

Phytochemical and Gravimetric Analysis of Aqueous Extract of *Bryophyllum pinnatum* as a Green Corrosion Inhibitor for Cold-Rolled Steel in 1 M HCl

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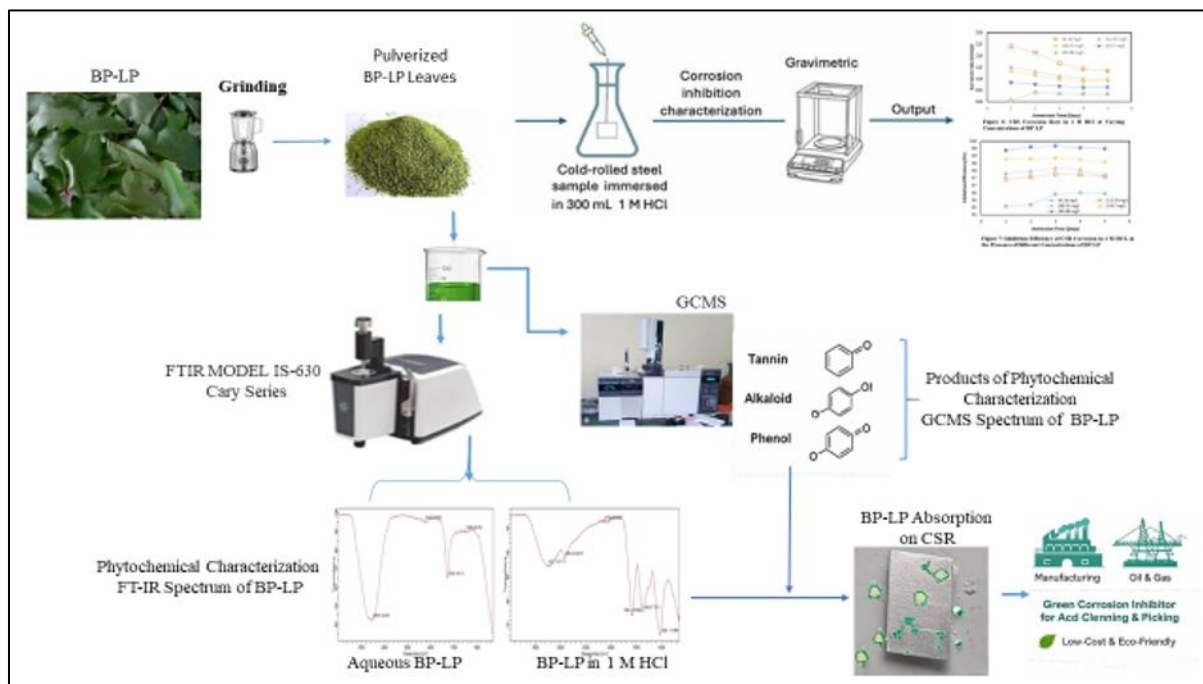
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Abstract

Bryophyllum pinnatum (BP-LP) – a Life Plant used as an herbal remedy for various ailments has been evaluated as Cold Rolled Steel (CRS) corrosion inhibitor in Hydrochloric acid environment. Fourier Transform infrared (FTIR) and Gas Chromatography Mass Spectrometry (GCMS) were used to characterize the aqueous extracts of BP-LP to determine its phytochemical content, while gravimetric analysis was done to determine the potency of BP-LP as a green corrosion inhibitor. The results of FTIR and GCMS showed that BP-LP contains phytochemical organic compounds such as - Tannin, Alkaloid, Phenol with functional groups – N - H stretch, C = O stretch, C = C aromatic stretch that contain heteroatoms (O, N, P,) and conjugated bonds - C = C – H that support the adsorption of molecules on CRS surface. The study on the inhibition efficiency of aqueous extract of BP-LP in the corrosion of CRS in 1 M HCl environment using gravimetric measurement reveal that BP-LP is an inhibitor of CRS corrosion in HCl environment. The study further showed the inhibition efficiency of BP-LP increased with increase in the concentration of BP-LP with a record of 94% inhibition efficiency. The findings highlight the potential of aqueous extract of BP-LP as a low-cost, eco-friendly green corrosion inhibitor for acid cleaning and pickling processes in manufacturing and oil and gas industries.

