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Corrosion Inhibition of Zinc in Hydrochloric Acid by *Ocimum sanctum*: A Critical Review of Adsorption, Thermodynamic, Electrochemical and Surface-Characterization Evidence

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Abstract: *Zinc is widely employed in galvanizing, sacrificial protection, batteries and other industrial applications because of its favourable electrochemical and protective characteristics. Nevertheless, its relatively high reactivity in acidic environments, particularly hydrochloric acid (HCl), can result in rapid anodic dissolution and significant material loss. The use of corrosion inhibitors is therefore essential in industrial operations involving acid pickling, descaling and cleaning. Conventional inorganic and synthetic organic inhibitors can provide effective protection but are increasingly constrained by concerns regarding toxicity, persistence and environmental impact. Consequently, plant-derived corrosion inhibitors have received considerable attention as potentially sustainable alternatives. This review critically examines the reported corrosion-inhibition performance of Ocimum sanctum (Holy basil/Tulsi) extracts for zinc exposed to hydrochloric acid, with particular emphasis on adsorption behaviour, thermodynamic and kinetic parameters, electrochemical response, and surface characterization. Available studies indicate that O. sanctum contains diverse potentially active constituents, including eugenol, phenolic compounds, flavonoids, tannins, saponins and other oxygen- and nitrogen-containing molecules capable of interacting with metal surfaces. Adsorption-isotherm analyses predominantly support Langmuir-type behaviour, although Freundlich and Temkin models provide complementary evidence of surface heterogeneity and adsorbate–adsorbate interactions. Reported negative Gibbs free-energy values indicate spontaneous adsorption, while the variation of enthalpy, entropy and activation-energy parameters suggests that the inhibition process can involve both physical and chemical interactions, depending on extract composition and experimental conditions. Electrochemical investigations generally demonstrate increased charge-transfer resistance and reduced corrosion activity in the presence of the extract, while polarization measurements indicate suppression of both anodic zinc dissolution and cathodic hydrogen evolution. SEM, EDX and FTIR observations further support the formation of an adsorbed organic protective layer on the zinc surface. However, substantial differences in extraction procedures, phytochemical composition, inhibitor concentration, acid concentration, temperature and electrochemical protocols make direct comparison among published results difficult. Future research should therefore prioritize extract standardization, identification of the dominant active constituents, mechanistic studies combining electrochemical measurements with molecular modelling, long-term stability assessment, and techno-economic evaluation of scale-up. Overall, O. sanctum represents a promising plant-derived corrosion inhibitor, but its transition from laboratory investigation to industrial application requires greater experimental standardization and mechanistic validation.*

Keywords: *Ocimum sanctum; zinc; hydrochloric acid; adsorption; electrochemical impedance spectroscopy; phytochemicals*

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1. 0 Introduction

Corrosion remains one of the most significant degradation processes affecting metallic materials and constitutes a major economic, technological and environmental challenge across industrial sectors. The global economic burden of corrosion has been estimated at approximately US$2.5 trillion annually, equivalent to about 3–4% of global gross domestic product, highlighting the importance of effective corrosion prevention and control (Koch et al., 2022). Beyond direct material loss, uncontrolled corrosion can contribute to equipment degradation and failure, production downtime, increased inspection and maintenance requirements, energy losses and safety hazards. Consequently, effective corrosion management is essential for improving the reliability, service life and sustainability of industrial infrastructure.

Zinc occupies a distinctive position among technologically important metals because of its extensive use in galvanizing, sacrificial anodes, batteries, protective coatings and other corrosion-control applications. Its relatively high electrochemical activity enables zinc to preferentially oxidize and thereby provide sacrificial protection to less active structural metals. However, this same electrochemical reactivity renders zinc susceptible to accelerated dissolution in aggressive acidic environments. Hydrochloric acid (HCl) is particularly important in this context because it is widely employed in industrial pickling, acid cleaning, descaling and surface-treatment operations. Experimental investigations have demonstrated that zinc undergoes substantial corrosion in hydrochloric acid, with corrosion severity being influenced by acid concentration, temperature, exposure time and other interfacial conditions (Noor & Al-Moubaraki, 2008). More broadly, understanding the interfacial behaviour of zinc in reactive electrolytes remains important for controlling zinc degradation in both conventional industrial environments and emerging electrochemical technologies (Li et al., 2022).

The overall corrosion process in hydrochloric acid involves anodic oxidation of zinc to zinc ions and cathodic reduction of hydrogen ions to molecular hydrogen:

$$Zn \rightarrow Zn^{2+} + 2e^{-} \quad (1)$$

$$H^{2+} + 2e^{-} \rightarrow H_2 \quad (2)$$

The rate of these interfacial reactions is governed by several physicochemical factors, including acid concentration, temperature, chloride activity, surface condition, exposure time and hydrodynamic conditions. Under strongly acidic conditions, the dissolution of zinc is facilitated by the high activity of hydrogen ions, while aggressive anions can modify the metal/electrolyte interface and influence the stability of surface films.

Consequently, effective corrosion control requires either modification of the metal surface or suppression of the electrochemical reactions responsible for metal dissolution. The effectiveness of corrosion inhibitors in reducing metal loss in acidic environments has been demonstrated for both conventional organic compounds and plant-derived materials (Eddy & Ita, 2011; Odoemelam & Eddy, 2008; Odoemelam et al., 2009).

Historically, inorganic compounds and synthetic organic molecules have been extensively investigated as corrosion inhibitors because of their ability to interact with metallic surfaces and interfere with anodic and/or cathodic reactions. Studies involving heterocyclic compounds, hydrazone derivatives and pharmaceutical molecules have demonstrated that appropriately functionalized organic molecules can substantially modify the corrosion behaviour of metals in acidic media (Eddy et al., 2008; Odoemelam & Eddy, 2008; Odoemelam et al., 2009). The inhibition process is generally associated with adsorption of inhibitor molecules at the metal/electrolyte interface, where the adsorbed species can occupy active corrosion sites and alter the transport and charge-transfer processes associated with metal dissolution. However, concerns regarding the toxicity, persistence, environmental compatibility and disposal of some conventional inhibitors have encouraged increasing interest in naturally derived alternatives.

Plant extracts have consequently emerged as important candidates for the development of more environmentally compatible corrosion inhibitors. Their potential arises from the presence of numerous naturally occurring organic compounds containing functional groups capable of interacting with metallic surfaces. Hydroxyl, carbonyl, ether, amino, carboxyl and aromatic π-electron systems can provide potential adsorption sites through electrostatic interactions, donor–acceptor interactions, coordination and other interfacial processes. Importantly, the corrosion-inhibition behaviour of a plant extract depends on the combined action of its constituents rather than necessarily being attributable to a single compound. This principle is illustrated by the study of Eddy et al. (2011), in which chemical information obtained from GC–MS analysis of an ethanol extract was related to the corrosion-inhibition potential of *Andrographis paniculata* in hydrochloric acid. Similarly, ethanol extract of *Musa* species peels has been investigated as a green corrosion inhibitor, with its inhibition behaviour interpreted using kinetic, adsorption and thermodynamic parameters (Eddy et al., 2008).

