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Green Plant Extracts Corrosion Inhibition of Copper in Corrosive Environment - A Review

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Abstract: ***This review explores the application of green plant extracts as corrosion inhibitors for copper in various corrosive environments, emphasizing their eco-friendly, cost-effective, and sustainable advantages over conventional inhibitors. Multiple experimental techniques, including potentiodynamic polarization (PDP), electrochemical impedance spectroscopy (EIS), weight loss analysis, and surface characterization were employed across different studies to evaluate inhibition efficiency and adsorption behavior. Results consistently demonstrated that plant extracts significantly reduce corrosion rates, with efficiency generally increasing at higher concentrations but declining with elevated temperatures. Adsorption studies revealed that most inhibitors follow Langmuir, Freundlich, or Temkin isotherms, with both physisorption and chemisorption mechanisms observed depending on the extract and medium. Surface analyses confirmed smoother, less pitted copper surfaces in the presence of inhibitors, validating their protective action. Overall, the findings establish plant extracts as promising green alternatives for copper corrosion control, offering effective performance while aligning with sustainability and environmental protection goals.***
Keywords: Copper corrosion inhibition; Green plant extracts; Electrochemical techniques; Adsorption isotherms; Surface characterization; Eco-friendly inhibitors.

I. INTRODUCTION

Studies of the performance of green plants extracts corrosion inhibition on metallic materials (Sheydaei, 2024) in various corrosive media will continuous to surface. The reason is that industrial developments and their determinants such as the oil industry and its operation depend on metallic materials (Miralrio, & Vázquez 2020). Steel alloys, aluminum and copper are the major players. Their successful utilization is always hampered by corrosion which is the destructive attack of the metallic materials by their operational environment (Morais, 2023; *Tari-Ukuta, et al., 2024*). These destructive attacks from mild to catastrophic forms are not welcome because they cause contamination of product and short down operation due failure of the metallic materials sometimes leading to destruction of lives and properties (Hefnaw & Ali, 2017; *Holla, et al., 2023; Himeur, et al.,2026;* Žbulj, 2014). The cost of corrosion is running into high percentages of countries' gross domestic products (GDPs) (1 to 4%) in billion dollars (*Kostić, et al., 2022*; Mazumder, 2020; Paterson, 2023; *Vashi, et al., 2021).*

Corrosion inhibition methods such materials selection and coating/lamination of metallic surfaces are costly. For example, the cost of stainless steel is higher than mild steel in hundreds of percents. Inorganic inhibitors are also costly and not environmentally friendly too *(*El-Enin & Amin, 2015; Bilgiç, 2023; *Emmanuel, et al., 2024).*

Green plants extracts inhibitors are the new brides in town for corrosion study because of their readily availability, low cost, their environmental friendliness and contained heteroatoms such as nitrogen, sulphur, oxygen etc (*Bandeira, et al., 2025; Holla, et al., 2024*). Several studies have been carried out on their effectiveness on different metallic materials and in different corrosion media. This study also wishes to build on the gains of the effectiveness of green plant extracts corrosion inhibition on copper alloys in different corrosion media and the various methods used for the studies.

II. METHODS

A. Electrochemical Techniques

1) Potentiodynamic Polarization (PDP)

Potentiodynamic Polarization is an electrochemical technique popularly used to study corrosion behavior *(Fouda, et al, 2015)* by sweeping the electrode potential and recording the current response. It provides information about corrosion rate, passivation, and breakdown potential of materials.

In PDP, the potential of a working electrode that is the metal sample is varied linearly with time while the resulting current is measured. Oxidation reaction on the anode and reduction reaction on the cathodic occurring in the surface are revealed.

$\eta = a + b\log 10(j)$ (1)

η = overpotential (difference between applied potential and equilibrium potential)

j = current density

a = intercept (related to exchange current density j_0)

b = Tafel slope (depends on reaction mechanism and temperature)

The Tafel equation is used in corrosion studies to analyze the kinetics of electrochemical reactions by relating electrode potential to the logarithm of current density. It helps determine corrosion rates by extrapolating the linear portions of anodic and cathodic polarization curves to find the corrosion current density. This provides insight into how fast a material corrodes and the effectiveness of protective measures.