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Graphical Abstract



Keywords: *Bryophyllum pinnatum*; Inhibitor; Plant Extract; Phytochemical Characterization; Gravimetric; Aqueous Extraction.

1. Introduction

The acceptance and trial of plant extracts as green corrosion inhibitors of metals and their alloys by researchers has increased over the years [1-3]. This is first driven by the need to reduce the impact of synthesized **inhibitors** on the immediate environment, human lives and the eco-system, while reducing the degradation of substrates. Then, there is also the need to reduce the economic implications of corrosion control and the need for adaptability, availability, and abundance of alternatives in nature [4,5]. To address these needs, several researchers have explored the use of biopolymers and extracts from plants. Narrowing in on plants, researchers have used different parts of plants – leaf, stem bark, roots, flower, and other parts of plants to develop green inhibitors [4,5]. The health and environmental advantage of plant based inhibitors over synthesized organic inhibitors gives the reason for the wide acceptability of plant based corrosion inhibitors [4-6]. While synthesized inhibitors are toxic to humans and the environment, plant based inhibitors are natural and organic like their source. They decompose without damage to the environment [7, 8]. Several studies have turned up positive outcomes in corrosion inhibition using plants extracts, and most of the successes recorded with the use of plant extracts have been attributed to the presence of phytochemical compounds - Tannin, Alkaloid, Phenol molecules that contain - C = O, - N - H [7 - 10], the presence of conjugated bonds - C = C - H, C = C, aromatics, -C≡N, >C=C<, >C=N-, -N=N-, -N=O, and those that contain heteroatoms (O, N, P) [2,11,12,13].

Non aqueous extract of *Bryophyllum Pinattum* (BP-LP), Figure 1, have been reported as containing these functional groups and atoms that support BP-LP molecular adsorption on mild steel [12,13,14]. In 2015 Verma [12] reported that 10 g of the BP-LP extract was refluxed in 0.5 HCl solution for 4 hours. The resulting solution was Filtered and the filtrate was made up to 100 ml and used as the stock solution for the study. Another researcher, Kolo et al., [13] in 2018 used ethanol as the extraction medium. Kolo et al reported that the filtrate was evaporated and 0.1 0.2, 0.3, 0.4 and 0.5g of the solid residue was dissolved in 250 ml solution of 0.1 M H₂SO₄. In this study, aqueous extraction of BP-LP (Figure 1) was carried out. The use of aqueous extraction method for extraction of specific plants components have been demonstrated in different studies, such as the extraction of Tannin, Alkaloid, and Phenol [15,16,17,18,19,20] In order to assess the efficacy of aqueous extracts of BP-LP as an inhibitor for CRS corrosion in HCl environment, this study characterized the aqueous extract of BP-LP, identified the phytochemical composition and any organic compounds and heteroatoms in extracts of BP-LP that facilitates BP-LP adsorption on the surface of CRS. The study also measured the inhibition efficiency of BP-LP through gravimetric analysis.



Figure 1 *Bryophyllum Pinnatum* leaf

2. Materials and Methods

2.1. Materials

Analytical grades of Hydrochloric acid, 98% Ethanol, and 98% Acetone were purchased and used without further treatment. Using the conventional dilution approach, a 1 M HCl solution was prepared and kept as the experiment's stock solution. PARSTAT-2273 Advanced Electrochemical System with PowerSuite software and XL-30FEG scanning electron microscope was used for BP-LP morphology study. BP-LP leave was collected from Rivers State University farm. CRS was sourced from the steel market in Port Harcourt.

2.2. Methods

2.2.1. Plant Extract Preparation

The experimental specimens were prepared following International standard [21] and as previously reported [22,23]. BP-LP leaves collected from RSU Farm were treated as described by Izionworu et al., [23]. The dried leaves grinded, sieved with a 75 μ sieve and 20 g of it soaked for 48 hours in 2 L of cold deionized water. The solution was occasionally stirred. Whatman filter paper was used to filter the solution containing BP-LP. There were three iterations of the filtration procedure. The filtrate was increased to 2000 milliliters by adding distilled water. The end product was inhibitor stock that was refrigerated for preservation. 56.175, 112.35, 168.53, 224.70 and 280.88 mg/L concentrations of the extract were used for the experimental work at ambient temperature.