The adsorption of organic inhibitor molecules onto metal surfaces is central to the interpretation of corrosion inhibition. Depending on the chemical structure of the inhibitor and the nature of the metal/electrolyte interface, adsorption may involve electrostatic attraction, donor interactions, coordination with surface metal atoms or combinations of these processes. Experimental and theoretical investigations have demonstrated the usefulness of adsorption models and molecular-level calculations in examining these interactions (Eddy & Ita, 2011). Similarly, investigations of zinc corrosion using organic pharmaceutical inhibitors demonstrate that adsorption behaviour, inhibition efficiency and thermodynamic parameters can be used collectively to evaluate the interaction between an inhibitor and the zinc surface (Odoemelam et al., 2009). These studies provide an important methodological basis for evaluating plant-derived inhibitors of zinc in acidic environments.

Among plant species with potential for corrosion control, *Ocimum sanctum* L., commonly known as Holy basil or Tulsi, is of particular interest because of its chemically diverse phytochemical composition. The plant belongs to the family Lamiaceae and contains secondary metabolites that may include phenolic compounds, flavonoids, tannins,

saponins, alkaloids and essential-oil constituents such as eugenol. The presence of oxygen- and nitrogen-containing functional groups, together with aromatic π-electron systems, provides plausible sites for interaction with a metal surface. Such structural characteristics are consistent with the general molecular requirements for adsorption-based corrosion inhibition established in experimental and theoretical studies of organic inhibitors (Eddy & Ita, 2011; Eddy et al., 2011). The inhibition process can be evaluated through several complementary forms of evidence. Adsorption-isotherm analysis provides information about the relationship between inhibitor concentration and surface coverage and can indicate whether adsorption approximates Langmuir, Freundlich, Temkin or other models. Kinetic and thermodynamic parameters, including activation energy, Gibbs free energy, enthalpy and entropy, provide additional information concerning the temperature dependence, energetic feasibility and characteristics of the adsorption process. These approaches have been successfully applied in studies of plant extracts and synthetic organic inhibitors in acidic corrosion environments (Eddy et al., 2008; Odoemelam & Eddy, 2008; Eddy & Ita, 2011). In addition, surface and electrochemical techniques can provide independent evidence for modification of the metal/electrolyte interface and formation of protective inhibitor films.

Despite the increasing interest in plant-derived corrosion inhibitors, comparison among published studies remains difficult because experimental conditions vary considerably. Differences in plant species, plant part, geographical origin, extraction solvent, extraction procedure, inhibitor concentration, acid concentration, temperature, exposure period and metal surface preparation can substantially affect the resulting inhibition efficiency and adsorption parameters. The chemical composition of a crude plant extract may also change considerably according to extraction conditions, making reproducibility an important concern. Consequently, high inhibition efficiency reported for one extract under a particular set of conditions should not automatically be assumed to represent the intrinsic performance of the plant under all conditions.

Another important limitation concerns the interpretation of adsorption and thermodynamic parameters. A good correlation with an adsorption isotherm does not, by itself, establish the molecular mechanism of adsorption. Similarly, the magnitude of Gibbs free energy or activation energy should not be used in isolation to classify an inhibitor unequivocally as undergoing physisorption or chemisorption. The combination of experimental and theoretical approaches provides a more reliable basis for mechanistic interpretation. This integrated approach has been demonstrated in corrosion studies in which experimental inhibition measurements were complemented by theoretical investigations of molecular structure and reactivity (Eddy & Ita, 2011). Such an approach is particularly relevant to *O. sanctum*, whose crude extract contains multiple constituents that may possess different adsorption affinities and interaction mechanisms.

The available literature therefore supports the need for a critical assessment of *O. sanctum* as a corrosion inhibitor rather than a simple compilation of reported inhibition efficiencies. Of particular importance is the integration of adsorption behaviour, thermodynamic and kinetic parameters, phytochemical characteristics and surface evidence to determine whether the proposed inhibition mechanism is consistently supported. Studies of zinc inhibition by organic compounds further demonstrate the value of combining adsorption and thermodynamic analyses when interpreting inhibitor–zinc interactions in acidic environments (Odoemelam et al., 2009).

Accordingly, this review critically examines the corrosion-inhibition potential of *O. sanctum* for zinc in hydrochloric acid, with emphasis on four interconnected areas: (i) adsorption behaviour and isotherm modelling, (ii) thermodynamic and kinetic characteristics, (iii) electrochemical evidence, and (iv) surface and spectroscopic characterization. Particular attention is given to the influence of inhibitor concentration, temperature, acid concentration and extract characteristics on inhibition performance. The review also evaluates the extent to which current adsorption and thermodynamic interpretations are supported by independent experimental evidence, identifies limitations affecting comparison and reproducibility, and discusses the research priorities required to advance *O. sanctum*-based corrosion inhibitors from laboratory-scale investigations toward standardized and industrially relevant applications.

2.0 Review Methodology

2.1 Literature Search Strategy

This review was designed to critically synthesize published evidence concerning the inhibition of zinc corrosion in hydrochloric acid by *Ocimum sanctum* and related plant-derived inhibitors. Literature was identified from major scientific databases and publisher platforms using combinations of the keywords "*Ocimum sanctum*", "Holy basil", "Tulsi", zinc corrosion, hydrochloric acid, HCl, corrosion inhibition, green inhibitor, adsorption, Langmuir, Freundlich, Temkin, thermodynamics, electrochemical impedance spectroscopy, potentiodynamic polarization, SEM, EDX and FTIR. Additional relevant studies were identified by screening the reference lists of highly cited articles and review papers.

Priority was given to peer-reviewed experimental studies that reported quantitative corrosion-inhibition parameters, including inhibition efficiency, corrosion rate, surface coverage, adsorption equilibrium constants, thermodynamic quantities, polarization parameters and electrochemical impedance data. Studies involving other metals or acidic media were considered primarily for mechanistic comparison and contextual interpretation rather than as direct evidence for zinc/HCl/*O. sanctum* systems.

The literature was critically assessed according to four principal evidence categories: (i) adsorption behaviour, (ii) thermodynamic and kinetic characteristics, (iii) electrochemical response and (iv) surface and spectroscopic characterization. Particular attention was given to differences in experimental conditions (Table 1) because inhibitor efficiency and adsorption behaviour are strongly dependent on acid concentration, temperature, extract concentration, extraction solvent, plant part and exposure time.

Because crude plant extracts contain numerous constituents whose concentrations can vary substantially, the reported inhibition efficiency of *O. sanctum* should not be considered an intrinsic constant of the plant. Instead, it represents the combined response of the extract under a particular set of experimental conditions. This distinction is important when comparing studies obtained using different extraction protocols and test environments.

2.2 Critical Approach to Literature Comparison

Direct numerical comparison of reported inhibition efficiencies requires caution. Inhibition efficiency is affected by inhibitor concentration, acid concentration, temperature, immersion period, metal surface preparation, extract solvent and electrochemical measurement conditions. Two studies reporting, for example, 90% and 95% inhibition efficiency cannot necessarily be ranked solely on these percentages if their experimental conditions differ substantially. For weight-loss measurements, inhibition

efficiency is commonly calculated using equation 3 (Vagapov *et al*., 2022)

$$\%IE = \frac{W_0 - W_i}{W_0} \times \frac{100}{1} \quad (3)$$

where W_0 is the corrosion rate or mass loss of the uninhibited specimen and W_i is the corresponding value in the presence of the inhibitor. However, when corrosion rate rather than mass loss is used, the same relationship can be expressed according to equations 4

$$\%IE = \left(1 - \frac{CR_i}{CR_0}\right) \times \frac{100}{1} \quad (4)$$

where CR_0 and CR_i represent the corrosion rates in the absence and presence of the inhibitor, respectively.