2) Electrochemical Impedance Spectroscopy

Electrochemical Impedance Spectroscopy (EIS) is powerful AC technique for studying corrosion *(Fouda, et al, 2015)* because it reveals how a metal electrolyte interface responds to small sinusoidal voltage (5–10 mV sometimes up to 20 mV) perturbations across a wide frequency range. It provides information about double layer capacitance, charge transfer resistance and diffusion processes which are directly linked to corrosion rates and mechanisms.

i. The impedance (Z), measures how a material resists the flow of alternating current at different frequencies. By analyzing the impedance response, researchers can model the electrochemical processes occurring at the metal–electrolyte interface, such as charge transfer and diffusion. This helps identify corrosion mechanisms, estimate corrosion rates, and evaluate the effectiveness of protective coatings or inhibitors.

Impedance (Z), $Z(\omega) = \frac{E_{(\omega)}}{I_{(\omega)}}$ (2)

Where E(ω) is the applied AC potential and I(ω) is the measured current at angular frequency ω. Results are often shown in Nyquist plots (imaginary vs. real impedance) or Bode plots (magnitude and phase vs. frequency).

ii. The polarization resistance R_p (slope near zero frequency) is linked to corrosion current density j_{corr} as stated in equation

$j_{corr} = \frac{B}{R_p}$ (3)

Where B is the Stern–Geary constant (depends on anodic and cathodic Tafel slopes).

iii. The Warburg impedance equation is used in corrosion studies to describe the effect of ion diffusion on the electrochemical response of a metal surface. It shows how impedance increases with decreasing frequency, reflecting the limited transport of reactants like oxygen or ions to the electrode. This helps identify when corrosion is controlled by mass transport rather than charge transfer, giving insight into the mechanisms and severity of corrosion.

$Z_W = \frac{\sigma \cdot (1-j)}{\omega}$ (4)

Where, Z_W is the Warburg impedance, σ is the Warburg coefficient (related to diffusion rate), j is the imaginary unit, and ω is the angular frequency.

3) Open circuit potentials

Open Circuit Potential (OCP) is a fundamental electrochemical technique used to study corrosion because it reflects the natural equilibrium potential of a metal in a given environment without any external current applied. By monitoring OCP, researchers can assess whether a material is passivated, actively corroding, or undergoing film breakdown.

OCP itself is measured directly, but its interpretation often involves electrochemical relationships:

The Nernst Equation stated in equation (5) calculates equilibrium potential of a half-cell reaction:

$E = E^{\circ} - \frac{RT}{nF} \ln Q$ (5)

Where E is electrode potential, E∘is standard electrode potential, R is gas constant, T is temperature (K), n is number of electrons transferred, F is Faraday's constant and Q is reaction quotient

At OCP, the anodic current that is metal dissolution equals the cathodic current which is reduction reaction:

$j_{anodic} = j_{cathodic}$ (6)

This balance defines the corrosion potential often approximated OCP.

In relation to corrosion rate when combined with polarization resistance as given in equation (7):

$$j_{corr} \approx \frac{B}{Rp} \quad (7)$$

Where i_{corr} is the corrosion current density, Rp is polarization resistance, and B is a constant. OCP provides the equilibrium potential needed before applying small perturbations for Rp measurement.

4) Linear Polarization Resistance (LPR)

This is also one of the electrochemical techniques to study corrosion because it allows estimation of the corrosion rate quickly and non-destructively. It works by applying a small potential perturbation around the open circuit potential (OCP) and measuring the resulting current response. In this, the potential resistance is measured directly as provided in equation (7)

$$B = \frac{\beta a \cdot \beta c}{303(\beta a + \beta c)} \quad (8)$$

Equation (8) is known as the Tafel constant or Stern–Geary constant**.**

Where, βa and βc are the anodic and cathodic Tafel slopes, and the constant B is used in the Stern–Geary equation to calculate the corrosion current density (jcorr), which directly relates to the corrosion rate. In corrosion studies, this equation is crucial because it links measurable polarization data to the actual rate of material degradation, allowing engineers to quantify how fast a metal corrodes under given conditions. Once icorr is known, it can be converted into corrosion rate (e.g., mm/year) using Faraday's law and material-specific constants.

B. Weight loss

Weight loss is one of the simplest and most traditional methods used to study corrosion *(Fouda, et al, 2015).* It involves exposing a metal specimen to a corrosive environment for a known period, then measuring the reduction in mass due to corrosion. This direct measurement provides an estimate of the corrosion rate.