The stock BP-LP extract concentration was calculated using expression (1) as previously reported [2].

$$Q_{ex} = W_{q1} - (W_{q3} - W_{q2}) \quad (1)$$

Where Q_{ex} represent the stock BP-LP inhibitor concentration in 2000 ml double distilled water, W_{q1} – Original weight of dissolved BP-LP in the 2000 ml double distilled water, W_{q2} - weight of the 110 mm diameter filter paper alone, W_{q3} - residue of BP-LP plus 110 mm diameter filter paper.

2.2.2. Characterization of Extract of BP-LP

BP-LP extracts were identified and characterized using Fourier Transform Infrared Spectroscopy and Gas Chromatography – Mass Spectrometry (GC-MS). An IS-630 Cary Series Model Agilent Technologies' FTIR running at 400–4000 nm wavelength was employed. The protective layer that was seen on the CRS's surface after 72 hours and the spectra for the inhibitors under study were obtained in the manner that is detailed by [22,23,24]. The Agilent 6890 gas chromatograph with a 5973 MS detector and a 60 m x 0.25 mm, i.d. 0.25 μ m/MS DB-WAX capillary column (Agilent) was used to perform the gas chromatography analysis [24]. To determine the phytochemical components, present in the sample of BP-LP, the resulting mass chromatogram spectral peak value were compared with known chromatogram peak value from the database of National Institute of Science and Technology (NIST) 2014. Then, the details about their molecular formula, molecular weight, retention time and percentage content were also obtained [22,23,24].

2.2.3. Cold-Rolled Steel Coupon preparation

Substrates of cold-rolled steel (CRS) were employed. The CRS had a density of 7.86 g/cm³ and was composed of 98.97% Fe, Mn = 0.6, P = 0.35, Si = 0.03, and C = 0.05%. The metal was mechanically press-cut into coupons of 3 cm x 3 cm x 0.14 cm for weight Loss measurement. Each coupon was cleaned mechanically by scrubbing with emery paper (#200 to #1000), and put through a chemical cleaning procedure [22, 24]) that involved degreasing with acetone and drying with ethanol. After that, they were double dried in hot air. Before being used, the treated coupons were kept in a desiccator and further dried with warm air.

2.2.4. Gravimetric Measurement

The gravimetric analysis was carried out according to ASTM, 2004 and Izionworu et al. [22]. To ensure dependability, three CRS coupons were dipped into a batch reactor at room temperature (28 ± 1), and the weight loss was calculated from the mean measurement. Using the formula (2), the corrosion rate (C_r) of CRS in the test solution was calculated in millimeters per year (mm/y).

$$C_r = 87,600\Delta W/\rho At \quad (2)$$

Where the surface area and contact time (hours) are represented by A and t respectively, ρ is the CRS density (g/cm³), and ΔW is the change in weight (g). For every exposure time, the surface of CRS covered by BP-LP (θ) and efficiency of BP-LP as inhibitor (IE%) were calculated via expressions (3) and (4), respectively.

$$\theta = (1 - (C_r^{inh}/C_r^{blk})) \quad (3)$$

$$IE\% = (1 - (C_r^{inh}/C_r^{blk})) \times 100\% \quad (4)$$

3. Results and Discussion

3.1. Characterization of Aqueous Extracts of BP-LP

3.1.1. FTIR Classification of Aqueous Extracts of BP-LP

Figures 2 and 3 presents the infrared spectra of the BP-LP in water and BP-LP in 1 M HCL solution, respectively. The suggested interpretations of the spectrums are presented in Table 2 for BP-LP dissolved in water, while Table 3 shows the data set for BP-LP dissolved 1 M HCl solution. The result shows presence of very strong (vs) C-O-C asymmetric stretch, O - H stretch, COOH dimmers and nitrogen to hydrogen (N-H) bonds of amines. These indicate presence of amines (Alkaloid) and other functional groups of - aromatics, aliphatic, and aldehydes having heteroatoms - oxygen (O), Sulphur (S), Nitrogen (N), and conjugated bonds in BP-LP extract. These polar functional groups adsorbs on the surface of metals are present (Coates in 2000) [10,22,23].