For electrochemical measurements, inhibition efficiency based on corrosion current density can be estimated using equation 5 (Eddy *et al*., 2022)

$$\%IE = \frac{i^0_{corr} - i^i_{corr}}{i^0_{corr}} \times \frac{100}{1} \quad (5)$$

where i^0_{corr} and i^i_{corr} are the corrosion current densities of the uninhibited and inhibited systems, respectively.

Table 1. Principal evidence categories used in evaluating *O. sanctum* as a corrosion inhibitor for zinc in HCl

Evidence category	Principal techniques/parameters	Information obtained	Major interpretive value
Corrosion performance	Weight loss, corrosion rate, inhibition efficiency	Extent of metal protection	Quantifies macroscopic inhibitor performance
Adsorption	Langmuir, Freundlich, Temkin and related isotherms	Surface coverage and adsorption affinity	Provides evidence concerning adsorption behaviour
Thermodynamics	ΔG°ads, ΔH°ads, ΔS°ads	Spontaneity and energetic characteristics	Helps distinguish adsorption regimes
Kinetics	Activation energy, Arrhenius relationship	Temperature dependence of corrosion	Evaluates effect of inhibitor on corrosion kinetics
Electrochemical	EIS, Rct, Cdl, polarization, Ecorr, Icorr	Interfacial charge transfer and reaction kinetics	Provides direct electrochemical evidence of inhibition
Surface morphology	SEM	Surface roughness, pits and corrosion damage	Visual evidence of protection
Elemental composition	EDX/EDS	Surface elemental distribution	Supports changes associated with corrosion products or inhibitor films
Molecular characterization	FTIR	Functional groups and band shifts	Identifies chemical groups potentially involved in adsorption
Molecular modelling	DFT, molecular dynamics	Adsorption sites, molecular reactivity and interaction energy	Provides molecular-level mechanistic interpretation

Also, for impedance measurements, inhibition efficiency may alternatively be estimated from the charge-transfer resistance using equation 6 (Pais & Rao, 2020)

$$\%IE = \left(1 - \frac{R_{ct}^{0}}{R_{ct}^{i}}\right) \times \frac{100}{1} \quad (6)$$

where R_{ct}^{0} and R_{ct}^{i} are the charge-transfer resistances without and with inhibitor, respectively.

The use of these relationships allows results obtained using different experimental techniques to be interpreted within a common framework, although they should not be regarded as perfectly interchangeable measures of corrosion protection.

3. 0 Corrosion of Zinc in Hydrochloric Acid: Mechanism and Context

3.1 Electrochemical Basis of Zinc Corrosion

Corrosion of zinc in hydrochloric acid is an electrochemical process involving simultaneous oxidation of zinc and reduction of hydrogen ions (equation 2). At anodic sites on the zinc surface, metallic zinc loses electrons and enters the electrolyte as zinc ions (equation 1)

A combination of the two half-reactions gives the following overall reaction (Parmar *et al*., 2024)

$$Zn_{(s)} + 2HCl_{(aq)} \rightarrow ZnCl_{2(aq)} + H_{2(g)} \quad (7)$$

From equation 7, it is evidence that the overall corrosion process involves the transfer of electrons from zinc to hydrogen ions. The rate of metal dissolution depends on the relative kinetics of the anodic and cathodic reactions and on the condition of the metal/electrolyte interface.

In hydrochloric acid, chloride ions contribute importantly to the aggressive nature of the environment. Chloride is highly mobile and can participate in the destabilization of surface films, while the high proton activity promotes cathodic hydrogen evolution. Consequently, the protective capacity of naturally occurring surface films on zinc is generally insufficient to prevent continued dissolution under strongly acidic conditions.

Fig. 1 shows zinc corrosion in hydrochloric acid and its inhibition by *O. sanctum* phytochemicals. The left panel shows the uninhibited corrosion process, where zinc undergoes anodic dissolution to Zn^{2+} and cathodic reduction of H^{+} to H_2, accompanied by electron flow through the metal and active gas evolution.

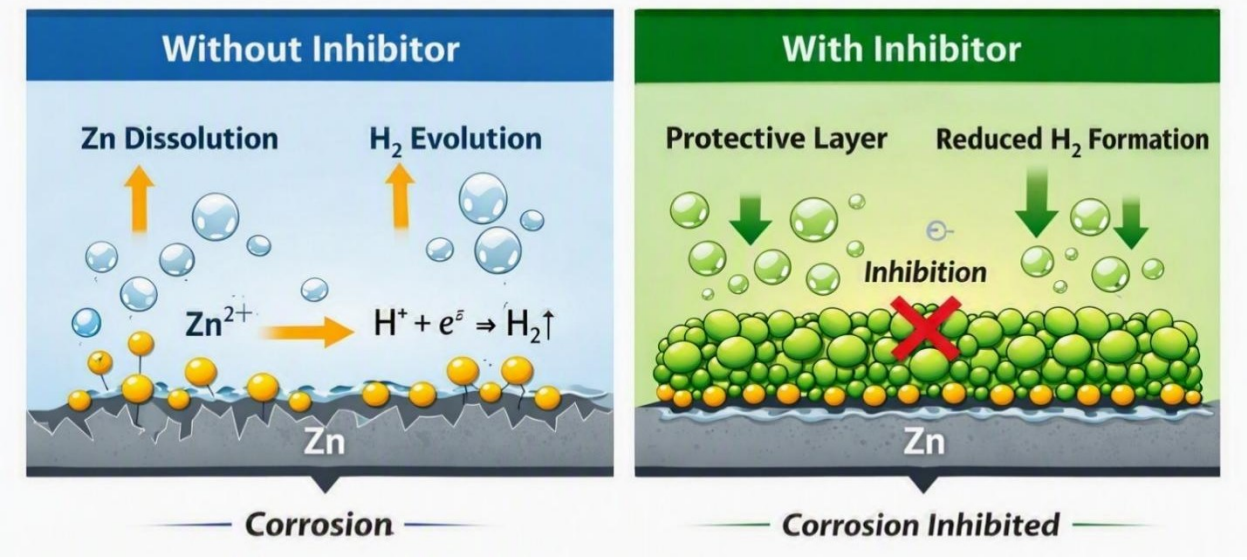


Fig. 1. Schematic representation of zinc corrosion in hydrochloric acid and the proposed action of *O. sanctum* phytochemicals.

The right panel depicts the inhibited system containing *O. sanctum* extract, in which phytochemical molecules adsorb onto the zinc surface, forming a protective layer that partially blocks anodic and cathodic sites. This adsorbed film reduces Zn^{2+} release and suppresses H_2 formation, thereby mitigating corrosion through combined electrostatic and chemical interactions.

3.2 Influence of Hydrochloric Acid Concentration

Increasing hydrochloric acid concentration generally increases the corrosivity of the environment because a greater concentration of hydrogen ions enhances the cathodic hydrogen-evolution reaction. At the same time, increased chloride activity can facilitate the breakdown of surface films and modify the interfacial chemistry of zinc.

The corrosion rate can therefore be expected to increase as the HCl concentration increases, provided other experimental variables remain constant. However, the relationship need not be perfectly linear because corrosion involves coupled electrochemical reactions, changes in surface condition and possible modification of the inhibitor adsorption equilibrium (Parmar & Desai, 2026).