The procedure is using clean, weighed metal coupon is placed in the corrosive medium. After a set exposure time, the specimen is removed, cleaned of corrosion products, and reweighed. The difference in weight represents the mass of metal lost due to corrosion.

Weight Loss (W): $W = W_{initial} - W_{final}$ (10)

2. Corrosion Rate (CR) is often expressed in mm/year (millimeters per year) using the formular

$$CR = \frac{K \cdot W}{A \cdot T \cdot D} \quad (11)$$

Where W = weight loss (mg), A = exposed surface area (cm^2), T = exposure time (hours or days), D = density of the metal (g/cm^3) and K = constant (depends on unit system; e.g., 8.76×104 for mm/year when W in mg, A in cm^2, T in hours, D in g/cm^3).

C. Surface Characterization

1) Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy (SEM) *(Fouda, et al, 2015)* is a powerful tool for studying corrosion because it provides high-resolution images of the corroded surface, revealing morphology, microstructural changes, and localized attack such as pitting or intergranular corrosion. Unlike bulk methods, SEM allows direct visualization of how corrosion progresses at the microscopic level.

2) Atomic Force Microscopy (AFM)

Atomic Force Microscopy (AFM) is widely used in corrosion research because it allows direct visualization of surface changes at the nanometer scale, tracking pit formation, oxide film breakdown, and inhibitor effectiveness in real time. By combining AFM with electrochemical control (EC-AFM), researchers can monitor corrosion processes dynamically under different environmental conditions. AFM maps nanoscale roughness and pit growth during corrosion, detects breakdown of protective oxide or polymer coatings, Measures how corrosion inhibitors alter surface morphology, EC-AFM, potential is applied to the sample, allowing simultaneous imaging and electrochemical monitoring.

3) X-ray Photoelectron Spectroscopy (XPS)

X-ray Photoelectron Spectroscopy (XPS) is a powerful tool for studying corrosion because it provides chemical and elemental information about the thin surface layers where corrosion reactions occur. Since corrosion often involves oxidation, film formation, and chemical changes at the top few nanometers of a material, XPS is ideal for detecting these transformations.

XPS identifies the composition and thickness of protective oxide layers, distinguishes between metallic, oxidized, and hydroxide states of elements (e.g., Fe^{2+} vs. Fe^{3+} in steel corrosion) and evaluates how corrosion inhibitors modify surface chemistry. The tool uses sputtering to measure changes in composition as corrosion penetrates deeper.

4) Energy Dispersive X-ray Spectroscopy (EDX)

Energy Dispersive X-ray Spectroscopy (EDX) is commonly used in corrosion studies to identify the elemental composition of corroded surfaces and corrosion products. It is typically coupled with Scanning Electron Microscopy (SEM), allowing researchers to correlate surface morphology with chemical composition. EDX detects elements present in corrosion products (e.g., oxides, hydroxides, salts) and provides spatial distribution of elements across corroded regions. It estimates relative concentrations of elements to assess corrosion severity and helps determine whether protective coatings or oxide layers remain intact.

D. Spectroscopic methods

1) UV-Vis spectroscopy

UV-Vis spectroscopy is used in corrosion studies to monitor the release of metal ions into solution and to evaluate the effectiveness of corrosion inhibitors. Since corrosion often involves dissolution of metals e.g., Fe^{2+}, Cu^{2+}, Zn^{2+} etc, UV-Vis can track their concentration by measuring absorbance at characteristic wavelengths. It is particularly useful for studying corrosion kinetics and inhibitor adsorption in aqueous environments.

The process identifies and quantifies dissolved corrosion products (metal ions). Time-dependent absorbance changes reveal corrosion rates. Tracks spectral changes when inhibitors interact with metal ions and detects leaching of compounds from protective coatings.

Beer–Lambert Law (core equation for UV-Vis)

$$A=\varepsilon \cdot c \cdot L \quad (12)$$

Where A is Absorbance (measured by spectrometer), ε is Molar absorptivity (depends on the species and wavelength), c is Concentration of absorbing species (e.g., Fe^{2+} ions from corrosion) and L is Path length of the cuvette

Corrosion Rate from Concentration Change is given as

$$V = \frac{\Delta c}{\Delta t} \quad (13)$$

Where v = Corrosion rate (mol/L·s), Δc = Change in concentration of ions detected and Δt: Time interval

Absorbance Ratio Method (for multi-component systems)

$$\frac{A_1}{A_2} = \frac{\varepsilon_1 c_1}{\varepsilon_2 c_2} \quad (14)$$

Where A_1,A_2 = absorbances at two different wavelengths, ε_1,ε_2 = molar absorptivity (extinction coefficients), and c_1,c_2 = concentrations of the absorbing species.

