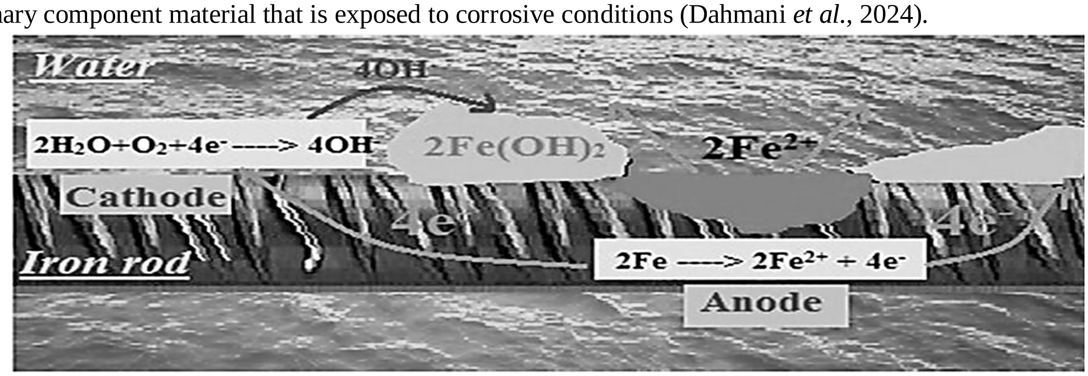

Figure- Mechanism of iron corrosion

In recent years, corrosion research has spread into several additional fields. Optical technology has dramatically changed the field. Some surface analytical techniques that offer more information on the type, thickness, structure, composition, and influence of surface oxides on corroded metals and alloys include X-ray photoelectron spectroscopy (XPS), X-ray diffraction (XRD), scanning electron microscopy (SEM), atomic emission spectroscopy (AES), Fourier transform infrared spectroscopy (FTIR), and atomic force microscopy (AFM).

II. CORROSION INHIBITERS

The protection of metals or alloys against corrosion can be achieved either by special treatment of the medium to depress its aggressiveness or by introducing into it small amounts of special substances called corrosion inhibitors. Numerous substances, both organic and inorganic, are employed as metal corrosion inhibitors in various hostile conditions (Brixi *et al.*, 2022). However many researchers reviewed the work on the mechanism of corrosion inhibition and other researchers consolidated the work carried out on the effectiveness of green inhibitors. Numerous heterocyclic compounds have been identified as corrosion inhibitors, and research into novel synthetic heterocyclic compounds is continuously ongoing. Despite the promising studies on several inhibitors, the majority of corrosion inhibitors are not only costly but also non-biodegradable.

As a consequence of the toxicity of traditional corrosion inhibitors to living beings and their non-biodegradable nature, the demand for natural corrosion inhibitors that have either no or little adverse effect on the environment is highly anticipated (Zakeri *et al.*, 2022). This has lead to the search for their replacement. In recent days many rare earth elements and organic compounds have been developed an alternative eco-friendly corrosion inhibitor. In this context, plant extracts (phytochemicals) are being utilized extensively as a green, effective, economically viable, and eco-friendly alternative to traditional toxic corrosion inhibitors.

III. HERBAL CORROSION INHIBITERS

According to Zunita and Rahmi (2024), plant extract often contains a variety of active phytochemicals that are extensively distributed worldwide. Better adsorptive qualities and improved anti-corrosive behaviour are the results of plant extracts with functional groups that contain O, N, and S. Due to the growing need for green chemistry in all scientific and technological domains; there is a great need these days for the development of green corrosion inhibition tactics (Abdel-Gaber *et al.*, 2023). Plant extracts can be considered environmentally acceptable and sustainable materials for their usage as corrosion inhibitors for metals and alloys in harsh media, such as HCl, H_2SO_4, H_3PO_4, and HNO_3, due to their natural and biological origin and environmentally benign isolation.

The utilization of plant extracts as corrosion inhibitors is a green and environmentally friendly approach because most of the phytochemicals are water-soluble metabolites like organic acids, quinones, phenolic compounds, flavonoids, alkaloids, catechins, terpenoids, co-enzymes, etc., including amino acids, plant-derived proteins, polysaccharides, and vitamins that have no significant adverse effect on living organisms and the environment. The compounds derived from plant extracts are broadly classified as alkaloids, terpenes, and polyphenols. Because of the low cost, renewable nature, biodegradable, biocompatible, and ease of application, several plant extracts have been used in the past.

