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Integrated Gravimetric, Electrochemical, Kinetic, and Thermodynamic Evaluation of *Dioscorea bulbifera* (Bitter Yam) Leaf Extract as a Green Corrosion Inhibitor for Mild Steel in Hydrochloric Acid

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Abstract

Corrosion of mild steel in acidic media remains a major challenge in industrial operations, necessitating the development of environmentally sustainable corrosion inhibitors. This study investigated the corrosion inhibition performance of *Dioscorea bulbifera* leaf extract on mild steel in hydrochloric acid using complementary phytochemical, gravimetric, electrochemical, kinetic, and thermodynamic analyses. Phytochemical screening confirmed the presence of bioactive constituents, including flavonoids, tannins, alkaloids, saponins, phenolics, and terpenoids, which are responsible for the adsorption and protective properties of the extract. Gravimetric measurements revealed a concentration-dependent reduction in weight loss and corrosion rate, while the inhibition efficiency increased from 19.17% at 0.5 g L^{-1} to 83.48% at 2.5 g L^{-1}, accompanied by a maximum surface coverage (ϑ) of 0.8348. Electrochemical impedance spectroscopy (EIS) showed a significant increase in charge transfer resistance from 32.1 to 253.8 Ω cm^{-2} and a decrease in double-layer capacitance from 103.5 to 8.5 µF cm^{-2}, confirming the formation of a protective adsorbed film. Potentiodynamic polarization (PDP) measurements further demonstrated a reduction in corrosion current density from 847.5 to 69.7 µA cm^{-2}, achieving a maximum inhibition efficiency of 91.8%. Kinetic analysis revealed a progressive decrease in the corrosion rate constant from 0.01234×10^{-3} to 0.00285×10^{-3} h^{-1} and an increase in half-life from 54.14 to 242.65 h, indicating enhanced corrosion resistance. Thermodynamic analysis yielded negative Gibbs free energy values ($\Delta G°_{ads}$ = −12.3 to −19.9 kJ mol^{-1}), confirming spontaneous adsorption predominantly through physisorption. The combined gravimetric, electrochemical, kinetic, and thermodynamic findings demonstrate that *Dioscorea bulbifera* leaf extract is an effective, eco-friendly mixed-type corrosion inhibitor for mild steel in hydrochloric acid, with inhibition occurring through spontaneous adsorption and the formation of a stable protective surface film.

Keywords: *Dioscorea bulbifera*, green corrosion inhibitor, mild steel, electrochemical impedance spectroscopy, adsorption mechanism

1. Introduction

Corrosion is one of the most persistent and economically significant challenges affecting metallic materials used in industrial, marine, petroleum, transportation, and construction sectors. Mild steel remains one of the most widely utilized engineering materials because of its excellent mechanical properties, low cost, ease of fabrication, and high availability. Despite these advantages, mild steel exhibits poor corrosion resistance, particularly in acidic environments commonly encountered during industrial operations such as acid pickling, descaling, chemical cleaning, and oil-well acidification. The deterioration of mild steel through electrochemical reactions results in enormous economic losses associated with equipment replacement, maintenance, production downtime, and environmental contamination [1,2].

Corrosion is fundamentally an electrochemical process involving simultaneous anodic metal dissolution and cathodic reduction reactions. During corrosion, iron atoms lose electrons and dissolve into the surrounding electrolyte, while cathodic reactions involving hydrogen evolution or oxygen reduction occur on adjacent areas of the metal surface. This continuous electrochemical process gradually weakens metallic structures, reduces their service life, and compromises operational safety. Worldwide studies estimate that corrosion-related costs account for approximately 3–4% of the global gross domestic product, emphasizing the necessity for effective corrosion protection strategies [3].

Among the numerous corrosion control methods, the use of corrosion inhibitors remains one of the most practical and economically viable techniques. Corrosion inhibitors are chemical substances added in relatively small concentrations to corrosive media to reduce the rate of metal dissolution through adsorption or film formation on the metal surface. Conventional corrosion inhibitors, including chromates, phosphates, amines, and other synthetic organic compounds, generally exhibit excellent inhibition efficiencies. However, many of these compounds possess serious drawbacks, including toxicity, poor biodegradability, environmental persistence, and increasing regulatory restrictions due to their adverse effects on human health and aquatic ecosystems [4].

Growing environmental awareness and the global movement toward sustainable industrial practices have stimulated intensive research into environmentally benign alternatives known as green corrosion inhibitors. Green inhibitors are naturally occurring substances obtained from renewable biological resources, particularly plant extracts, which can provide biodegradable and readily available alternatives to conventional inhibitors. Their corrosion inhibition properties are commonly associated with phytochemicals such as flavonoids, alkaloids, tannins, saponins, phenolic compounds, terpenoids, glycosides, and steroids. These compounds contain heteroatoms and conjugated π-electron systems that can participate in adsorption onto metallic surfaces and contribute to the formation of protective films that retard anodic and cathodic corrosion reactions [5–10].

Plant-derived inhibitors have been investigated extensively for mild steel in acidic media. *Azadirachta indica* leaf extract has been reported to inhibit mild steel corrosion in hydrochloric acid, with experimental and computational results supporting strong adsorption and protective film formation [5]. *Mangifera indica* leaf extract has likewise shown high inhibition efficiency for mild steel in 1 M HCl, with electrochemical, surface, and molecular-simulation results indicating suppression of both anodic dissolution and cathodic hydrogen evolution [6]. *Vernonia amygdalina* stem extract has been shown to inhibit mild carbon steel in 1 M HCl, while *Carica papaya* leaf extract has demonstrated appreciable protection of mild steel in hydrochloric acid [11,12]. *Moringa oleifera* leaf extract has also exhibited high inhibition efficiency for mild steel in acidic media [7], while *Aloe vera* and *Ocimum gratissimum* extracts have been reported as effective inhibitors for mild steel in hydrochloric acid and sulphuric acid, respectively [13,14]. These studies provide direct experimental evidence for the use of plant extracts as corrosion inhibitors of steel in acidic environments.

Dioscorea bulbifera, commonly referred to as aerial yam or air potato, is a perennial climbing plant widely distributed throughout tropical Africa and Asia. The plant has attracted considerable medicinal interest because of its rich phytochemical composition and biological activities, including antioxidant, antimicrobial, anti-inflammatory, antidiabetic, and anticancer properties. Phytochemical investigations have identified substantial quantities of flavonoids, phenolic acids, alkaloids, tannins, saponins, terpenoids, and steroidal compounds within the leaves of *Dioscorea bulbifera*. These bioactive constituents possess multiple adsorption centers capable of coordinating with vacant d-orbitals of iron atoms, thereby forming stable protective films that significantly retard corrosion processes [15–17].

Although several investigations have demonstrated the corrosion inhibition potential of *Dioscorea bulbifera* using either gravimetric techniques or electrochemical methods individually, relatively few studies have integrated both approaches with adsorption and kinetic analyses to provide a comprehensive understanding of the inhibition mechanism. Gravimetric measurements provide valuable information regarding weight loss, corrosion rate, inhibition efficiency, immersion time effects, activation

energy, half-life, and adsorption behavior, whereas electrochemical techniques such as potentiodynamic polarization (PDP) and electrochemical impedance spectroscopy (EIS) offer deeper mechanistic insights into charge transfer resistance, corrosion current density, polarization behavior, and inhibitor film formation at the metal–solution interface. The combination of these complementary techniques enables a more reliable evaluation of inhibitor performance and adsorption mechanisms [17].