In corrosion studies, this relation is used to analyze the concentration of corrosion products or inhibitors in solution by comparing absorbance values. Diffusion and reaction rates can then be inferred from how these concentrations change, helping researchers monitor corrosion progress and evaluate protective treatments. It is used when multiple corrosion products absorb at different wavelengths.

2) Fourier Transform Infrared Spectroscopy (FTIR)

Fourier Transform Infrared Spectroscopy is widely used in corrosion studies because it helps identify the chemical bonds and functional groups present on corroded surfaces or corrosion products. By analyzing the infrared absorption spectra, researchers can determine what oxides, hydroxides, or salts have formed during corrosion, and track changes in protective coatings or inhibitors. It detects oxide layers (e.g., Fe_2O_3, Fe_3O_4) and hydroxides on metals and also identifies organic corrosion inhibitors adsorbed on surfaces. It monitors degradation of protective coating**s** (like polymers or paints). It also compares spectra before and after exposure to corrosive environments to see chemical changes.

E. Raman Spectroscopy

1) Density functional theory

Density Functional Theory (DFT) is a computational quantum mechanical method used to study corrosion at the atomic and electronic level. It helps researchers understand how metals interact with corrosive environments, how protective coatings or inhibitors adsorb on surfaces, and what electronic properties drive corrosion reactions.

DFT calculates how molecules like oxygen, water, or inhibitors adsorb on metal surfaces, revealing binding energies and preferred sites.

It shows changes in electron density and band structure when corrosion products form. DFT helps predict activation energies for oxidation/reduction reactions involved in corrosion.

By modeling inhibitor molecules on metal surfaces, DFT quantifies their effectiveness in blocking corrosion sites.

2) Molecular Dynamics (MD)

Molecular Dynamics (MD) is a computational simulation method used to study corrosion by modeling the motion of atoms and molecules over time. It provides insights into how corrosive agents (like water, oxygen, chloride ions) interact with metal surfaces at the nanoscale, complementing experimental techniques and quantum-level methods like DFT.

It tracks how water molecules and ions diffuse and adsorb on metal surfaces, simulates oxide layer growth or breakdown during corrosion. MD evaluates how organic inhibitors form protective layers and resist desorption. It models how mechanical stress accelerates atomic scale corrosion processes.

MD is based on Newton's laws of motion, with atoms treated as classical particles interacting via force fields as given in equation (15)

i. Newton's equation of motion which is core of MD is

$$F_{i=}m_i \frac{d_2 r_1}{d1} \quad (15)$$

Where m_i is mass of atom i, r_i is position vector and Fi is net force on atom

ii. Force from potential energy in the inter atomic interactions within the corrosion is

$$F_i = -\nabla U(r_1, r_2, \ldots, r_N) \quad (16)$$

Where U(r1,r2,…,rN) is the potential energy of the system, which depends on the positions of all N particles which includes van der Waals, Coulombic and bond stretching, $-\nabla$ is the negative gradient, meaning the force is directed along the steepest descent of potential energy

iii. Diffusion coefficient important for ion transport in corrosion is given as

$$D=\frac{1}{6t}\langle |r(t)-r(0)|^2 \rangle \quad (16)$$

This is derived from the mean square displacement (MSD) of particles where D is Diffusion coefficient, a measure of how fast particles spread out over time, t is Time spent, r(t) is Position of a particle at time t, r(0) is Initial position of the particle and $|r(t)-r(0)|^2$ is The mean square displacement (MSD), that is, the average squared distance particles move from their starting point. So, the diffusion coefficient D quantifies how quickly corrosive species like oxygen, chloride ions, or metal cations move**.** A higher D means faster transport, which often accelerates corrosion.