It's crucial to note that every plant extract has a number of organic chemicals that can efficiently adsorb on metallic surfaces and function as corrosion inhibitors. There are a number of benefits to using plant extracts instead of organic corrosion inhibitors, including a lower environmental risk because most plant extracts are safe, biodegradable, and non-toxic, and they have very little negative impact on the environment. The corrosion-inhibiting qualities of plant extracts, which include their leaves, bark, seeds, fruits, and roots, have been extensively studied.

According to research by Desai *et al.* (2024), datura extract prevents zinc from corroding in solutions containing 0.05–0.1 M HCl. Higher inhibitor concentrations cause the *Datura* extract to inhibit more effectively. The polarization curves demonstrate that in the 0.05 M HCl solution, *Datura* extract inhibits Zn surface corrosion in a mixed-type manner.

Hjouji *et al.* (2023) evaluated the effects of several *Datura stramonium* plant seed extracts on mild steel corrosion in a 1 M HCl solution using a variety of solvents (hexane, ether, chloroform, and methanol). The inhibitors were of a mixed kind and selectively prevented the active sites that cause corrosion, according to the polarisation curves obtained in the presence of various *Datura* seed extracts.

Devanda *et al.* (2023) assessed the effects of leaf extracts from *Trigonella foenum graecum* and *Ficus benghalensis* on corrosion inhibition at 28 ± 1 °C outside. The inhibitory mechanism of the leaf extracts of both plants was explained by the activation parameters and the increase in IE% with concentration, which showed significant chemisorption of both plant extracts on the mild steel surface.

Al-Bataineh *et al.* (2022) investigated the use of *Capparis decidua* extract to reduce the corrosion of aluminium. The investigation was conducted in a 1.0 M hydrochloric acid (HCl) solution and mass loss as well as electrochemical and polarisation techniques were used to track the progress. The *Capparis decidua* adsorption on the aluminium surface has a high regression coefficient value according to the Langmuir adsorption model.

Haque *et al.* (2021) employed electrochemical, surface, and computational demonstrations to assess the corrosion inhibition of *Thevetia peruviana* (Kaner) flower extract (TPFE) for mild steel in 1M HCl solution. AFM, SEM-EDX, FT-IR, and UV-visible surface investigations were used to further support the adsorption mechanism of corrosion prevention.

Mohammed *et al.* (2020) used fresh olive leaves as a natural corrosion inhibitor in a medium solution created at the following concentration to mimic the oil extraction field environment in order to preserve steel tubing and equipment used in the oil extraction field at temperatures (25°C and 45°C). Using a calomel electrode as a reference, a potentiostat device was used to evaluate the rate of corrosion of steel samples.

IV. MECHANISM OF CORROSION INHIBITION

Adsorption is the process by which molecules from gases, liquids, and dissolved environmental substances form an incredibly thin layer that sticks to the surface of solids. Through electron transfer, inhibitors can form a coordinate kind of bond with the metal surface, resulting in a robust binding and effective inhibition. Anions, neutral molecules, lone pairs of electrons, p-electron systems connected to triple bonds or organic ring systems, and functional groups composed of elements from groups V or VI of the periodic table are examples of species with relatively loosely bound electrons that exhibit more effective inhibition. With declining electronegativity and following the sequence, a stronger coordinate bond is more likely to form, $O < N < S < P$.

Electrochemical methods based on alternating currents can be used to determine the effectiveness of corrosion control measures such as coatings and inhibitors. In an alternating current circuit, impedance regulates the current's amplitude at a specific voltage. Through impedance, voltage and current are proportionate to each other. The electrode/electrolyte interface circuit models are used in electrochemical impedance spectroscopy (EIS) to comprehend how an electrode reacts to variable frequency alternating potential signals.

V. METHODOLOGY FOR CORROSION TESTS

Various techniques can be employed to determine the protection efficiency of metals and their alloys. The weight loss test is one of the main important tests found in several studies. Numerous analytical techniques for investigations include optical microscopy, scanning electron microscopy (SEM) to observe and characterise the surface morphology, energy dispersive spectroscopy (EDX) to analyse and determine the elemental composition of the sample surface, X-ray diffraction (XRD) to characterise the crystal parameters of corrosion product, Raman spectroscopy to illustrate the type of oxide and compositional analysis, FT-Infra Red spectroscopy to determine the bond type and functional groups from the frequency of absorption, UV-visible spectroscopy, and atomic absorption spectroscopy (AAS) for quantitative analysis of iron in acid medium, X- ray Photon Spectroscopy (XPS) to get quantitative details regarding the composition and depth profile of the oxide layer and Atomic Force Microscopy (AFM) to understand the surface roughness and cross sectional profile of the sample, were attempted by researchers to support their findings to prove the mechanism of corrosion inhibition process.