Therefore, this study presents an integrated investigation of the corrosion inhibition performance of *Dioscorea bulbifera* leaf extract on mild steel in hydrochloric acid solution using phytochemical characterization, gravimetric measurements, adsorption and kinetic analyses, and electrochemical techniques. Specifically, the study evaluates the phytochemical composition of the extract, weight loss behavior, corrosion rate, surface coverage, inhibition efficiency, immersion time effects, activation energy, half-life, equilibrium adsorption constant (K_{ads}), PDP and EIS. The combined analytical approach provides a comprehensive understanding of the inhibition mechanism and further establishes *Dioscorea bulbifera* leaf extract as a promising, sustainable, and environmentally friendly alternative to conventional synthetic corrosion inhibitors for industrial applications.

2. Materials and Method

2.1. Materials

Fresh leaves of *Dioscorea bulbifera* (Fig. 1) were collected from Rivers State, Nigeria, and authenticated in the Department of Plant Science and Biotechnology, Rivers State University. Analytical-grade hydrochloric acid (HCl), ethanol, distilled water, acetone, sodium hydroxide, ferric chloride, Wagner's reagent, Mayer's reagent, Dragendorff's reagent, concentrated sulphuric acid, chloroform, and other chemicals used for phytochemical screening were obtained from standard chemical suppliers and used without further purification [18].



Figure 1. *Dioscorea bulbifera* leaf.

2.2. Mild steel preparation

Mild steel coupons were employed as the metal substrates for all corrosion experiments. The mild steel was obtained from a local steel distributor in Port Harcourt, Rivers State, Nigeria. The steel sheets were mechanically cut into rectangular coupons of uniform dimensions and perforated near one edge to facilitate suspension during immersion experiments. The exposed surfaces were successively polished using silicon carbide abrasive papers of different grit sizes to obtain a smooth and homogeneous surface finish. After polishing, the coupons were thoroughly rinsed with distilled water, degreased with acetone to remove surface contaminants, washed again with distilled water, and finally dried in air before use. Each coupon was weighed using a digital analytical balance with a precision of ±0.001 g, and the initial mass was recorded before immersion in the test solutions [18].

Prior to each experiment, freshly prepared 0.5 M hydrochloric acid solution was used as the corrosive medium. Different concentrations of *Dioscorea bulbifera* leaf extract was prepared and added to the acid solution to investigate their corrosion inhibition performance. The preparation of metal coupons followed standard gravimetric corrosion testing procedures widely reported for evaluating plant-derived corrosion inhibitors [19,20].

2.3. Preparation of *Dioscorea bulbifera* leaf extract

Fresh leaves of *Dioscorea bulbifera* were thoroughly washed under running tap water to remove adhering dust and soil particles, followed by rinsing with distilled water. The cleaned leaves were air-dried under laboratory conditions for approximately three weeks until a constant weight was achieved. The dried leaves were ground into fine powder using an electric laboratory grinder and stored in airtight polyethylene containers until extraction. The plant extract was prepared by maceration using ethanol as the extraction solvent.



Figure 2. Plant extract soaked in ethanol and HCl solutions.

A measured quantity of the powdered leaf material was soaked in ethanol for 72 h with intermittent stirring to facilitate maximum extraction of bioactive constituents. The resulting mixture was filtered using Whatman No. 1 filter paper, and the filtrate was concentrated using a

rotary evaporator followed by gentle evaporation on a water bath to obtain the crude extract. The concentrated extract was preserved in airtight containers at 4°C until required for corrosion experiments. Stock inhibitor solutions were prepared by dissolving appropriate quantities of the crude extract in 0.5 M hydrochloric acid to obtain inhibitor concentrations of 0.5, 1.0, 1.5, 2.0, and 2.5 g L^{-1} for gravimetric studies (Fig. 2). The same stock solution was used for electrochemical investigations.

2.4. Phytochemical analysis

Qualitative phytochemical screening was performed to identify the presence of major secondary metabolites, including alkaloids, flavonoids, tannins, saponins, phenols, terpenoids, glycosides, steroids, anthraquinones, and reducing sugars, using established phytochemical procedures. Quantitative determination of the major phytochemicals was subsequently carried out according to standard analytical methods to determine the concentrations of the identified bioactive constituents relevant to corrosion inhibition. The corrosion-inhibiting activity of such phytochemicals is associated with electron-rich heteroatoms, particularly oxygen and nitrogen, and conjugated π-electron systems that can interact with iron surfaces through donor–acceptor interactions and contribute to protective adsorption films [8–10,19,20].

2.5. Corrosion studies

The corrosion inhibition performance of *Dioscorea bulbifera* leaf extract was evaluated sequentially using gravimetric, electrochemical, kinetic, and thermodynamic analyses. The gravimetric method quantified weight loss, corrosion rate, surface coverage, and inhibition efficiency, whereas PDP and EIS provided electrochemical evidence of changes at the metal–solution interface. Adsorption, kinetic, and thermodynamic parameters were subsequently used to interpret the inhibition mechanism.

2.5.1. Gravimetric (weight loss) measurements

Weight loss experiments were conducted using the immersion method in accordance with ASTM G31 procedures. Pre-weighed mild steel coupons were immersed in 100 mL of 0.5 M hydrochloric acid containing different concentrations of *Dioscorea bulbifera* leaf extract (0.5–2.5 g L^{-1}). A blank solution without inhibitor served as the control. The immersed coupons were withdrawn after predetermined exposure periods, washed with distilled water, cleaned with acetone to remove loosely adhered corrosion products, dried, and reweighed. The difference between the initial and final masses was recorded as the weight loss. The corrosion rate (CR) was calculated using Eq. (1) [18]:

$$\mathrm{CR} = \frac{\Delta \mathrm{W}}{\mathrm{At}} \quad (1)$$

Where ΔW = weight loss (g), A = surface area (m^2), t = immersion time (h). The inhibition efficiency ($IE\%$) was determined using Eq. (2) [19,20]:

$$\mathrm{IE}(\%) = \frac{W_o - W_i}{W_o} \times 100 \quad (2)$$

Where W_o = weight loss in the uninhibited solution, W_i = weight loss in the inhibited solution. The degree of surface coverage (ϑ) was calculated from Eq. (3) [19,20]:

$$\theta = \frac{W_o - W_i}{W_o} \quad (3)$$

The influence of immersion time, inhibitor concentration, and temperature on corrosion behaviour was evaluated using the gravimetric results.

2.5.2. Electrochemical measurements

Electrochemical investigations were carried out using PDP and EIS. Electrochemical measurements were performed using a conventional three-electrode electrochemical cell consisting of mild steel as the working electrode, platinum as the counter electrode, and a saturated calomel electrode (SCE) as the reference electrode. The electrolyte consisted of 0.5 M HCl with and without different concentrations of *Dioscorea bulbifera* leaf extract.