III. GREEN LEAVES USED IN CORROSION INHIBITION ON COPPER

Fouda, et al (2015) studied the effectiveness Hyoscyamus Muticus Extract (HME) as corrosion inhibitor copper in 1 M HNO_3 solution. They made use of weight loss, potentiodynamic polarization, electrochemical impedance spectroscopy (EIS) and electrochemical frequency modulation (EFM) techniques. Morphological study was carried out on the surface using scanning electron microscope (SEM). The thermometric corrosion study was carried out at a temperature range of 25-45 ºC at different concentrations. Polarization curves reveal that the investigated extract is a cathodic behavior. Increase in inhibitor concentration increases the corrosion efficiency and decrease with increase in solution temperature. The adsorption of the inhibitor on copper surface was found to obey the Langmuir's adsorption isotherm. They also carried out similar studies using zygophyllum coccineum and morus alba extracts (Fouda, et al., 2014 & 2021). All showed similar results

Xanthosoma spp Leaf extracts (XLE) corrosion inhibitive action on copper in sea water was studied by Hart, et al., (2016) using thermometric. 1%,2%,3%,4% and 5% v/v concentrations of XLE were used at different temperatures (303, 313, 323 and 333K). Efficiency of the inhibition was found to increase with increasing inhibitor concentration. Temperature affected the corrosion inhibition of copper by XLE negatively. It was observed that an increase in temperature increase the corrosion rate thereby decreased the inhibition efficiency. The highest inhibition efficiency of was obtained at lowerest temperature with inhibitor concentration of 5%v/v and the least inhibition efficiency of 18.11% at 333K with inhibitor concentration 1%v/v. Adsorption characteristeristics of inhibitor molecules on metal surface were obtained from the thermodynamic data calculated. Experimental data fitted into Langmuir's adsorption isotherm.

Plantain peduncle extract (PPE) as an inhibitor on copper in 1 M hydrochloric acid (HCl) using electrochemical, adsorption, and surface analysis techniques was studied by Fayomi **(**2025**)** at a temperature range of 30–50°C. Ethanol-extracted PPE was tested at concentrations of 0.1–0.3 mL. Potentiodynamic polarization (PDP) and open circuit potential (OCP) measurement which are electrochemical processes were employed. The outcomes proved that PPE inhibit corrosion current density (Jcorr) by a maximum of 88% and anodically shift corrosion potential (Ecorr), with the maximum inhibition efficiency of 89.5% occurring at 0.3 mL PPE and 40°C. Similarly, Freundlich isotherm was found to be $R^2 = 0.906$ at 40°C which showed that adsorption took place on the surface of copper sample. Heterogeneous multilayer physisorption was confirmed by Gibbs free energy values (ΔG_{ads} = -16.58 to - 19.78 kJ/mol). Minimal pitting and smooth surfaces in ideal conditions at 0.3 mL PPE, 40°C, when compared to extensive corrosion in uninhibited samples as confirmed by the optical micrographs examination. Statistical comparison using Analysis of Variance, (ANOVA) revealed the significant influence of concentration ($p < 0.0001$) and temperature ($p = 0.0048$), with their interaction ($p = 0.0213$) showing the necessity of balanced operating parameters. While PPE functioned well under middle temperatures, efficiency reduced at 50°C (IE% = 80.2%), reflecting thermal limitations.

Aicha, et al., (2018) studied the copper corrosion inhibition by the mineralization of the red alga gellidium in nitric acid (1M HNO_3) using gravimetric, electrochemical and thermometric methods. The outcome of the experiments revealed that increase alga gellidium concentration reduce the rate of corrosion. The efficiency increase up to 84% as inhibitor concentration increase increased. Polarization measurements showed that the inhibitor is of cathodic type. The results obtained by means of various methods are similar

Udom , et al., (2018) studied corrosion inhibition and adsorption characteristics of myrianthus arboreus leaves extract (MALE) on copper in sulphuric acid solution using gravimetric cum thermometric methods. Thermodynamic and kinetic analyses were done too. The study revealed that increase MALE concentration reduced the H_2SO_4 corrosion on copper. It was done percentage increase of the efficiency. Spontaneous and first order reactions were revealed by the kinetic and thermodynamic studies respectively as MALE was adsorbed on the surface of copper. The adsorption curves obeyed Freundlich and Temkin adsorption isotherms.

Scendo and Uznanska (2011) studied the influence of the concentration of the 1-Butyl-3-methylimidazolium chloride (BMIMCl) and 1-Butyl-3-methylimidazolium bromide (BMIMBr) as ionic liquids (ILs) on the corrosion inhibition of copper in 1.0M Cl^- solutions of pH 1.0 was studied using electrochemical polarization methods, electrochemical quartz crystal microbalance (EQCM) technique and scanning electron microscopy (SEM). The inhibition efficiency increases with an increase in the concentration of BMIMCl and BMIMBr. Adherent layers of inhibitors were postulated to account for the protective effect. Both of the compounds act as a mixed-type inhibitor. The values of standard free energy of adsorption suggest the chemical adsorption BMIMCl and BMIMBr on the copper surface.