For a plant extract inhibitor, increasing acid concentration can also influence inhibitor performance in two opposing ways. Greater proton concentration may enhance protonation of heteroatom-containing phytochemicals, which can modify their electrostatic interaction with the zinc surface. Conversely, increased competition from chloride and aggressive dissolution of the metal can make it more difficult for a stable inhibitor film to remain intact (Eddy *et al*., 2023). Therefore, inhibitor efficiency should always be reported together with the corresponding HCl concentration.

3.3 Effect of Temperature

Temperature is another major variable controlling zinc corrosion and inhibitor performance. Increasing temperature generally accelerates electrochemical reactions, increases ionic mobility and can enhance the transport of corrosive species toward the metal surface. Consequently, the uninhibited corrosion rate normally increases with increasing temperature.

The response of an inhibitor-containing system is more complex. If adsorption is predominantly physical, increasing temperature may weaken relatively weak surface interactions and promote desorption, resulting in a decrease in inhibition efficiency. Conversely, if a substantial contribution from chemical adsorption exists, elevated temperature may facilitate interfacial rearrangement and strengthen the interaction of certain inhibitor molecules with the surface.

The temperature dependence of corrosion can be examined using the Arrhenius relationship written below as equation 8 and transformed through the logarithm of both sides to equation 9 (Akinbulumo *et* al., 2020; Feliu *et al*., 2019)

$$CR = Aexp\left(\frac{-E_a}{RT}\right) \quad (8)$$

$$lnCR = lnA - \frac{E_a}{RT} \quad (9)$$

where CR is the corrosion rate, A is the Arrhenius pre-exponential factor, E_a is the apparent activation energy, R is the universal gas constant and T is the absolute temperature. Based on equation 9, plotting of $lnCR$ versus 1/T should give a straight line with slope equal to E_a/R and intercept equal to lnA

3.4 Surface Coverage and the Role of an Adsorbed Inhibitor Film

The central concept underlying plant-extract corrosion inhibition is the formation of an adsorbed layer at the metal/electrolyte interface. If (\theta) represents the fraction of the zinc surface covered by inhibitor molecules, it can be approximated from inhibition efficiency as $\theta = \%IE/100$. An increase in inhibitor concentration generally increases (\theta) until the available adsorption sites become increasingly occupied. Once the surface approaches saturation, additional

inhibitor may produce only a relatively small improvement in protection.

The proposed inhibition process can therefore be represented conceptually as:

$$Inhibitor_{solution} + Surface_{free} = Inhibitor_{adsorbed} \quad (10)$$

$Inhibitor_{solution}$ = Inhibitor molecules present in the bulk solution phase, $Surface_{free}$ = Unoccupied or active site on the metal surface, and $Inhibitor_{adsorbed}$ = Inhibitor molecules bound to the surface, forming a protective barrier that reduces corrosion.

The equilibrium between dissolved and adsorbed inhibitor species is central to understanding the adsorption isotherms discussed in the next section.

For *O. sanctum*, the complexity of the extract means that the protective film is unlikely to consist of a single molecular species. Rather, it is more appropriately viewed as a dynamic interfacial layer containing several classes of phytochemicals with different adsorption affinities and molecular orientations. Some constituents may provide strong surface anchoring through heteroatoms or π-electron systems, whereas others may contribute to film cohesion, hydrophobicity or surface coverage.

3.5 Why Zinc/HCl Provides a Useful Model System

The zinc/HCl system is particularly suitable for evaluating green corrosion inhibitors because it provides a strongly aggressive environment in which changes in corrosion behaviour can be readily detected. The relatively rapid dissolution of zinc enables meaningful differences between uninhibited and inhibited conditions to be observed using gravimetric and electrochemical techniques.

At the same time, the aggressive nature of HCl makes mechanistic interpretation important. A high apparent inhibition efficiency may result from several simultaneous phenomena, including adsorption of organic molecules, modification of the double layer, blocking of active sites, changes in hydrogen evolution kinetics and formation of corrosion-product/inhibitor films. Consequently, a robust assessment of *O. sanctum* should not rely on inhibition efficiency alone.

A more convincing mechanistic interpretation emerges when several independent observations converge as listed in Table 2. For example, a decrease in corrosion current density, increase in charge-transfer resistance, reduction in surface roughness, changes in EDX elemental composition and FTIR evidence for involvement of functional groups collectively provide stronger evidence for inhibitor-film formation than any single measurement.

Table 2. Principal variables governing zinc corrosion and *O. sanctum* inhibition in HCl

Variable	Expected effect on uninhibited zinc corrosion	Possible effect on inhibitor performance
HCl concentration	Generally increases corrosion rate	May alter protonation, adsorption and film stability
Inhibitor concentration	Not applicable	Usually increases surface coverage and inhibition until saturation
Temperature	Generally accelerates corrosion	May promote adsorption or desorption depending on mechanism
Immersion time	Can increase cumulative metal loss	May produce initial film formation followed by stabilization or degradation
Extraction solvent	Does not apply	Strongly affects phytochemical composition and therefore inhibition

Plant part	Does not apply	Leaves, stems and seeds may possess different active constituents
pH	Lower pH generally increases aggressiveness	Alters protonation state and adsorption of phytochemicals
Surface preparation	Determines initial surface condition	Influences reproducibility of adsorption and electrochemical response
Chloride concentration	Promotes aggressive interfacial chemistry	May compete with or modify inhibitor adsorption
Hydrodynamic conditions	Can increase mass transport	May remove weakly adsorbed inhibitor species
Extract composition	Does not apply	Determines adsorption sites, film structure and protective efficiency

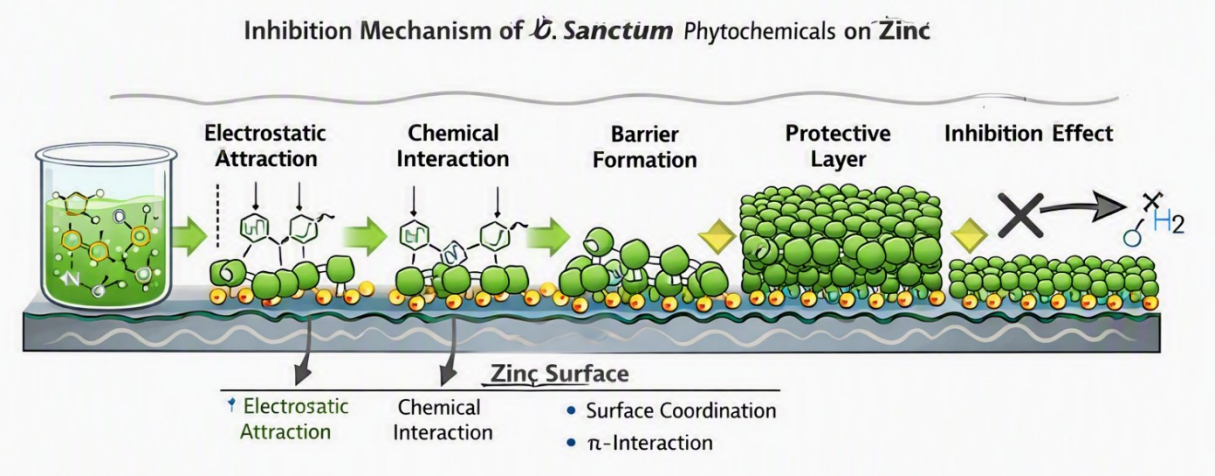
3.6 Mechanistic Framework for O. sanctum Protection of Zinc

Based on the combined electrochemical and adsorption concepts, the inhibition process can be conceptualized as a sequence of interconnected events. First, phytochemical constituents diffuse from the bulk solution toward the zinc/electrolyte interface. Second, molecules interact with the charged or partially charged metal surface through electrostatic forces and/or donor interactions involving heteroatoms and π-electron systems. Third, adsorbed molecules progressively occupy active sites and reduce the area available for zinc dissolution and hydrogen evolution. Finally, increasing surface coverage produces a barrier to the transport of corrosive species and modifies the interfacial charge-transfer process.