Prior to polarization measurements, the working electrode was immersed in the test solution until a stable open circuit potential (OCP) was attained. PDP scans were then recorded over suitable potential ranges at a constant scan rate. The corrosion potential (E_{corr}), corrosion current density (I_{corr}), anodic Tafel slope (β_a), cathodic Tafel slope (β_c), and inhibition efficiency were determined from the polarization curves using Tafel extrapolation. The inhibition efficiency obtained from PDP measurements was calculated using the Eq. (4) below [21]:

$$IE_{PDP}(\%) = \left(1 - \frac{\mathrm{i_{corr}}}{\mathrm{i^0_{corr}}}\right) \times 100 \quad (4)$$

where i^0_{corr} and i_{corr} are the corrosion current densities in the absence and presence of *Dioscorea bulbifera* leaf extract, respectively. EIS measurements were subsequently performed over a wide frequency range using a sinusoidal perturbation signal of small amplitude. The impedance spectra were analyzed using Nyquist and Bode plots to determine the solution resistance (R_s), charge transfer resistance (R_{ct}), and double-layer capacitance (C_{dl}). The inhibition efficiency from EIS measurements was calculated using Eq. (5) [22]:

$$IE_{EIS}(\%) = \left(1 - \frac{\mathrm{R^0_{ct}}}{\mathrm{R_{ct}}}\right) \times 100 \quad (5)$$

where R^0_{ct} and R_{ct} represent the charge transfer resistance values in the absence and presence of the inhibitor, respectively. Increased charge transfer resistance and decreased double-layer capacitance were interpreted as

evidence of protective adsorption of inhibitor molecules on the mild steel surface.

2.5.3. Kinetic and thermodynamic analysis

The adsorption behaviour of *Dioscorea bulbifera* leaf extract on the mild steel surface was evaluated using the adsorption equilibrium constant K_{ads} and the standard Gibbs free energy of adsorption ΔG°_{ads}. The adsorption

equilibrium constant K_{ads} was calculated from the adsorption equilibrium relationship using the surface coverage values obtained from the gravimetric measurements, while the corresponding Gibbs free energy of adsorption ΔG°_{ads} was determined using Eq. (6) below [22], thereby providing insight into the spontaneity and nature of the adsorption process.

$$\Delta G^{\circ}_{ads} = -RT\ln(55.5K_{ads}) \quad (6)$$

where *R* is the universal gas constant (8.314 J mol^{-1} K^{-1}), *T* is the absolute temperature (K), and 55.5 is the molar concentration of water. Activation energy E_a for the corrosion process was determined from corrosion rate data obtained at different temperatures using the Arrhenius equation as illustrate in Eq. (7) [23]:

$$\ln(CR) = \ln A - \frac{E_a}{RT} \quad (7)$$

where *CR* is the corrosion rate, *A* is the Arrhenius pre-exponential factor, E_a is the activation energy (kJ mol^{-1}), *R* is the universal gas constant, and *T* is the absolute temperature. The half-life $t_{1/2}$ of mild steel in both inhibited and uninhibited media was also calculated using the first-order kinetic relationship to evaluate the durability of the protective film formed by the inhibitor using Eq. (8) below [23]:

$$t_{1/2} = \frac{0.693}{K} \quad (8)$$

where *K* is the first-order corrosion rate constant. Combining the adsorption parameters, activation energy, half-life, and electrochemical measurements enabled a comprehensive interpretation of the corrosion inhibition mechanism of *Dioscorea bulbifera* leaf extract.

3. Results and Discussion

3.1. Phytochemical analysis

The phytochemical screening presented in Table 1 revealed that *Dioscorea bulbifera* leaf extract contains several bioactive secondary metabolites, including alkaloids, flavonoids, saponins, tannins, phenolic compounds, terpenoids, glycosides, and steroids. The presence of these compounds indicates that the plant possesses numerous functional groups capable of interacting with mild steel surfaces through adsorption. Most of these phytochemicals contain heteroatoms such as oxygen and nitrogen together with conjugated π-electron systems, which facilitate the formation of protective adsorption films on metallic surfaces. Such adsorption decreases the active sites available for anodic metal dissolution and cathodic hydrogen evolution, thereby reducing the overall corrosion rate.

The quantitative phytochemical composition presented in Table 2 further confirms that the leaf extract contains appreciable concentrations of these corrosion-inhibiting constituents. Variations in the concentrations of individual phytochemicals are expected because plant metabolites are influenced by environmental conditions, geographical location, harvesting season, extraction method, and plant maturity. Nevertheless, the collective presence of these compounds contributes synergistically to the corrosion inhibition performance of the extract rather than the action of a single constituent [24].

Among the detected metabolites, flavonoids play an important role in corrosion inhibition because of their polyphenolic structures containing multiple hydroxyl groups. These hydroxyl groups readily coordinate with vacant d-orbitals of iron atoms, resulting in stable adsorption layers that isolate the metal surface from aggressive chloride ions present in hydrochloric acid. Furthermore, flavonoids possess strong antioxidant properties capable of scavenging reactive oxygen species and minimizing oxidative degradation of the metal surface.

Table 1. Qualitative phytochemical analysis of *Dioscorea bulbifera* leaf extract.

Phytochemicals	Observation	Bioavailability
Saponin	Persistent foaming	++
Flavonoid	A yellowish coloration	++
Carbohydrate	Brown ring formation at the interface	++
Phenol	A greenish coloration	+++
Reducing sugar	A brick red precipitate	+++
Tannin	A blue-black coloration	+++
Glycoside	A brick red coloration	+++
Steroid	Color change from violet to green	+++
Terpenoid	Terpenoid Color change from pink to violet	+++
Alkaloid	Ppt was formed	+++

Note: ++ = moderate level of bioavailability; +++ = high level of bioavailability.

This observation agrees with the findings of Medupin *et al.* [19], who reported that flavonoid-rich plant extracts generally exhibit superior inhibition efficiency because of enhanced electron donation and stable surface adsorption.

Phenolic compounds similarly contribute significantly to corrosion protection through their electron-rich aromatic rings and hydroxyl functional groups. These compounds increase the adsorption strength of the inhibitor molecules while simultaneously improving the stability of the protective film formed on the mild steel surface. Phenolic compounds have repeatedly been identified as major contributors to adsorption-controlled corrosion inhibition in acidic media due to their ability to donate lone-pair electrons to metallic surfaces [20,24].

Table 2. Quantitative phytochemical analysis of *Dioscorea bulbifera* leaf extract.

Phytochemical	Mean ± std (mg/100g)
Total phenolics	1121.02 ± 5.67
Total tannins	64.68 ± 1.08
Total flavonoid content	320.15 ± 1.83
Terpenoids	149.41 ± 3.64
Steroids	20.84 ± 0.13
Saponins	5.07 ± 0.86
Glycosides	50.38 ± 0.16
Reducing sugar	2410.87 ± 6.15
Carbohydrates	3223±3.95

The presence of tannins observed in Table 1 also supports the corrosion inhibition capability of the extract. Tannins are high molecular weight polyphenolic compounds capable of forming stable coordination complexes with iron ions produced during metal dissolution. This complexation process generates an insoluble protective layer that minimizes further contact between the corrosive electrolyte and the metal surface. Similar observations have been reported by Alrefaee *et al.* [25], who demonstrated that tannin-containing plant extracts effectively reduce corrosion through adsorption and metal chelation mechanisms.