Chaubey, et al., (2015) studied the inhibitive effect of fruit extracts as green inhibitors on copper corrosion in nitric acid solution.*Citrus aurantium* (CAU), *Capsicum annuum* (CAN) and *Moringa oleifera* (MOL) fruit extracts' adsorption and inhibition effects on copper corrosion in nitric acid medium were studied. Gravimetric, electrochemical impedance spectroscopic and potentiodynamic polarization techniques were used to evaluate the inhibition efficiency. Fruit extracts' effectiveness were revealed when the electrochemical analysis was done. The results that these fruit extracts acted as predominantly cathodic mixedinhibitors. Further investigations revealed that the adsorption of fruit extracts on the copper surface followed Langmuir adsorption isotherm which lead to the inhibition of corrosion process.

Ugi (2021) studied the corrosion inhibition of Cu-Zn-Fe alloy in hydrochloric acid medium by crude ethanol extracts from roots-leaves synergy of *solanummelongena*. Gravimetric and gasometric methods were used. Different concentrations of the inhibitor were used. The inhibition was peaked at 3g/l concentration. Increase in temperature increase the corrosion rate and efficiency reduced from 99.2 > 88.4 > 85.6 %. Thermodynamic parameters showed that physisorption on the surfaces of the metal as the adsorption curves obeyed the Langmuir adsorption isotherm.

Green inhibitor, Argan hulls extract(AHE), was used to study corrosive behaviour of copper in 2M aqueous solution using Potentiodynamic polarization method at 298K. Corrosion rate of copper decreased significantly in the presence of the Argan hulls extract. Efficiency of AHE increases with increase in concentration to attain 91% when inhibitor was of mixed type. Impedance measurements showed that the charge transfer resistance increased and double layer capacitance decreased with increase in the inhibitor's concentration *(Mounir, et al., 2015).*

Thivagaran, *et al., (2023)* studied the corrosive inhibition effectiveness of Mangifera indica (MI) or mango leaf in 1 M HCl solution. Ethanol was the solvent used for the extraction of MI at concentrations of 0, 0.4, 0.6 and 0.8 mg/ml. UV-Vis Spectrophotometer was used to analyzed the prepared MI extract analyzed and it revealed that a shoulder peak at about 370 nm, resulting from the $\pi \rightarrow \pi^*$ and $n \rightarrow \pi^*$ electronic transition of aromatic C=C and carbonyl (C=O) functional groups. A Fourier transform infrared spectroscopy

(FTIR) found that the MI extract exhibits aromatic C=C, C=O groups of phenolic compounds, C-OH, and C-O stretching vibrations. The electrochemical impedance spectroscopy (EIS) and Tafel plot analysis evaluate that the optimum corrosion inhibition of copper was achieved at 0.6 mg/ml concentration. The result is supported by a positive shift in the corrosion potential, *E*corr, lower corrosion current, *I*corr and corrosion rate (CR) at -0.233 V, 4.39 μA/cm2 and 0.05 mm/yr, respectively. The morphological study of the surface of the copper substrate after the corrosion test evaluated using metallurgical microscopy revealed significant corrosion inhibition due to the adsorption of the molecules from the MI extracts.

IV. CONCLUSION

The central objective of this review was to examine how plant extracts act as green corrosion inhibitors for copper in different corrosive media, using various experimental and computational methods. Across the literature, techniques such as potentiodynamic polarization, electrochemical impedance spectroscopy, weight loss, and surface characterization consistently demonstrated that plant derived inhibitors reduce corrosion rates significantly. Studies on extracts from leaves, fruits, roots, and algae revealed that inhibition efficiency generally increases with concentration but decreases with rising temperature, highlighting thermal limitations. Adsorption studies showed that most inhibitors obey Langmuir, Freundlich, or Temkin isotherms, with adsorption being either physisorption or chemisorption depending on the extract and medium. Surface analyses confirmed smoother, less pitted copper surfaces when inhibitors were present, validating their protective action. Overall, the findings establish plant extracts as cost-effective, eco-friendly, and efficient alternatives to synthetic inhibitors for copper corrosion control in acidic and saline environments.