This mechanism can be represented schematically as:

The precise contribution of each step depends on the chemical composition of the extract and the physicochemical conditions of the corrosion environment. This consideration is especially important for *O. sanctum*, because its crude extract contains multiple classes of phytochemicals rather than a single defined inhibitor molecule.

Fig. 2 is a schematic illustration depicts a left-to-right sequence of interfacial processes governing corrosion inhibition. In the first stage, phytochemical molecules dispersed in bulk HCl migrate toward the zinc/electrolyte interface. Subsequent electrostatic attraction facilitates initial adsorption, followed by surface coordination through oxygen- and nitrogen-containing functional groups and π-system interactions with the metal surface. Progressive accumulation of adsorbed species leads to the formation of a compact organic barrier that impedes charge transfer and mass transport. The final stage shows the inhibited surface, where zinc dissolution and hydrogen evolution are markedly suppressed. Distinct interaction modes—electrostatic adsorption, chemical coordination, and physical barrier formation—are represented by separate arrows and labels, emphasizing that individual phytochemical molecules may follow different adsorption pathways rather than a single uniform mechanism.



Fig, 2. Proposed multistep inhibition mechanism of *O. sanctum* phytochemicals on zinc in HCl.

4. 0 *Ocimum sanctum*: Botanical and Phytochemical Basis of Corrosion Inhibition

4.1 Botanical Characteristics

Ocimum sanctum L., commonly referred to as Holy basil or Tulsi, belongs to the family *Lamiaceae*. The plant is widely cultivated in tropical and subtropical regions and has attracted scientific interest because of its diverse secondary metabolites and essential-oil constituents.

For corrosion-inhibition applications, the chemical composition of the plant is more important than its botanical classification alone. The concentrations and relative proportions of its bioactive constituents can vary with geographical origin, genotype, plant maturity, climatic conditions, soil characteristics, harvesting period, plant part and extraction procedure. These sources of variability are important because they can produce substantially different corrosion-inhibition responses even when the same plant species is used.

4.2 Phytochemical Constituents Relevant to Adsorption

The corrosion-inhibition potential of *O. sanctum* is commonly associated with phenolic compounds, flavonoids, tannins, saponins, alkaloids and constituents of the essential-oil fraction. Table 3 shows phytochemical classes of some of these comonstituents. Among the reported volatile components, eugenol is particularly noteworthy because of its aromatic ring, methoxy group and phenolic hydroxyl functionality.

From an adsorption perspective, the relevant molecular characteristics are the presence of heteroatoms and delocalized electron systems. Oxygen- and nitrogen-containing functional groups can act as electron donors, while aromatic systems can participate in interactions with the metal surface. Phenolic hydroxyl and carbonyl-containing groups may also contribute to surface coordination or hydrogen-bonding interactions within the adsorbed layer.

4.3 Extraction as a Critical Determinant of Inhibitor Performance

An important issue that should receive greater attention in the literature is the effect of extraction procedure on corrosion-inhibition performance. Water, ethanol, methanol, hydroalcoholic mixtures and other solvents differ substantially in their ability to extract polar, moderately polar and non-polar phytochemicals. Consequently, two *O. sanctum* extracts prepared from apparently identical plant material may possess very different chemical profiles.

For a high-quality corrosion-inhibition study, the extract should therefore be characterized

using appropriate analytical techniques, preferably including chromatographic or spectrometric identification of its major constituents. Reporting only a qualitative phytochemical screening is insufficient for establishing reproducibility.

The subsequent sections examine how these phytochemical constituents are proposed to interact with zinc and how adsorption, thermodynamic and electrochemical measurements can be integrated to evaluate the resulting inhibition mechanism.

Table 3:Phytochemical classes of *O. sanctum* and their possible contribution to zinc corrosion inhibition

Phytochemical class	Representative structural features	Possible interaction with zinc	Potential contribution to inhibition
Eugenol/phenylpropanoids	Aromatic π system, phenolic –OH, methoxy group	π interaction and oxygen-donor interaction	Surface adsorption and barrier formation
Flavonoids	Multiple phenolic –OH and carbonyl groups	Electron donation/coordination	Strong surface attachment and surface coverage
Tannins	Numerous phenolic hydroxyl groups	Multiple adsorption sites	Formation of a relatively dense organic layer
Phenolic acids	Phenolic and carboxyl groups	Electrostatic and coordination interactions	Surface adsorption
Alkaloids	Nitrogen-containing heterocycles	Lone-pair donation/electrostatic interaction	Interfacial adsorption
Saponins	Amphiphilic glycosidic structures	Surface association and intermolecular interactions	Film organization and barrier effects
Other oxygenated compounds	Ether, alcohol, carbonyl and related groups	Donor interactions and hydrogen bonding	Additional surface coverage

5. 0 Adsorption Behaviour of *Ocimum sanctum* on Zinc

The effectiveness of a plant-derived corrosion inhibitor is fundamentally related to its ability to accumulate at the metal/electrolyte interface and form a protective adsorbed layer. For *Ocimum sanctum*, this process is complicated by the multicomponent nature of the extract. Rather than behaving as a single inhibitor molecule, the extract contains phytochemicals with different molecular sizes, polarities, functional groups and adsorption affinities. Consequently, the experimentally observed inhibition efficiency represents the collective

effect of several species competing for and interacting with active sites on the zinc surface. Adsorption can modify the corrosion process in several ways. An adsorbed organic layer may reduce the number of exposed anodic and cathodic sites, alter the interfacial electric double layer, restrict access of hydrogen ions and chloride ions to the surface, and increase the resistance to electron-transfer reactions. The extent of these effects depends on surface coverage, molecular orientation, inhibitor concentration, temperature and the physicochemical properties of the extract.

A useful representation of inhibitor adsorption was represented in equation 10 and rhe fraction of surface covered as $\theta = \%IE/100$.

This approximation is most appropriate when the inhibition efficiency is derived from the same experimental response used to construct the adsorption isotherm and when the inhibited and uninhibited systems are directly comparable.

5.1 Langmuir Adsorption Isotherm

The Langmuir model is one of the most frequently applied adsorption models in corrosion-inhibition studies. Its classical formulation assumes a finite number of equivalent adsorption sites, monolayer coverage and negligible lateral interaction between adsorbed species.

The Langmuir equation is expressed as equation 11 (Xhang *et al*., 2026)

$$\frac{C}{\theta} = \frac{1}{k_{ads}} + C \qquad (11)$$

where C is the inhibitor concentration, θ is the fraction of the metal surface covered by the inhibitor and k_{ads} is the adsorption equilibrium constant.

A plot of $\frac{C}{\theta}$ against C should produce an approximately linear relationship if the experimental system follows the Langmuir model. The inverse of the intercept is equal to k_{ads} while the slope is ideally close to unity.