Saponins detected may further enhance corrosion resistance through their amphiphilic molecular structures. These compounds readily adsorb onto metallic surfaces to produce compact molecular films that serve as physical barriers against aggressive ions. Their surfactant characteristics improve the uniformity of the adsorbed inhibitor layer and consequently enhance inhibition efficiency. Recent investigations have shown that saponin-rich extracts exhibit excellent corrosion inhibition because of improved surface coverage and stronger adsorption characteristics [26]. Alkaloids are another important group of phytochemicals identified in the extract. The nitrogen atoms present in alkaloid molecules possess lone pairs of electrons that readily coordinate with iron atoms on the metal surface. This interaction strengthens adsorption and promotes the formation of stable inhibitor films capable of reducing both anodic and cathodic electrochemical reactions. Nitrogen-containing organic compounds are widely recognized as effective adsorption centers for green corrosion inhibitors because they increase electron density at the metal–solution interface [24,27].

Terpenoids and steroids detected in the extract may also contribute to corrosion protection by increasing the hydrophobicity of the adsorbed layer. These relatively non-polar compounds reduce water permeability through the inhibitor film, thereby limiting electrolyte penetration and decreasing corrosion kinetics. Their synergistic interaction with other phytochemicals contributes to improved inhibition efficiency and greater stability of the protective film over extended immersion periods.

The combined presence of flavonoids, phenolics, tannins, alkaloids, saponins, terpenoids, glycosides, and steroids therefore provides a strong scientific explanation for the corrosion inhibition performance observed in the gravimetric and electrochemical investigations. These phytochemicals possess numerous adsorption centers and functional groups capable of donating electrons to the mild steel surface, resulting in the formation of an adsorbed protective barrier that minimizes metal dissolution in hydrochloric acid. Consequently, the phytochemical profile presented in Tables 1 and 2 confirms that *Dioscorea bulbifera* leaf extract possesses the necessary chemical

Table 3. Weight loss of mild steel at different inhibitor concentrations and immersion times.

	Concentrations (g/L)					
Time (*hrs*)	Blank	0.5	1.0	1.5	2.0	2.5
1	0.32	0.24	0.18	0.16	0.15	0.10
2	0.47	0.41	0.19	0.18	0.17	0.12
3	0.54	0.46	0.21	0.20	0.19	0.18
4	0.69	0.58	0.24	0.23	0.24	0.19
5	0.72	0.60	0.26	0.24	0.25	0.20

characteristics required of an efficient, environmentally friendly corrosion inhibitor.

3.2. Gravimetric (weight loss) analysis

The corrosion inhibition performance of *Dioscorea bulbifera* leaf extract was evaluated using the gravimetric (weight loss) method. The analysis focused on weight loss, corrosion rate, surface coverage, and inhibition efficiency to assess the effectiveness of the extract in mitigating mild steel corrosion in 0.5 M HCl. The results are listed in Table 3. The same concentration-dependent trend was observed across the immersion conditions examined in this study. Weight loss decreased as inhibitor concentration increased because a larger population of phytochemical molecules became available to occupy active corrosion sites on the mild steel surface. The resulting increase in surface coverage reduced the portion of the metal directly exposed to the acidic electrolyte and favoured formation of a more continuous protective film. This interpretation is consistent with the progressive increase in surface coverage and inhibition efficiency observed in Table 4 and with reports for other plant-derived inhibitors, in which increased inhibitor concentration enhanced adsorption and surface shielding [5–7,11–14].

As presented in Table 3, the blank solution (0 g/L inhibitor) recorded the highest weight loss throughout the immersion period, demonstrating the aggressive nature of hydrochloric acid toward mild steel. The continuous increase in weight loss with exposure time is expected because prolonged immersion allows more iron atoms to dissolve into the acidic medium through anodic oxidation reactions. In contrast, mild steel coupons immersed in solutions containing *Dioscorea bulbifera* extract experienced considerably lower weight losses, confirming that the phytochemical constituents of the extract effectively reduced metal dissolution by blocking active corrosion sites. The reduction became increasingly pronounced as inhibitor concentration increased from the lowest to the highest concentration investigated.

Table 4. Corrosion rate, inhibition efficiency, and degree of surface coverage at different inhibitor concentrations.

Conc.(g/l)	*CR*	*%I.E*	ɵ
Blank	0.0126	-	-
0.5	0.0103	19.17	0.1920
1.0	0.00718	42.40	0.4240
1.5	0.00577	52.90	0.5290
2.0	0.00433	62.40	0.6240
2.5	0.001843	83.48	0.8348

The reduction in weight loss can be attributed to the adsorption of phytochemical compounds such as flavonoids, tannins, alkaloids, saponins, terpenoids and phenolic compounds present in *Dioscorea bulbifera* leaves. These compounds contain oxygen-rich functional groups, nitrogen atoms and aromatic π-electron systems capable of interacting with vacant d-orbitals of iron atoms, thereby producing a compact protective barrier that isolates the mild steel surface from the corrosive hydrochloric acid solution. The phytochemical analyses conducted in the three studies consistently confirmed the abundance of these bioactive compounds, which are widely recognized as the active adsorption centers responsible for green corrosion inhibition.

Figure 3 further illustrates that weight loss increased almost linearly with immersion time for all experimental conditions. Nevertheless, the rate of increase became progressively smaller as inhibitor concentration increased. This behaviour indicates that although corrosion continued during prolonged exposure, the adsorbed inhibitor molecules substantially slowed the dissolution process by continuously occupying available active sites on the metal surface. The highest inhibitor concentration produced the lowest weight loss throughout the immersion period, suggesting greater surface coverage and improved stability of the adsorbed protective film. This trend demonstrates that increasing the availability of inhibitor molecules enhances adsorption efficiency until near-complete surface coverage is approached.

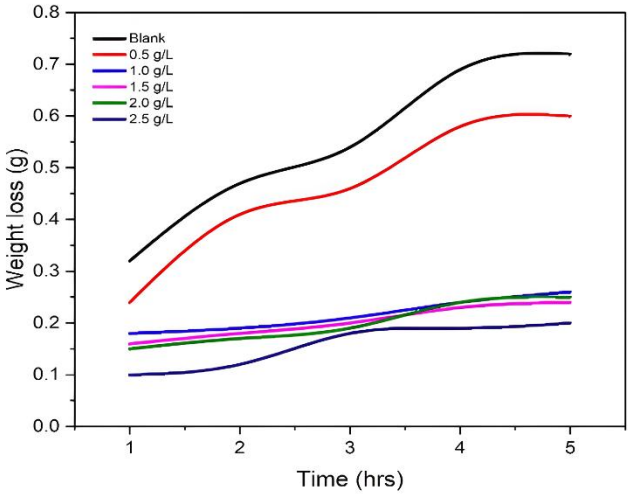


Figure 3. Variation of weight loss with immersion time at different concentrations of *Dioscorea bulbifera* leaf extract.

The observed behaviour also indicates that the inhibition mechanism is predominantly adsorption-controlled. As inhibitor concentration increases, a greater number of phytochemical molecules become available for adsorption, leading to the formation of a thicker and more compact protective film on the mild steel surface. Consequently, diffusion of aggressive chloride ions and hydrogen ions toward the metal surface becomes increasingly restricted, resulting in lower metal dissolution and reduced weight loss. Similar adsorption-controlled inhibition mechanisms have been widely reported for

plant-derived corrosion inhibitors in acidic environments [19,20].