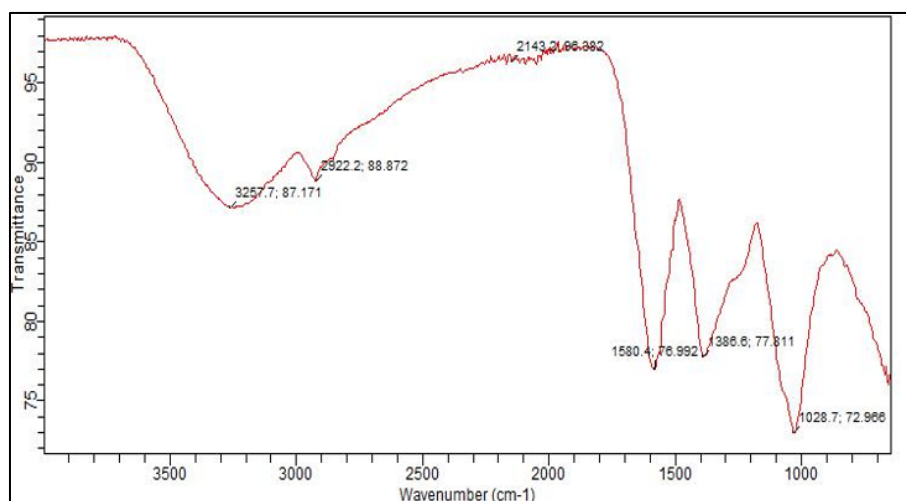


Figure 2 FT-IR Spectrum of BP-LP in Water

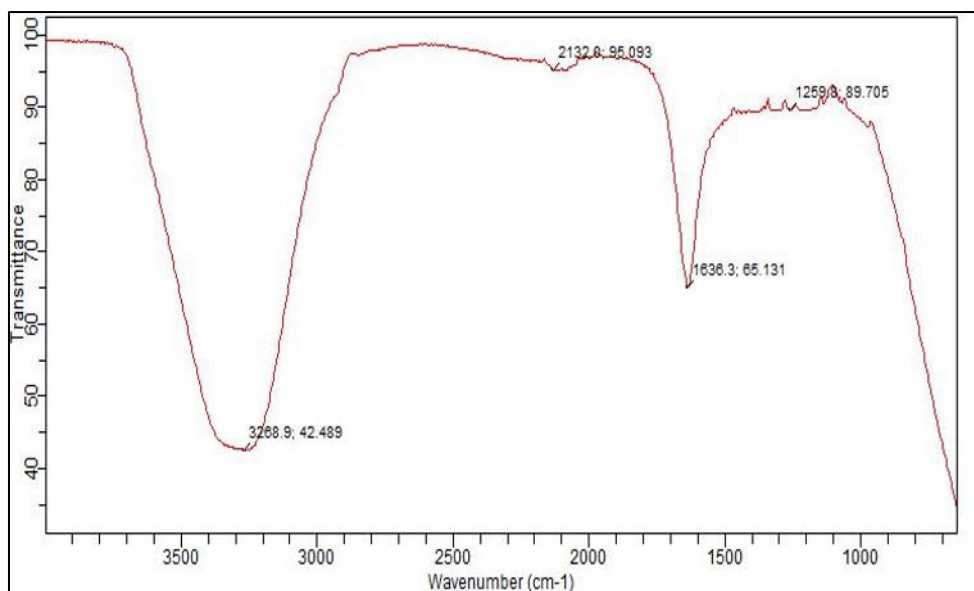


Figure 3 FT-IR Spectrum of BP-LP in 1 M HCl Solution

Table 1 Analysis of FT-IR Spectra of BP-LP in Deionized Water

Peaks (Vcm ⁻¹)	Likely Functional Groups
1028.7	C-O stretch (v) C - C skeletal vibration (iv)
1386.6	C - H bending, aliphatic (v)
1580.4	N - H bend (v) C = C aromatic stretch (m)
2922.2	COOH dimmers (w, br), alkanes (v), C - H stretch Two bands, C - H stretch, aldehydes (w) O - H stretch
3267.7	COOH dimmers (w, br), Amines, N - H stretch O - H stretch C = C - H (sh), C - H stretch H - bonded, O - H stretch (br)