The Langmuir model is attractive because it provides a relatively simple quantitative description of inhibitor adsorption. However, a high coefficient of determination R^2 should not automatically be interpreted as proof that the physical adsorption process is genuinely Langmuirian. Linearized isotherms can produce apparently good correlations even when the underlying assumptions are not fully satisfied. In particular, crude plant extracts contain multiple adsorbing species, making the assumptions of identical adsorption sites and negligible adsorbate–adsorbate interaction idealizations rather than experimentally established facts.

Consequently, Langmuir agreement should be interpreted together with the slope of the fitted line, the adsorption constant, residual behaviour and comparison with alternative models.

5.2 Freundlich Adsorption Isotherm

The Freundlich isotherm provides an alternative model for heterogeneous surfaces and systems in which adsorption energies vary among available sites. It can be expressed as equation 12 and 12, when converted to a linear model (Kokalj,, 2023)

$$\theta = k_F C^n \qquad (12)$$

$$log\theta = logk_F + nlogC \qquad (13)$$

where k_F is the Freundlich adsorption constant and (n) represents an empirical adsorption-intensity parameter.

The Freundlich model may be particularly relevant to crude plant extracts because the zinc surface is unlikely to be chemically and energetically homogeneous during corrosion. Different surface regions may contain metallic zinc, corrosion products, adsorbed chloride and previously adsorbed organic species. Furthermore, phytochemicals of different molecular structures may compete for surface sites.

A good Freundlich fit therefore provides evidence that adsorption may occur on a heterogeneous surface. However, it does not necessarily contradict a good Langmuir fit. The two models can provide complementary

descriptions of different aspects of a complex adsorption system.

5.3 Temkin Adsorption Isotherm

The Temkin model accounts, in an approximate manner, for changes in adsorption energy resulting from interactions between adsorbed molecules. Its linearized form can be expressed as equation 14 and as a linear model (equation 15)(Abeng *et al*., 2026)

$$\theta = \frac{1}{f} ln(k_T C) \quad (14)$$

$$\theta = \frac{1}{f} lnk_T + lnC \quad (15)$$

wherek_T represents the Temkin adsorption constant and f is the energetic factor of surface heterogeneity (molecular interaction parameter).The model becomes relevant when adsorbate–adsorbate interactions cannot reasonably be neglected. This possibility is important for *O. sanctum* because several phytochemical molecules can simultaneously occupy neighbouring surface sites. Intermolecular interactions may influence molecular orientation, packing density and the overall stability of the protective layer.

5.4 Comparative Interpretation of Adsorption Isotherms

The simultaneous consideration of several isotherm models provides a more robust interpretation than selecting the model with the highest (R^2) alone. For a high-quality review, reported adsorption data should ideally be evaluated using the coefficient of determination, model parameters, physical plausibility and consistency with independent electrochemical and thermodynamic observations. In Table 4, the list of common isotherms, the model equations, interpretation and significance are shown. From the Table, different adsorption isotherms have different significance. Therefore, care should be taken in fitting the best isotherms.

Table 4. Interpretation of commonly applied adsorption isotherms in plant-extract corrosion inhibition

Isotherm	Principal assumption	Key relationship	What agreement may indicate	Important limitation for crude extracts
Langmuir	Equivalent sites; approximate monolayer coverage	$\frac{C}{\theta} = \frac{1}{k_{ads}} + C$	Predominantly monolayer-type surface coverage	Real plant extracts contain multiple competing adsorbates
Freundlich	Heterogeneous adsorption sites	$log\theta = logk_F + nlogC$	Surface heterogeneity and variable adsorption energies	Empirical model; does not identify molecular mechanism
Temkin	Adsorbate–adsorbate interactions	$\theta = \frac{1}{f} lnk_T + lnC$	Interaction among adsorbed species and changing adsorption energy	Simplified treatment of a complex multicomponent film
El-Awady/modified models	Multiple-site occupation may occur	$ln\left(\frac{\theta}{1-\theta}\right) = lnk_{EA} + ylnC$	Possible interaction of one inhibitor species with several sites	Parameters can be difficult to assign physically in crude extracts

The collective interpretation of adsorption models suggests that *O. sanctum* inhibition should not be conceptualized as the adsorption of a single uniform molecular layer. A more realistic model is a heterogeneous interfacial film in which strongly adsorbing constituents provide surface anchoring while other molecules contribute to surface coverage and barrier formation.

6.0 Thermodynamic Characteristics of *O. sanctum* Adsorption

Adsorption thermodynamics provides an important second line of evidence for interpreting corrosion inhibition. The principal parameters considered in corrosion-inhibitor studies are the standard Gibbs free energy of adsorption ((\Delta G^\circ_{\mathrm{ads}})), enthalpy of adsorption ((\Delta H^\circ_{\mathrm{ads}})) and entropy of adsorption ((\Delta S^\circ_{\mathrm{ads}})). These quantities should not be interpreted independently. Their combined behaviour provides information about whether adsorption is thermodynamically favourable, whether heat is absorbed or released during adsorption, and how the degree of molecular disorder changes during interfacial adsorption.

6.1 Standard Gibbs Free Energy of Adsorption

The standard Gibbs free energy of adsorption can be calculated from the adsorption equilibrium constant according to equation 19 (Klink, 2025)

$$\Delta G_{ads} = -RTln(k_{ads}C) \qquad (16)$$

Where R is the universal gas constant, T is the absolute temperature, k_{ads} is the adsorption equilibrium constant and C is the standard-state concentration.

The inclusion of the standard-state term is important because adsorption equilibrium constants obtained from different formulations may have different dimensions. Care should therefore be taken when comparing reported ΔG_{ads}values from different studies.

A negative ΔG_{ads} indicates that the adsorption process is thermodynamically favourable under the conditions investigated. However, the sign alone does not establish whether adsorption is physical or chemical.

Values of ΔG_{ads}reported in the literature are often interpreted using approximate energetic ranges, with less negative values commonly associated with predominantly electrostatic interactions and more negative values associated with stronger surface interactions. These ranges should be treated only as qualitative guides because adsorption on real corroding surfaces is more complicated than the idealized distinction between physisorption and chemisorption.

In the case of *O. sanctum*, a negative free energy of adsorption would therefore support spontaneous accumulation of extract constituents at the zinc/HCl interface, but additional evidence is required to establish the exact bonding mechanism.

6.2 Enthalpy of Adsorption

The adsorption enthalpy provides information about the heat associated with the adsorption process. It can be obtained from the temperature dependence of the adsorption equilibrium constant using the van't Hoff relationship (equation 17)(Afifi, 2026)

$$lnk_{ads} = \frac{\Delta S^0_{ads}}{R} - \frac{\Delta H^0_{ads}}{RT} \qquad (17)$$

A negative value of ΔH^0_{ads} indicates an exothermic adsorption process, whereas a positive value indicates an endothermic process. For *O. sanctum*, an exothermic adsorption process would be consistent with the release of heat during the formation of inhibitor–surface interactions. However, the magnitude and sign of the enthalpy should be evaluated together with temperature-dependent inhibition efficiency and electrochemical measurements.

6.3 Entropy of Adsorption

The entropy of adsorption describes the change in disorder associated with the transfer of

inhibitor species from solution to the metal interface. It can be obtained from equation 17 is using plot or through the free energy change (equations18 and 19 after rearrangement

$\Delta G^0_{ads} = \Delta H^0_{ads} - T\Delta S^0_{ads}$ (19)

$\Delta S^0_{ads} = \frac{\Delta G^0_{ads} - \Delta H^0_{ads}}{T}$)20)

A positive entropy change can arise when adsorption results in the displacement of water molecules or other adsorbed species from the metal surface. Thus, even though inhibitor molecules become more constrained after adsorption, the release of previously organized interfacial water can result in a net increase in entropy.