The gravimetric results obtained in this study are further supported by the electrochemical investigations performed in the complementary study. The electrochemical measurements showed decreasing corrosion current density and increasing charge transfer resistance with increasing inhibitor concentration, confirming that the decrease in weight loss observed gravimetrically corresponds to improved electrochemical protection of the mild steel surface. The agreement between gravimetric and electrochemical techniques strengthens the reliability of the corrosion inhibition performance of *Dioscorea bulbifera* leaf extract.

The present findings agree with numerous recent studies on green corrosion inhibitors. Kumar and Yadav [13] reported that *Aloe vera* extract significantly reduced the weight loss of API 5L steel through concentration-dependent adsorption of phytochemicals. Similarly, Hussein and Khadom [28] observed that okra leaf extract effectively reduced weight loss and corrosion rate of steel in sulphuric acid, with inhibition efficiency increasing as inhibitor concentration increased. El Nemr *et al.* [29] likewise reported that camphor tree bark extract formed a protective adsorbed layer that significantly minimized metal dissolution in acidic media. Comparable observations were also reported by Zakeri *et al.* [9], who concluded that phytochemicals present in plant extracts are principally responsible for reducing corrosion through surface adsorption mechanisms.

The gravimetric results clearly demonstrate that *Dioscorea bulbifera* leaf extract functions as an effective green corrosion inhibitor for mild steel in hydrochloric acid solution. The progressive reduction in weight loss with increasing inhibitor concentration confirms that the extract provides significant protection by forming an adsorbed protective film, thereby minimizing direct interaction between the metal surface and the corrosive environment. The consistency of these findings with the phytochemical characterization, adsorption studies and electrochemical measurements provides strong evidence that *Dioscorea bulbifera* leaves represent a promising environmentally friendly alternative to conventional synthetic corrosion inhibitors.

The progressive reduction in weight loss with increasing inhibitor concentration can be attributed to the greater availability of phytochemical molecules for adsorption onto the mild steel surface. At higher extract concentrations, more inhibitor molecules can occupy previously exposed active sites, increasing surface coverage and reducing the area directly accessible to hydrochloric acid. Continued adsorption can also promote a more continuous and compact protective film, which restricts the transport of aggressive species to the metal/electrolyte interface and consequently lowers metal dissolution. Comparable concentration-dependent improvements have been reported for *Azadirachta indica*, *Mangifera indica*, *Vernonia amygdalina*, *Carica papaya*, *Moringa oleifera*, *Aloe vera*, and *Ocimum gratissimum* extracts on steel in acidic media [5–7,11–14].

The progressive decline in corrosion rate suggests that increasing concentrations of *Dioscorea bulbifera* leaf extract enhanced the adsorption of phytochemical constituents onto the mild steel surface, thereby reducing direct contact between the metal and the aggressive hydrochloric acid solution. The phytochemical analyses conducted in this study identified the presence of flavonoids, tannins, alkaloids, saponins, terpenoids, and other phenolic compounds, all of which possess functional groups capable of adsorbing onto the metal surface to form a compact protective barrier against corrosion [30].

The trend observed in Fig. 4 further confirms that corrosion rate is inversely proportional to inhibitor concentration. The most pronounced reduction occurred at 2.5 g L^{-1}, where the corrosion rate reached its minimum value of 0.001843 g m^{-2} h^{-1}, indicating that the inhibitor molecules achieved near-complete coverage of the active corrosion sites. This observation agrees with the electrochemical measurements (PDP and EIS), which showed improved corrosion resistance with increasing inhibitor concentration, thereby validating the gravimetric results.

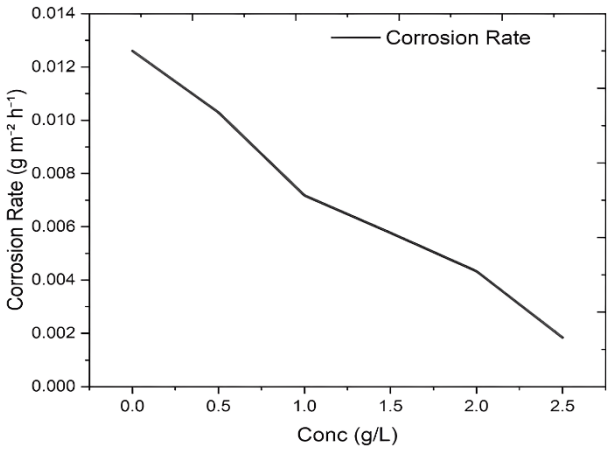


Figure 4. Effect of inhibitor concentration on corrosion rate.

The present findings are consistent with previous studies reporting that increasing the concentration of plant-based corrosion inhibitors significantly decreases the corrosion rate of mild steel through adsorption mechanisms. Kumar and Yadav [13] reported a similar concentration-dependent reduction in corrosion rate for *Aloe vera* extract, while Zakeri *et al.* [9] and Medupin *et al.* [19] concluded that phytochemical-rich plant extracts

effectively inhibit corrosion by forming protective adsorbed films on metal surfaces [31]. Therefore, the observed decrease in corrosion rate demonstrates that *Dioscorea bulbifera* leaf extract is an efficient, environmentally friendly corrosion inhibitor for mild steel in acidic media.

The degree of surface coverage (ϑ) increased progressively with increasing concentration of *Dioscorea bulbifera* leaf extract, indicating improved adsorption of the inhibitor molecules onto the mild steel surface. As shown in Table 4 and Fig. 5, no surface coverage was observed in the blank solution because no inhibitor molecules were present to adsorb onto the metal surface. However, upon the addition of the extract, the surface coverage increased from 0.1920 at 0.5 g/L to 0.4240 at 1.0 g/L, representing more than a two-fold increase in the fraction of the metal surface protected by the inhibitor. A further increase in inhibitor concentration resulted in θ values of 0.5290, 0.6240, and 0.8348 at 1.5, 2.0, and 2.5 g/L, respectively, demonstrating continuous improvement in surface protection with increasing extract concentration. The highest surface coverage of 0.8348 indicates that approximately 83.5% of the mild steel surface was covered by adsorbed inhibitor molecules at 2.5 g/L, leaving only a small portion of the surface exposed to the corrosive hydrochloric acid solution [32,33].

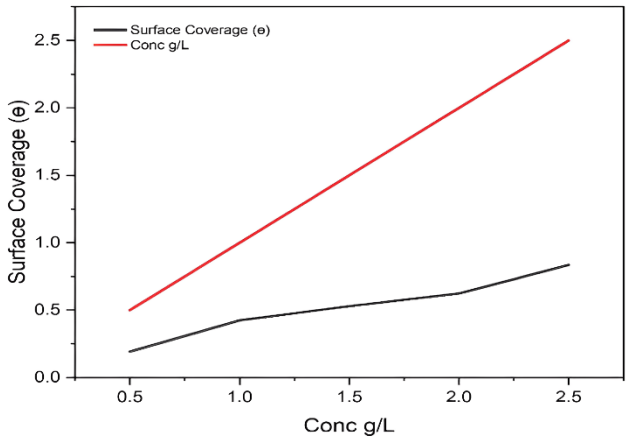


Figure 5. Effect of inhibitor concentration on surface coverage (ϑ).