Table 2 Analysis of FT-IR Spectra of BP-LP in Acidic Media

Peaks (Vcm^{-1})	Likely Functional Groups
1259.8	C - O - C asymmetric stretch (vs) C - O Stretch (v) C - C skeletal vibration (w)
1636.3	C = O stretch (v) could be an aliphatic amide C = C stretch, alkenes (v) C = C stretch, Ar - C = C (w-m) N - H bend (v) C = C aromatic stretch (m)
3268.9	N - H stretch, amines O - H stretch, COOH dimmers (w, br) C = C - H (sh), C - H stretch, O - H stretch (br), H - bonded

Based on the comparative analysis of FT-IR spectra of BP-LP in deionized water (Table 1) and acidic HCl media (Table 2), 1 M HCl significantly alters the phytochemical functional groups of *Bryophyllum pinnatum* (BP-LP) extract, indicating protonation and structural modifications that enhance corrosion inhibition. Table 3 presents a summary of the key changes observed.

A summary of Tables 1 and 2, with focus on the likely impact of 1 M HCl on BP-LP is presented in Table 3. It can be observed that the N-H bend shifted from $1580.4 \rightarrow 1636.3 \text{ cm}^{-1}$, while the N-H stretch remained at 3268.9 cm^{-1} . Azeez and Shenbagaraman [34] reported such chemical interactions and structural changes observed by FTIR on functional groups in materials such as graphene, cellulose, chitosan, clay, proteins, and gelatin. This shift results in the protonation of Nitrogen atoms (a heteroatoms) ($\text{R-NH}_2 + \text{H}^+ \rightarrow \text{R-NH}_3^+$) in BP-LP, leading to formation of positively charged ammonium ions. The implication of this in the use of BP-LP as a corrosion inhibitor is that protonated alkaloids can electrostatically adsorb onto negatively charged steel surface in HCl, forming protective film. This is also the same with Carboxylic groups as they become fully protonated in 1 M HCl. The C=O oxygen atoms (heteroatoms) coordinate with vacant d-orbitals of iron, forming chemisorption bonds. The O-H stretch in Phenols & Tannins (Polyhydroxy compounds) remained at $\sim 3268 \text{ cm}^{-1}$ (broad, H-bonded); C-O stretch shifted to 1259.8 cm^{-1} , suggesting that the Hydroxyl groups remain intact but experience stronger hydrogen bonding in acidic media. The corrosion inhibition property implication is that Phenolic -OH groups donate electrons to steel surface. The conjugated C=C bonds (also stretched from 1580.4 cm^{-1} to 1636.3 cm^{-1}) showing increase in intensity, which translates to enhanced conjugation thereby a heightened adsorption through π -electron donation.

Table 3 Impact of 1 M HCl on Specific Phytochemicals of BP-LP

Parameter	Deionized Water (Table 1)	1 M HCl Media (Table 2)	Interpretation
C-O stretch region	1028.7 cm^{-1} (C-O stretch, C-C skeletal)	1259.8 cm^{-1} (C-O-C asymmetric stretch, C-O stretch)	Shift to higher wavenumber ($+231.1 \text{ cm}^{-1}$) could indicate protonation of ether/alcohol groups and stronger C-O-C bonding in acidic media
C=O stretch	Not distinctly observed	1636.3 cm^{-1} (C=O stretch, aliphatic amide)	New peak appears $\rightarrow$ indicating possible protonation of carbonyl groups and formation of amide-like structures
C=C aromatic stretch	1580.4 cm^{-1} (N-H bend, C=C aromatic)	1636.3 cm^{-1} (C=C stretch, alkenes & aromatic)	Shift to higher wavenumber ($+55.9 \text{ cm}^{-1}$) with increased intensity, suggesting enhanced conjugation

N-H bend	1580.4 cm^{-1}	1636.3 cm^{-1}	Shift (+55.9 cm^{-1}) suggests protonation of amine groups (alkaloids) forming ammonium ions (NH_3^+)
N-H stretch	3267.7 cm^{-1} (Amines, N-H stretch)	3268.9 cm^{-1} (N-H stretch, amines)	Minimal shift (+1.2 cm^{-1}) → nitrogen atoms remain available for protonation and metal coordination
O-H stretch (H-bonded)	3267.7 cm^{-1} (broad, H-bonded)	3268.9 cm^{-1} (broad, H-bonded, COOH dimers)	Slight shift (+1.2 cm^{-1}) → hydroxyl groups of phenols/tannins remain but experience stronger H-bonding in acid
Aldehyde C-H stretch	2922.2 cm^{-1} (Two bands, aldehydes weak)	Absent	Disappearance suggests aldehyde oxidation or protonation in acidic environment
COOH dimers	2922.2 & 3267.7 cm^{-1} (weak, broad)	3268.9 cm^{-1} (weak, broad)	Consolidation → carboxylic acid groups remain protonated