For a multicomponent plant extract, interpretation of ΔS^0_{ads} is particularly challenging because different constituents may adsorb through different pathways and displace different numbers of solvent molecules.

6.4 Thermodynamic Criterion for Adsorption Mechanism

A common approach in corrosion literature is to classify adsorption as predominantly physical, chemical or mixed based on the magnitude of (\Delta G^\circ_{\mathrm{ads}}). Although useful as an initial guide, this approach has important limitations.

Physical adsorption generally involves relatively weak electrostatic interactions, whereas chemical adsorption involves stronger interactions such as coordinate bonding or electron sharing between inhibitor molecules and surface atoms. Plant extracts can plausibly exhibit both mechanisms simultaneously because their constituents differ considerably in molecular structure.

For *O. sanctum*, oxygen-containing phenolic and carbonyl groups, nitrogen-containing compounds and aromatic π systems may interact with the zinc interface through more than one mechanism. In addition, protonation of phytochemicals in HCl can alter their charge state and therefore their adsorption behaviour.

Accordingly, the most defensible conclusion is that thermodynamic parameters can support a proposed adsorption mechanism but should not be used as its sole proof. Strong mechanistic claims require convergence among thermodynamic, electrochemical, spectroscopic and, preferably, computational evidence.

Table 5. Thermodynamic parameters and their significance in corrosion-inhibition studies

Parameter	Typical calculation	Principal interpretation	Caution
ΔG^0_{ads}	$\Delta G_{ads} = -RTln(k_{ads}C)$	Thermodynamic favourability of adsorption	Magnitude alone does not prove adsorption mechanism
ΔH^0_{ads}	van't Hoff relationship	Endothermic or exothermic adsorption	Requires reliable temperature-dependent (K_{\mathrm{ads}})
ΔS^0_{ads}	Gibb free energy equation	Entropic change during adsorption	Strongly affected by solvent displacement and standard state
(E_a)	Arrhenius equation	Temperature dependence of corrosion kinetics	Not a stand-alone proof of physisorption or chemisorption

7. 0 Kinetic Analysis and Temperature Dependence

7.1 Activation Energy

The apparent activation energy of zinc corrosion can be estimated using the Arrhenius equation *equations 8 and 9). Comparison of

(E_a) values obtained in uninhibited and inhibited solutions can reveal how the inhibitor changes the apparent energy barrier associated with corrosion.

An increase in apparent activation energy following inhibitor addition may indicate that the inhibitor creates an additional kinetic barrier to corrosion. However, interpretation should remain cautious because the measured corrosion rate is the net outcome of coupled anodic and cathodic processes and may also reflect changes in surface coverage, transport and film stability.

7.2 Transition-State Analysis

A more detailed kinetic analysis can be obtained from transition-state theory. The corrosion rate can be related to temperature according to:

$$CR = \frac{RT}{Nh} exp\left(\frac{\Delta S^*}{R}\right) exp\left(\frac{-\Delta H^*}{RT}\right) \quad (21)$$

where N is Avogadro's number, h is Planck's constant, (ΔH^* *is the enthalpy of activation and* ΔS^* is the entropy of activation. A more useful form of this model is the linearized form gicen in equation 22

$$ln\left(\frac{CR}{T}\right) = ln\left(\frac{R}{Nh}\right) + \left(\frac{\Delta S^*}{R}\right) - \left(\frac{\Delta H^*}{RT}\right) \quad (22)$$

This approach can provide additional insight into the energetic and entropic characteristics of the corrosion transition state.

7.3 Temperature as a Diagnostic Variable

Temperature-dependent inhibition behaviour is particularly informative when interpreted alongside adsorption thermodynamics. If inhibition efficiency decreases substantially with increasing temperature, desorption or destabilization of relatively weakly adsorbed inhibitor species may be occurring. Conversely, retention or enhancement of inhibition at elevated temperatures may indicate stronger interfacial interactions or changes in the adsorption equilibrium.

Nevertheless, temperature trends should not be interpreted simplistically. An extract may contain constituents with different adsorption energies, meaning that some molecules may desorb while others remain attached. Temperature can also alter the solubility, protonation state, diffusion and chemical stability of phytochemicals.

The temperature dependence of *O. sanctum* inhibition should therefore be considered a property of the complete extract–metal–acid system, rather than as a direct fingerprint of a single adsorption mechanism.

Fig. 3 shows an integration of temperature, corrosion kinetics, adsorption equilibrium, and protective-film stability into a unified model describing the inhibition process.

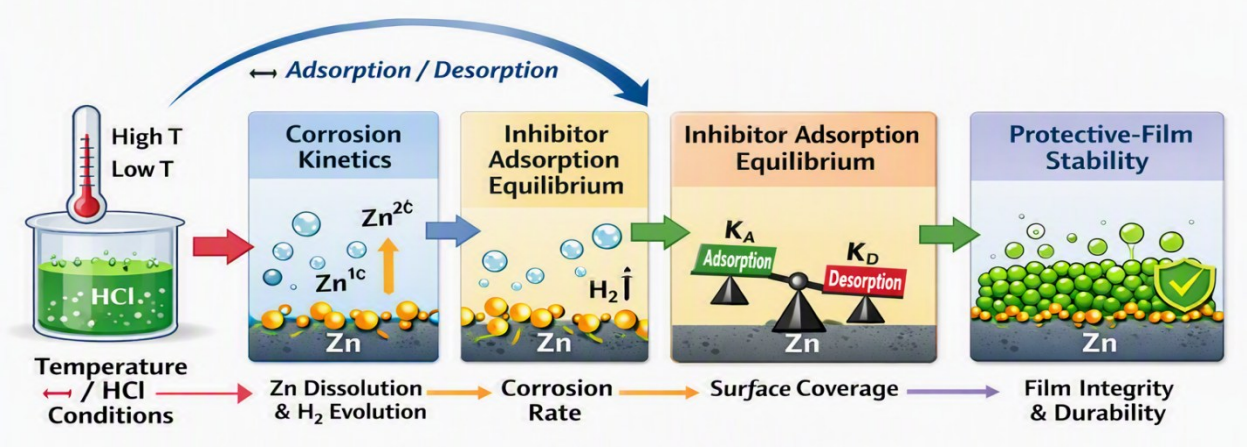


Fig. 3. Integrated thermodynamic and kinetic framework for *O. sanctum* inhibition of zinc.

Temperature and acid concentration influence both the rate of zinc dissolution and the adsorption–desorption balance of phytochemical molecules on the metal surface. The framework highlights that thermal effects

act simultaneously on corrosion reactions and inhibitor equilibrium, rather than solely on the integrity of the protective film. The resulting balance between kinetic acceleration and thermodynamic stabilization determines the overall corrosion resistance and durability of the inhibitor layer.

8.0 Integrated Interpretation of Adsorption, Thermodynamic and Kinetic Evidence

The adsorption, thermodynamic and kinetic results should ultimately be interpreted as interconnected rather than independent observations. Adsorption isotherms describe how inhibitor concentration is related to surface coverage; thermodynamic parameters describe the energetic feasibility and nature of adsorption; and kinetic parameters describe the effect of the inhibitor on the apparent energy barrier and temperature dependence of corrosion.