The steady increase in ϑ with inhibitor concentration confirms that the corrosion inhibition process is governed by adsorption of phytochemical constituents present in *Dioscorea bulbifera* leaf extract. Phytochemicals such as flavonoids, tannins, alkaloids, saponins, and terpenoids contain oxygen- and nitrogen-containing functional groups together with π-electron systems that readily adsorb onto the mild steel surface, forming a compact protective film that limits contact between the metal and the acidic medium. The phytochemical analyses reported in the three complementary studies support this adsorption mechanism by confirming the presence of these bioactive compounds in the extract [34–36].

The progressive increase in surface coverage corresponds well with the observed reduction in weight loss and corrosion rate, as well as the increase in inhibition efficiency, indicating that greater adsorption resulted in improved corrosion protection. Similarly, the electrochemical studies showed enhanced charge-transfer resistance and reduced corrosion current density with increasing inhibitor concentration, further confirming the formation of a stable protective film on the mild steel surface.

These findings are consistent with previous reports that surface coverage increases with inhibitor concentration because a larger number of phytochemical molecules become available for adsorption onto the metal surface [9,17,19]. Therefore, the high ϑ value of 0.8348 obtained at 2.5 g/L demonstrates the excellent adsorption capability of *Dioscorea bulbifera* leaf extract and confirms its potential as an effective and environmentally friendly corrosion inhibitor for mild steel in hydrochloric acid solution.

The inhibition efficiency of *Dioscorea bulbifera* leaf extract increased progressively with increasing inhibitor concentration, indicating enhanced corrosion protection of mild steel in 0.5 M HCl. As presented in Table 4 and Fig. 6, the inhibition efficiency increased from 19.17% at 0.5 g/L to 42.40% at 1.0 g/L, representing more than a two-fold improvement in corrosion protection. A further increase in concentration to 1.5 g/L and 2.0 g/L resulted in inhibition efficiencies of 52.90% and 62.40%, respectively, demonstrating the continued effectiveness of the extract in suppressing mild steel corrosion. The highest inhibition efficiency of 83.48% was obtained at 2.5 g/L, indicating that this concentration provided the maximum protection among the concentrations investigated.

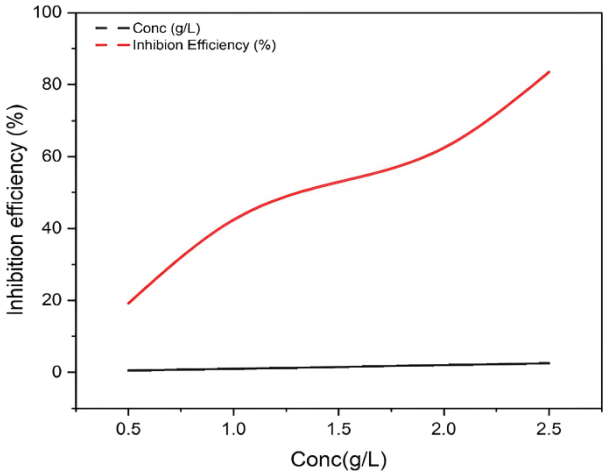


Figure 6. Variation of inhibition efficiency with inhibitor concentration.

The steady improvement in inhibition efficiency suggests that increasing the concentration of *Dioscorea bulbifera* leaf extract enhanced the availability of active phytochemical constituents capable of protecting the mild steel surface from acid attack. The remarkable increase of approximately 64 % between 0.5 g/L (19.17%) and 2.5 g/L (83.48%) demonstrates that the corrosion inhibition performance is strongly concentration-dependent. This trend is consistent with the reductions observed in weight loss and corrosion rate, confirming that higher extract concentrations provide more effective corrosion protection [37,38].

Furthermore, the inhibition efficiency exceeding 80% at 2.5 g/L indicates that *Dioscorea bulbifera* leaf extract is a highly effective green corrosion inhibitor for mild steel in acidic media. The electrochemical investigations (PDP and EIS) reported in the complementary study support these gravimetric findings by showing improved electrochemical behaviour at higher inhibitor concentrations, confirming the formation of a stable protective barrier on the mild steel surface. The observed concentration-dependent increase in inhibition efficiency agrees with recent findings by Hossain *et al.* [39], Lavanya [40], and Al-Moubaraki *et al.* [41], who reported that plant-derived corrosion inhibitors generally exhibit improved protective performance with increasing inhibitor concentration due to enhanced surface shielding and stronger interaction between inhibitor molecules and the metal surface. Therefore, the results demonstrate that *Dioscorea bulbifera* leaf extract possesses significant potential as an environmentally sustainable corrosion inhibitor for mild steel exposed to acidic environments.

3.3. Electrochemical studies

EIS and PDP techniques were employed to evaluate the corrosion inhibition behaviour of *Dioscorea bulbifera* leaf extract on mild steel in 0.5 M HCl. These complementary techniques provide information on the electrochemical characteristics and inhibition mechanism of the extract. The Nyquist plots for mild steel in 0.5 M HCl containing different concentrations of *Dioscorea bulbifera* (DB) leaf extract are presented in Fig. 7, while the corresponding electrochemical parameters are summarized in Table 5. The diameter of the capacitive semicircle increased progressively with increasing inhibitor concentration, indicating enhanced corrosion resistance due to adsorption of the inhibitor molecules on the mild steel surface. The charge transfer resistance (R_{ct}) increased significantly from 32.1 Ω cm² for the blank solution to 253.8 Ω cm² at 2.0 g L^{-1}, confirming that the extract effectively hindered electron transfer across the metal–electrolyte interface. Conversely, the double-layer capacitance (C_{dl}) decreased from 103.5 to 8.5 µF cm^{-2}, suggesting displacement of water molecules by adsorbed phytochemical constituents and the formation of a compact protective film on the steel surface [42].

Table 5. EIS parameters of mild steel in 0.5 M HCl in the absence and presence of DB at various concentrations and 30 °C.

Conc. (g L^{-1})	R_s (Ω cm^2)	R_{ct} (Ω cm^2)	C_{dl} (µF cm^{-2})	*n*	IE_{EIS} (%)
Blank	1.57	32.1	103.5	0.904	-
0.5	1.26	63.7	72.6	0.921	49.6
1.0	1.60	98.5	48.2	0.938	67.4
1.5	1.71	189.2	23.9	0.959	83.0
2.0	1.92	253.8	8.5	0.967	87.4

Note: R_s = solution resistance; R_{ct} = charge-transfer resistance; C_{dl} = double-layer capacitance; *n* = constant-phase-element exponent; IE_{EIS} = inhibition efficiency determined from EIS.

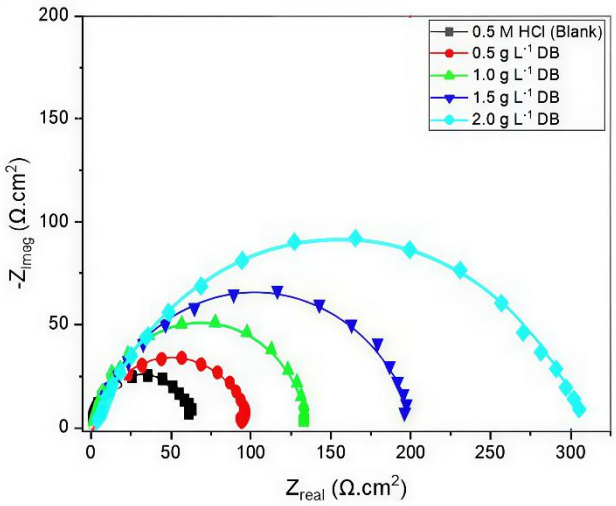


Figure 7. Nyquist plots for mild steel in 0.5 M HCl solution without and with different concentration of *Dioscorea bulbifera*.