3.1.2. Gas Chromatography – Mass Spectrometry Classification of BP-LP

Table 4 results show that Tannin, Alkaloid, Flavonoid and Phytate are present. All the phytochemicals are in good quantities of 18.03, 923.51, 8.42 and 15.01 mg/100 g respectively.

Tannin structurally illustrated in Figure 4 containing electron rich in O atoms and hydroxyl (-OH) groups, has been reported as an inhibiting compound used as a primer and inhibitor to rust formation [1,2,25]. Alkaloids are polar in nature [2,26,27,28, 29], and originate from amino acids that have nitrogen in the heterocycle and categorized as indole, isoquinoline, and pyridine (Figure 4) based on how similar their carbon skeletons are. They have conjugated double bonds, and unshared lone pair electrons on nitrogen and oxygen atoms that act as an active center for BP-LP binding with CRS surface. According to reports, phytate, or phytic acid with phosphate (Figure 4) is crucial for corrosion prevention [30, 31].

Also, the GC-MS result agrees with the FT-IR results on the presence of Phenol. The presence of these compounds indicate the availability of delocalized pie electrons suitable for corrosion inhibition.

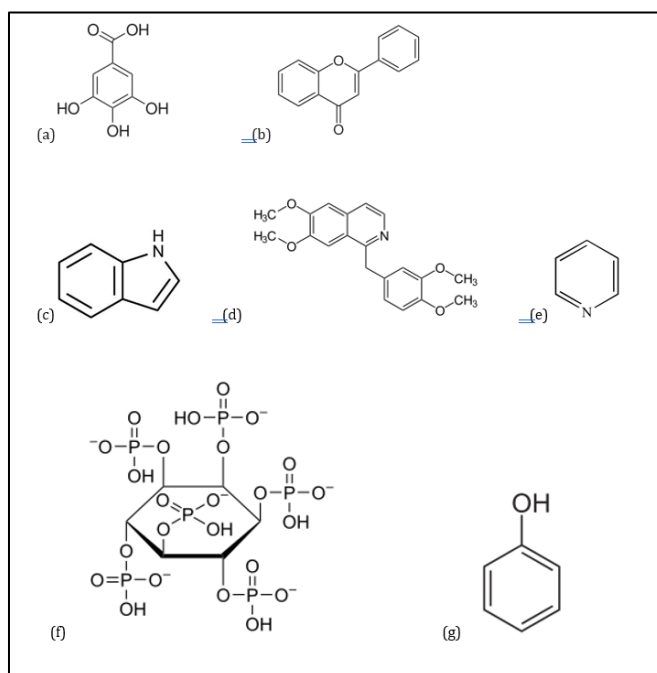


Figure 4 Structure of (a) Tannin (b) Flavonoid (c) Alkaloid (Indole); (d) Alkaloid (isoquinoline) (e) Alkaloid (pyridine) (f) Phytic acid (g) Phenol

Table 4 Phytochemical Quantification of BP-LP in Deionized Water and BP-LP in 1 M HCl Solution

Compound	BP-LP in Deionized Water (mg/100 g)	BP-LP in 1 M HCl (mg/100 g)
Terpenes	10.29	2.18
Phytosterol	4.80	0.49
Oxalate	0.93	0.34
Steroid	3.26	0.12
Tannin	18.03	8.74
Phenol	7.19	5.62
Saponin	4.76	3.98
Alkaloid	23.51	12.05
Coumarin	0.48	1.26
Anthocyanins	2.75	1.70
Flavonoid	8.42	6.19
Phytate	15.01	5.76
Cardiac Glycoside	2.34	1.03
Cyanogenic Glycoside	3.15	ND

The presence of Alkaloid and Terpenes were also reported by kolo [13] as physiochemical properties of the BP-LP extracted using alcohol. In this report aqueous extracts also indicates appreciable quantities of Alkaloid and Terpenes.