Table 6 illustrate that for *O. sanctum*, a coherent inhibition mechanism would therefore be expected to show several complementary features: increasing surface coverage with extract concentration, favourable adsorption free energy, measurable changes in adsorption equilibrium with temperature, reduced corrosion rate, modification of the apparent activation parameters and electrochemical evidence of reduced interfacial charge transfer.

Table 6. Evidence required for a robust mechanistic interpretation of *O. sanctum* inhibition

Observation	Interpretation supported	Interpretation not justified on its own
Negative ΔG^0_{ads}	Spontaneous/favourable adsorption	Definitive proof of chemisorption
Good Langmuir fit	Approximate Langmuir-type adsorption behaviour	Proof of a perfectly uniform monolayer
High k_{ads}	Stronger apparent adsorption affinity	Identification of a particular phytochemical
Increased R_{ct}	Greater resistance to charge transfer	Identification of exact molecular bonding
Reduced I_{corr}	Lower electrochemical corrosion rate	Proof of the structure of the inhibitor film
Increased surface coverage	Progressive occupation of active sites	Proof that all phytochemicals adsorb identically
FTIR band shift	Possible involvement of corresponding functional groups	Definitive proof of a specific chemical bond without complementary evidence
SEM surface smoothing	Reduced visible corrosion damage	Molecular identification of the protective film
EDX elemental changes	Alteration of surface composition	Direct identification of individual organic molecules
DFT adsorption energy	Molecular-level interaction tendency	Direct experimental proof of behaviour in the crude extract

This integrated approach is especially important for plant-derived inhibitors. Because crude extracts contain multiple constituents, the most scientifically defensible mechanism is one supported by **convergent evidence** rather than by any single calculated parameter.

10. Conclusion and Future Concerns

This review has critically examined the potential of *Ocimum sanctum* as a plant-derived inhibitor for the corrosion of zinc in hydrochloric acid, with emphasis on its phytochemical composition, adsorption behaviour, thermodynamic characteristics, corrosion kinetics and surface-protection mechanism. The available literature indicates that *O. sanctum* contains several classes of potentially surface-active constituents, including eugenol, phenolic compounds, flavonoids, tannins, saponins and nitrogen-containing compounds. The presence of hydroxyl, carbonyl, ether, amino and aromatic π-electron functionalities provides plausible sites for interaction with the zinc/acid interface. The inhibition process is principally associated with adsorption of phytochemical constituents onto active sites on the zinc surface. Reported adsorption studies frequently show satisfactory agreement with the Langmuir model, although Freundlich and Temkin relationships can also provide useful descriptions of surface heterogeneity and interactions among adsorbed species. Such behaviour suggests that the protective layer should not be regarded as a perfectly uniform film formed by a single compound, but rather as a complex interfacial layer produced by the collective adsorption of several constituents present in the extract.

Thermodynamic studies generally indicate favourable adsorption, as reflected by negative Gibbs free energies of adsorption. Enthalpy and entropy parameters provide additional evidence concerning the energetic and interfacial changes associated with adsorption, while kinetic analyses demonstrate that the extract can alter the apparent energy barrier and temperature dependence of zinc corrosion. Nevertheless, the commonly used numerical thresholds for distinguishing physisorption from chemisorption should be regarded as qualitative indicators rather than definitive mechanistic criteria. The available evidence is more appropriately interpreted as indicating that both physical and chemical interactions may contribute to the adsorption of *O. sanctum* constituents, with their relative importance depending on extract composition and experimental conditions.

The overall inhibition performance is strongly influenced by inhibitor concentration, temperature, HCl concentration, exposure time and extraction procedure. Increasing extract concentration generally promotes surface coverage and protection until the available adsorption sites approach saturation. Temperature, however, can either enhance or reduce protection depending on the stability and nature of the adsorbed species. This behaviour emphasizes that the corrosion-inhibition performance of *O. sanctum* is not an intrinsic fixed property of the plant but a system-dependent response arising from interactions among the extract, zinc surface and acidic environment.

Surface characterization further supports the formation of an organic protective layer by showing changes in surface morphology, elemental composition and functional-group behaviour following inhibitor exposure. Taken together, the adsorption, thermodynamic, kinetic and surface evidence establishes *O. sanctum* as a promising renewable source of zinc-corrosion inhibitors in hydrochloric acid. However, the current literature remains dominated by laboratory-scale investigations, and differences in plant source, extraction protocol, inhibitor concentration, acid strength and experimental procedures limit direct comparison among published results.

10.2 Future Concerns and Research Priorities

Despite the promising performance reported for *O. sanctum*, several issues must be addressed before its corrosion-inhibition potential can be translated into reliable industrial applications.

First, extract standardization is essential. The chemical composition of *O. sanctum*

varies with geographical origin, plant maturity, plant part, harvesting conditions and extraction method. Future investigations should therefore report extraction yield and quantitatively characterize the major constituents rather than relying exclusively on qualitative phytochemical screening. Chromatographic and spectrometric techniques should be used to establish reproducible chemical fingerprints for inhibitor formulations.

Second, the contributions of individual phytochemicals remain insufficiently resolved. Although eugenol, flavonoids, tannins, phenolic compounds and other constituents are frequently proposed as active species, the corrosion-inhibition contribution of each component should be established experimentally. Isolation of major constituents followed by individual and synergistic inhibition studies would help determine whether the high performance of the crude extract results from a dominant compound or from interactions among several constituents.

Third, mechanistic interpretation requires stronger validation. Adsorption isotherms and thermodynamic parameters provide valuable evidence but cannot, by themselves, establish the molecular structure or bonding nature of the inhibitor film. Future studies should combine experimental characterization with density functional theory, molecular dynamics simulations and other molecular-modelling approaches. Such approaches could identify preferred adsorption sites, molecular orientations, interaction energies and the influence of protonation in HCl.

Fourth, long-term stability must be investigated. Most laboratory studies employ relatively short exposure periods, whereas industrial acid-cleaning and pickling environments may involve repeated or prolonged exposure. The persistence of the protective film, possible degradation of phytochemicals, changes in extract composition and the reversibility of adsorption should therefore be evaluated over extended periods.

Fifth, the influence of environmental variables requires systematic investigation. Future experiments should independently examine HCl concentration, temperature, immersion time, hydrodynamic conditions, dissolved oxygen, chloride activity and surface roughness using standardized protocols. This would allow reliable prediction of inhibitor performance under different operating conditions.

Sixth, toxicity and environmental compatibility should be demonstrated rather than assumed. The designation of a plant-derived material as a "green inhibitor" does not automatically establish that the resulting formulation is non-toxic or environmentally benign. Ecotoxicological studies, biodegradability assessments and evaluation of the toxicity of extraction solvents, residual phytochemicals and corrosion-inhibitor formulations are therefore necessary.

Seventh, formulation and scale-up remain major challenges. The excellent inhibition efficiencies sometimes reported at laboratory scale do not necessarily translate directly to industrial systems. Future work should investigate formulation stability, storage life, dosage optimization, compatibility with industrial equipment and process fluids, regeneration or reuse possibilities, and the effect of large-scale extraction on chemical composition.

Finally, techno-economic assessment should accompany advanced laboratory studies. A commercially viable *O. sanctum*-based inhibitor must provide an acceptable balance between extraction cost, inhibitor dosage, protection efficiency, stability, availability of biomass and waste-management requirements. Comparative life-cycle and economic assessments against conventional inhibitors would provide a more rigorous basis for determining its practical sustainability.

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