The researchers recommended that industries should encourage the adoption of plant based extracts for copper corrosion control as sustainable, cost effective, and environmentally friendly alternatives to synthetic inhibitors. They also recommended that extract dosages should be carefully balance with the operating temperature, since efficiency improves with concentration but declines at higher temperatures and broaden research to include diverse plant sources (leaves, fruits, roots, algae) to identify new, highly efficient inhibitors with unique functional groups.

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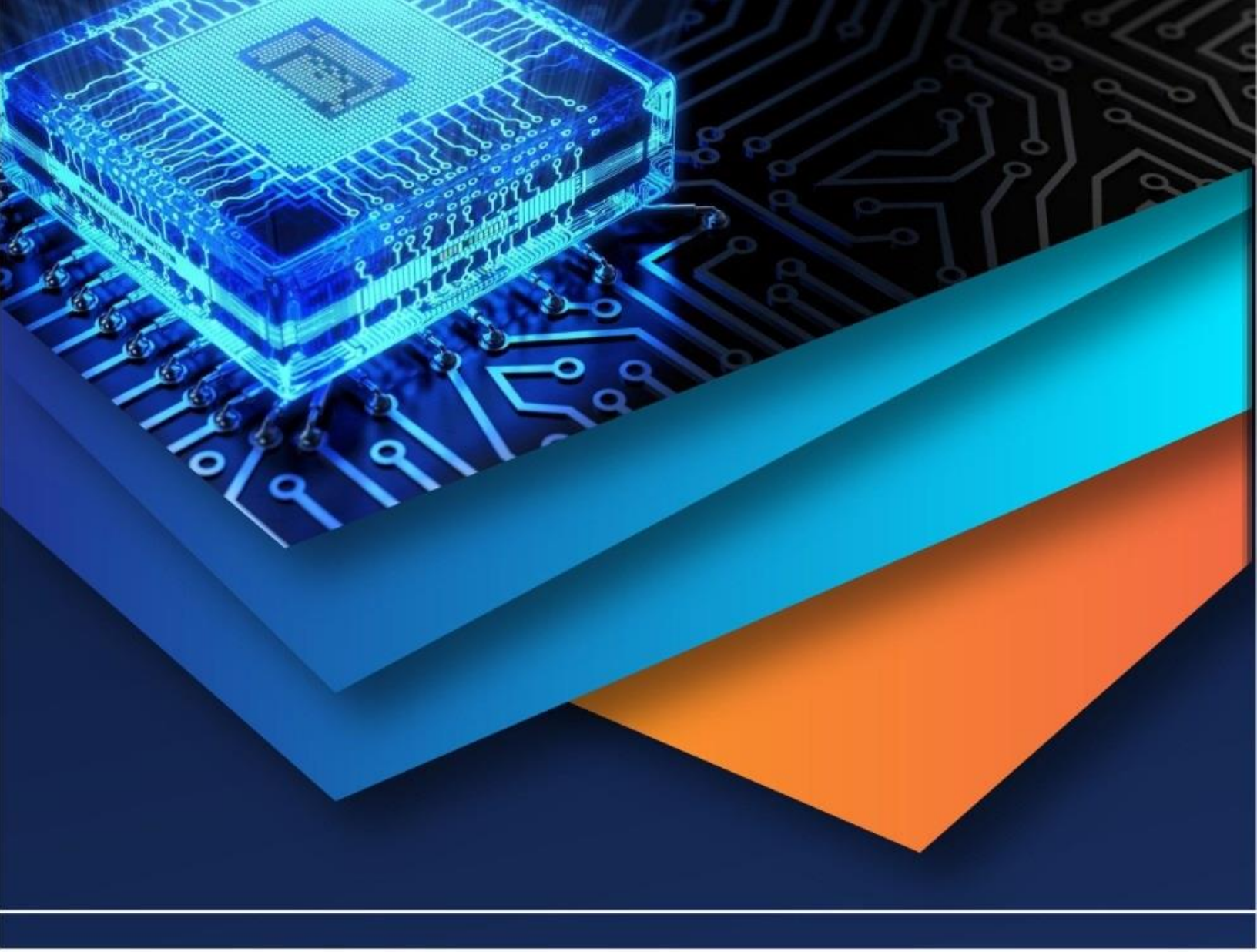

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