VI. CONCLUSIONS

Corrosion is still a major and expensive global problem that affects construction materials, transportation, oil and gas, and industrial infrastructure. To increase material longevity and lower financial losses, it is crucial to comprehend corrosion mechanisms and create efficient mitigation techniques. Conventional corrosion inhibitors have proven effective, but their long-term viability is limited by their high cost, non-biodegradable nature, and environmental toxicity.

Because of their renewable source, low toxicity, biodegradability, and affordability, plant-based corrosion inhibitors have become more attractive green substitutes in recent years. The adsorption capacity of phytochemicals with π-electron systems and heteroatoms (O, N, S, and P) on metallic surfaces is enhanced, resulting in protective coatings that prevent anodic and/or cathodic processes. Overall, green corrosion inhibition strategies align with the principles of sustainable development and green chemistry, offering environmentally responsible solutions for protecting metals in aggressive environments.

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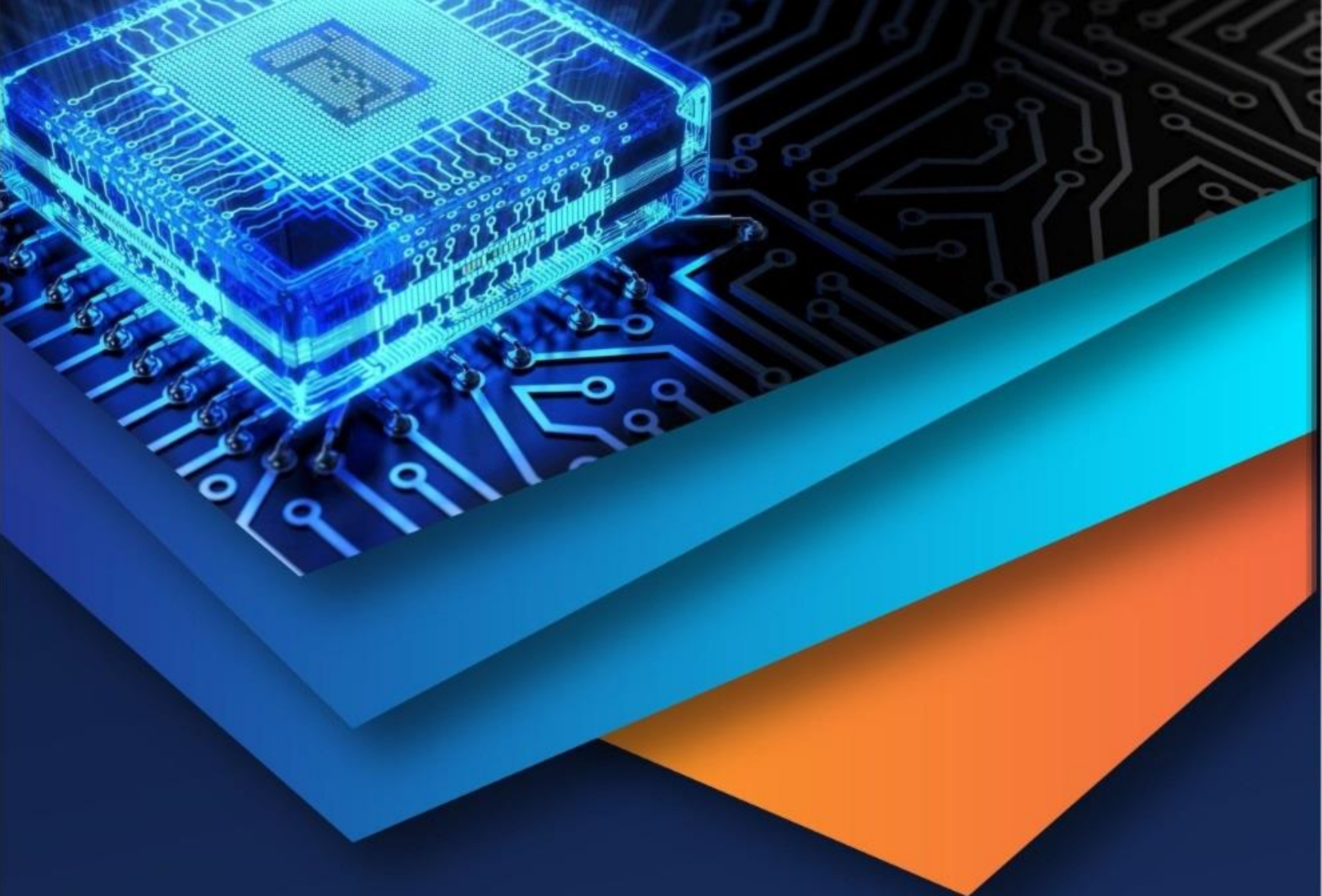

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