3.2. Gravimetric Measurement of BP-LP

The plots of Figure 5 give the variation of the corrosion rate of CRS with time in a 1 M HCL Corrodent solution containing different concentration of BP-LP extracts or the absence of it. The corrosion rate of CRS in the corrodent without BP-LP is observed to be high after the first day with a value of 48.945 mm/y compared to the value of 0.833 mm/y for the least concentration of BP-LP in HCl environment. The drastic drop in corrosion rate in the acidic environment with aqueous BP-LP inhibitor shows that aqueous extracts of BP-LP is an efficient corrosion inhibitor.

Figure 6 reveals that increase in concentration of aqueous extracts of BP-LP in corroding solution and the increase in immersion time results in corresponding decrease in corrosion rate. This implies that higher concentration of aqueous extracts of BP-LP effectively reduced the attack of the aggressive acid anions on the coupons. Aqueous extracts of BP-LP is therefore a concentration dependent inhibitor like other plant extracts such as Piper bittle, xanthan gum etc [32,33].

The observed drop in corrosion rate for blank solution during the five days test is as a result of iron dissolution in the acidic environment. Two mechanisms—an aqueous solution and an aqueous solution containing chloride ions (Cl^-)—are used in the dissolution of iron. The mechanisms can proceed concurrently. During the acid attack, complexes are formed. The acid's potency is diminished by the creation of these complexes and their buildup. Moreover, passivity occurs on the CRS during the five days. These concepts account for the observed reduced corrosion rate and this is in agreement with previous reports [22,23]

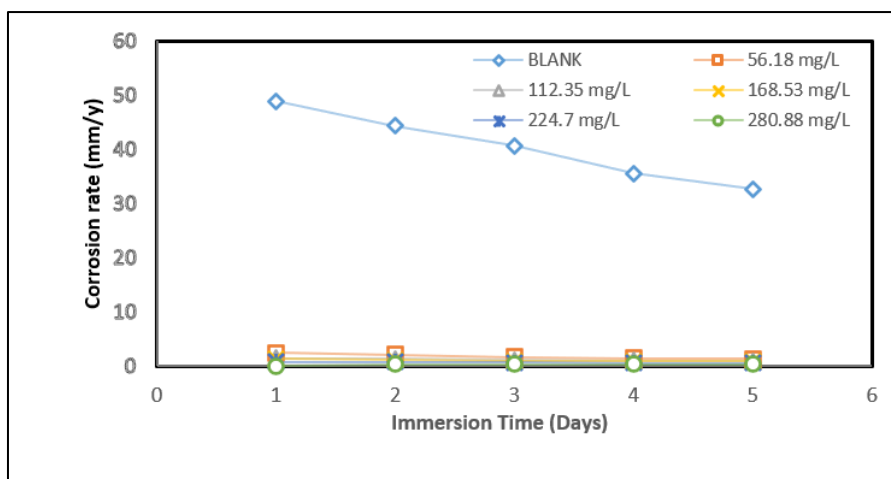


Figure 5 Variation of CRS Corrosion Rate with Immersion Time in HCl with and without Different Concentrations of BP-LP