The inhibition efficiency obtained from EIS increased from 49.6% to 87.4% with increasing inhibitor concentration, demonstrating that corrosion protection is concentration dependent. Similar increases in charge transfer resistance and corresponding decreases in double-layer capacitance have been reported for plant-based corrosion inhibitors such as *A. indica*, *Moringa oleifera*, and *V. amygdalina*, where adsorption of flavonoids, tannins, and phenolic compounds produced an insulating barrier that suppressed charge transfer

reactions [4,20,43]. Likewise, Obot and Umoren [22] reported that increasing inhibitor concentration enhanced the protective surface film, resulting in improved corrosion resistance. The increase in the constant phase element exponent (*n*) from 0.904 to 0.967 further suggests the formation of a more homogeneous and less porous adsorbed film.

The potentiodynamic polarization curves shown in Fig. 8 and the electrochemical parameters presented in Table 6, demonstrate that the addition of *Dioscorea bulbifera* leaf extract significantly reduced the corrosion current density (I_{corr}) of mild steel in 0.5 M HCl. The corrosion current density decreased markedly from 847.5 µA cm^{-2} for the blank solution to 69.7 µA cm^{-2} at 2.0 g L^{-1}, while the inhibition efficiency increased to 91.8%, indicating excellent corrosion protection.

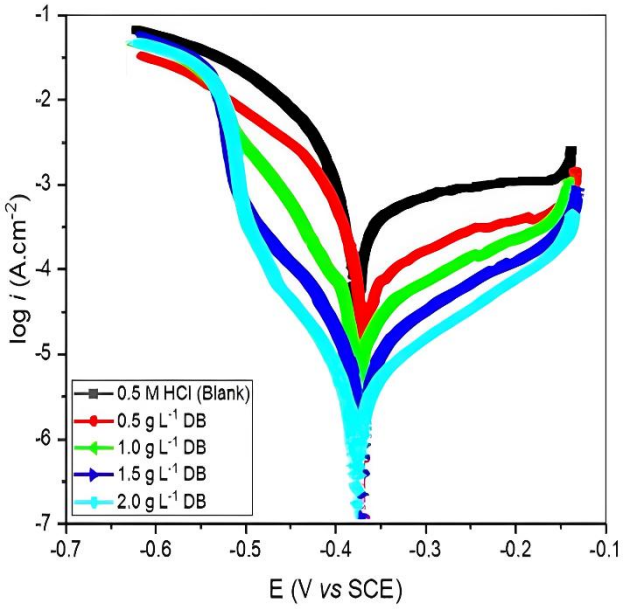


Figure 8. Potentiodynamic polarization curves of mild steel in 0.5 M HCl without and with different concentrations of Dioscorea bulbifera leaf extract.

Only slight changes were observed in the corrosion potential (E_{corr}), with a maximum shift of less than 85 mV relative to the blank solution. According to Ferreira *et al.* [21], such a small displacement in E_{corr} indicates that the inhibitor functions as a mixed-type inhibitor inhibitor, suppressing both anodic metal dissolution and cathodic hydrogen evolution reactions. This conclusion is further supported by the simultaneous reduction in both the anodic (βa) and cathodic (βc) Tafel slopes, suggesting that the extract modified the kinetics of both electrochemical reactions without preferentially affecting either process [41].

The observed decrease in corrosion current density and increase in inhibition efficiency are consistent with previous studies on green corrosion inhibitors. Verma *et al.* [20], Maduelosi *et al.* [42], and Maduelosi and Nakara [43] reported that phytochemical-rich plant extracts significantly reduced corrosion current density through adsorption of oxygen- and nitrogen-containing compounds onto the metal surface. Similarly, Eddy and Ebenso [44] and Medupin *et al.* [19] attributed the high inhibition efficiencies of plant extracts to the formation of stable adsorbed films by flavonoids, alkaloids, tannins, and phenolic compounds, which effectively isolate the metal from the corrosive environment. The high inhibition efficiency achieved by *Dioscorea bulbifera* leaf extract (91.8%) therefore demonstrates its strong potential as an environmentally friendly corrosion inhibitor for mild steel in acidic media. Furthermore, the close agreement between the PDP and EIS results confirms the reliability of the electrochemical measurements and supports the proposed adsorption-controlled inhibition mechanism [5,12,45].

3.4. Kinetic and thermodynamic analysis

Kinetic and thermodynamic analyses were conducted to provide further insight into the corrosion inhibition mechanism of *Dioscorea bulbifera* leaf extract on mild steel in 0.5 M HCl. The kinetic parameters, including activation energy (E_a), rate constant (K), and half-life ($t½$), were evaluated to assess the effect of the extract on the corrosion process, while the thermodynamic parameters, namely the adsorption equilibrium constant (K_{ads}) and Gibbs free energy of adsorption ($\Delta G°_{ads}$), were used to examine the adsorption behaviour and spontaneity of the inhibition process.

The kinetic parameters obtained for the corrosion of mild steel in 0.5 M HCl containing varying concentrations of *Dioscorea bulbifera* leaf extract are presented in Table 7. The activation energy (E_a), corrosion rate constant (K), half-life ($t_{½}$), and regression coefficient (R^2) were used to evaluate the effect of the extract on the corrosion process.

As shown in Table 7, the activation energy varied between 44.61 and 59.78 kJ mol^{-1} in the presence of the extract, compared with 60.00 kJ mol^{-1} for the uninhibited solution. Although slight fluctuations were observed with increasing inhibitor concentration, the generally high activation energy values indicate that the extract increased the energy barrier for the corrosion reaction, thereby retarding the dissolution of mild steel. This behaviour is characteristic of green corrosion inhibitors that adsorb onto the metal surface to reduce the rate of the electrochemical corrosion process [20,22]. The corrosion rate constant (K) decreased progressively from 0.01234 × 10^{-3} h^{-1} for the blank solution to 0.00285 × 10^{-3} h^{-1} at 2.5 g L^{-1} of the extract. The continuous reduction in the rate constant with increasing inhibitor concentration demonstrates that the phytochemical constituents of *Dioscorea bulbifera* effectively suppressed the corrosion

reaction by forming a protective adsorbed layer on the mild steel surface.

A corresponding increase in the half-life ($t_{½}$) of the mild steel specimens was also observed, rising from 54.14 h in the uninhibited solution to 242.65 h at the highest inhibitor concentration. The longer half-life indicates that the metal required a considerably longer time to undergo corrosion in the presence of the extract, confirming its protective effect. This increase in half-life is consistent with the decrease in corrosion rate constant and further demonstrates that increasing inhibitor concentration enhances the stability of the adsorbed protective film. The regression coefficients (R^2) ranged from 0.683 to 0.999, with most values exceeding 0.90, indicating a good fit of the experimental data to the adopted kinetic model [23]. The kinetic parameters confirm that *Dioscorea bulbifera* leaf extract effectively reduces the corrosion kinetics of mild steel in hydrochloric acid, with the greatest protection achieved at higher inhibitor concentrations.

Table 7. Kinetic parameters for mild steel corrosion in 0.5 m HCl containing *Dioscorea bulbifera* leaf extract

Conc. (g/L)	E_a (KJmol^{-1})	K (h^{-1})	$t^{1/2}$ (h)	R^2
Blank	60.00	0.01234	54.14	0.999
0.5	58.97	0.01027	67.48	0.683
1.0	44.61	0.00517	134.02	0.970
1.5	49.11	0.00458	151.18	0.929
2.0	55.43	0.00400	172.90	0.941
2.5	59.78	0.00285	242.65	0.999

The adsorption thermodynamic parameters of *Dioscorea bulbifera* leaf extract on mild steel in 0.5 M HCl are presented in Table 8 below. The adsorption equilibrium constant (K_{ads}) increased from 2.227 at 303 K to 12.195 at 313 K, indicating enhanced adsorption of the inhibitor molecules on the mild steel surface with increasing temperature. The increase in K_{ads} reflects a stronger affinity of the phytochemical constituents for the metal surface, leading to the formation of a more stable and protective adsorbed film that effectively suppresses the corrosion process [20].

Table 8. Adsorption thermodynamic parameters of *Dioscorea bulbifera* leaf extract on mild steel in 0.5 M HCl.

T (K)	K_{ads}	R^2	$\Delta G°_{ads}$ (kJ mol^{-1})
303	2.227	0.911	−12.3
313	12.195	0.978	−19.9

The Gibbs free energy of adsorption ($\Delta G°_{ads}$) was negative at both temperatures, with values of −12.3 kJ mol^{-1} and −19.9 kJ mol^{-1} at 303 K and 313 K, respectively. The negative values confirm that the adsorption process was spontaneous and thermodynamically favourable. Furthermore, the magnitude of $\Delta G°ads$, being less than 20 kJ mol^{-1}, suggests that the inhibition mechanism was predominantly governed by physical adsorption (physisorption) through electrostatic interactions between the protonated phytochemical constituents of the extract and the charged mild steel surface [22,44].

The more negative $\Delta G°_{ads}$ value at 313 K indicates stronger adsorption of the inhibitor molecules at elevated temperature, which is consistent with the observed increase in K_{ads}. The regression coefficients (R^2) of 0.911 and 0.978 indicate a good correlation between the experimental data and the adsorption model employed, demonstrating that the calculated thermodynamic parameters adequately describe the adsorption behaviour of *Dioscorea bulbifera* leaf extract on mild steel. The thermodynamic results confirm that the extract acts as an effective green corrosion inhibitor through spontaneous adsorption and the formation of a protective surface film.

The corrosion inhibition performance of *Dioscorea bulbifera* leaf extract can be attributed to the combined adsorption of its phytochemical constituents, including flavonoids, tannins, alkaloids, saponins, phenolics, and terpenoids. These constituents contain electron-rich oxygen- and nitrogen-containing functional groups and conjugated π-electron systems that can participate in donor–acceptor interactions with surface iron atoms. Literature on plant-derived and organic corrosion inhibitors indicates that lone-pair electrons on heteroatoms and π-electrons of aromatic or unsaturated systems can interact with vacant d-orbitals of iron, while protonated inhibitor species can also participate in electrostatic interactions at the metal/electrolyte interface [7–10,13,14]. Such adsorption blocks active surface sites and reduces access of the acidic electrolyte to the steel surface. In the absence of the inhibitor, mild steel undergoes anodic dissolution according to Eq. (9) [1]:

$$Fe \rightarrow Fe^{2+} + 2e^- \quad (9)$$

while the cathodic reaction in hydrochloric acid is dominated by hydrogen evolution in Eq. (10) [1]:

$$2H^+ + 2e^- \rightarrow H_2(g) \quad (10)$$

the overall corrosion process is therefore described in Eq. (11) [1]:

$$Fe + 2HCl \rightarrow FeCl_2 + H_2 \quad (11)$$

Upon the addition of *Dioscorea bulbifera* extract, the phytochemical molecules can adsorb onto the mild steel surface through a combination of electrostatic interactions

and donor–acceptor interactions involving heteroatom lone pairs and π-electrons. The latter interactions with surface iron provide a plausible contribution to film formation, while the thermodynamic data obtained in this study indicate that the overall adsorption is predominantly physical rather than exclusively chemisorptive. The adsorbed layer therefore acts as a barrier that blocks active corrosion sites and restricts both iron dissolution and hydrogen evolution, consistent with mechanisms proposed for plant-derived inhibitors on mild steel [8–11,14].

The proposed mechanism is supported by the experimental results obtained in this study. Gravimetric measurements showed progressive reductions in weight loss and corrosion rate together with increased inhibition efficiency and surface coverage as inhibitor concentration increased. In the electrochemical measurements, R_{ct} increased from 32.1 to 253.8 Ω cm² and C_{dl} decreased from 103.5 to 8.5 µF cm^{-2}, indicating increasing resistance to charge transfer and replacement of interfacial water by adsorbed inhibitor species. PDP measurements also showed a decrease in I_{corr} from 847.5 to 69.7 µA cm^{-2}, while the small E_{corr} displacement (<85 mV) and simultaneous changes in the anodic and cathodic Tafel slopes support mixed-type inhibition. Together, these observations are consistent with progressive adsorption and development of a protective film at the mild steel/acid interface [6,8–11].

Furthermore, the increase in K_{ads} and the negative Gibbs free energy values ($\Delta G°_{ads}$ = −12.3 to −19.9 kJ mol^{-1}) demonstrate that adsorption was spontaneous and predominantly physical. The corresponding increase in half-life and decrease in the corrosion rate constant indicate that the adsorbed film retarded corrosion kinetics. Thus, the experimental and thermodynamic evidence supports a predominantly physisorption-controlled inhibition process, with heteroatom and π-electron interactions contributing to the adsorption of the extract constituents and stabilization of the protective surface film [8–10].

4. Conclusion

Dioscorea bulbifera leaf extract effectively inhibited mild steel corrosion in hydrochloric acid. Increasing inhibitor concentration reduced weight loss and corrosion rate while increasing surface coverage and inhibition efficiency, with maximum gravimetric efficiency of 83.48% at 2.5 g L^{-1}. Electrochemical measurements confirmed the protective effect through increased charge-transfer resistance, decreased double-layer capacitance, and a maximum PDP inhibition efficiency of 91.8%. The negative $\Delta G°_{ads}$ values indicated spontaneous adsorption, predominantly through physisorption. Overall, the combined gravimetric, electrochemical, kinetic, and thermodynamic results demonstrate that *Dioscorea bulbifera* leaf extract forms an adsorbed protective film and has potential as a green inhibitor for mild steel in acidic environments.

Author contributions

Ngozi Jane Maduelosi conceptualized the study, conducted the literature review, performed the experimental laboratory work, analysed and interpreted the data, and prepared the initial manuscript. **Uchenna Samson Eze** provided technical guidance, reviewed the research findings, and contributed to manuscript refinement. **Emeka Emmanuel Joseph** provided academic supervision, critically reviewed the manuscript, and contributed to its revision and refinement. All authors reviewed and approved the final version of the manuscript.

Conflicts of interest

The author declares no competing interests.

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