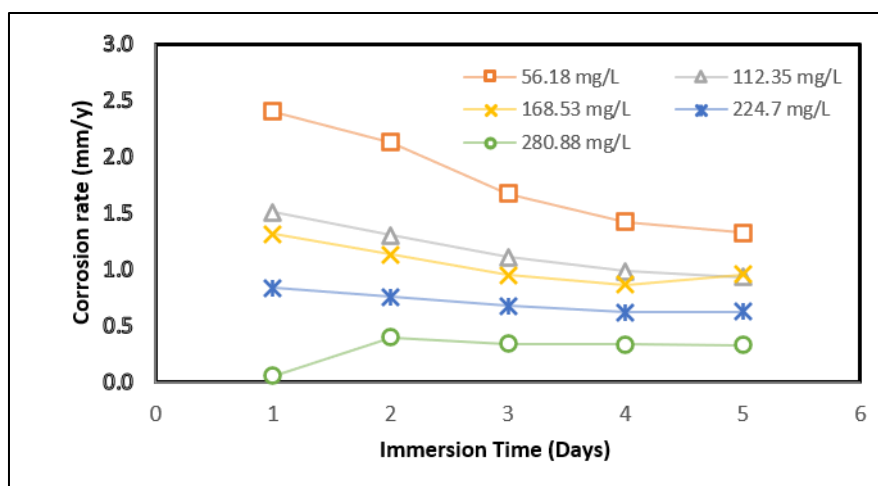


Figure 6 CRS Corrosion Rate in 1 M HCl at Varying Concentrations of BP-LP

The inhibition efficiency (IE%) of aqueous extracts of BP-LP is well presented in the plots of Figure 7. It is obvious that IE% of aqueous extracts of BP-LP increased as its concentration increased in the system. The aqueous extracts of BP-LP inhibitor system have a maximum inhibition efficiency of 98.99% and was stable for all tested concentrations of BP-LP in the aggressive acid which is a desirable property for a green inhibitor. The high inhibition efficiency indicates that there are lesser number of free corrosion active sites as most of the active sites were blocked by aqueous extracts of BP-LP inhibitor adsorption process. This concentration of aqueous extracts of BP-LP is sufficient as an industrial additive for CRS cleaning.

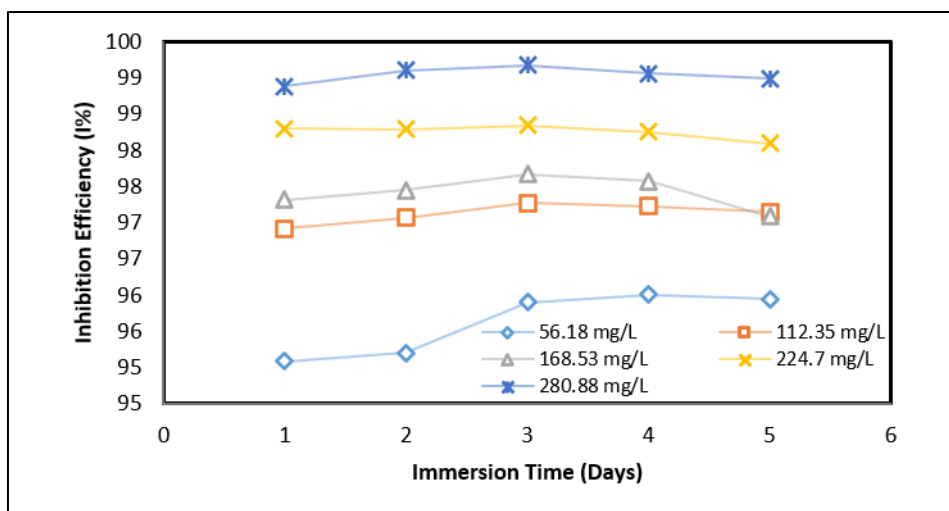


Figure 7 Inhibition Efficiency of Different Concentrations of BP-LP in CRS Corrosion in 1 M HCl

3.3. Proposed Mechanism of Adsorption for BP-LP

It has been established that in HCl environments, such as 1 M HCl, BP-LP phytochemicals undergo protonation of nitrogen atoms (alkaloids) leading to formation of cationic species, and the hydrogen bonding among O-H groups (phenols, tannins) is enhanced. Also, there is electron distribution strengthening conjugation bonds in C=O and C=C, and a retention of heteroatoms (O, N, P) and conjugated bonds (C=C-H) essential for adsorption. Therefore, it is safe to deduced that aqueous extract of BP-LP inhibited corrosion of CRS in 1 M HCl as illustrated in Figure 8, using:

- I. Protonated lone pair electrons (P, N, O) of heteroatoms of aromatics, phenyl ring, and phytate in aqueous extracts of BP-LP which reacted with empty d-orbitals of CRS.
- II. The delocalized pie electrons present in aqueous extracts of BP-LP also interact directly with empty d-orbitals in CRS to block Cl^- access to the CSR active cites (Figure 8).
- III. Inter play of I and II above. BP-LP lone pair electron from N, O, P, and free pie electrons in the double bonds adsorb on the CRS surface and prevent CRS corrosion by an **anodic reaction** at the anodic site of CRS such that the adsorbed pie and lone pair electron prevented or reduced the dissolution of CRS. In the **cathodic reaction** – the already adsorbed lone pair electrons avert or decrease hydrogen evolution.

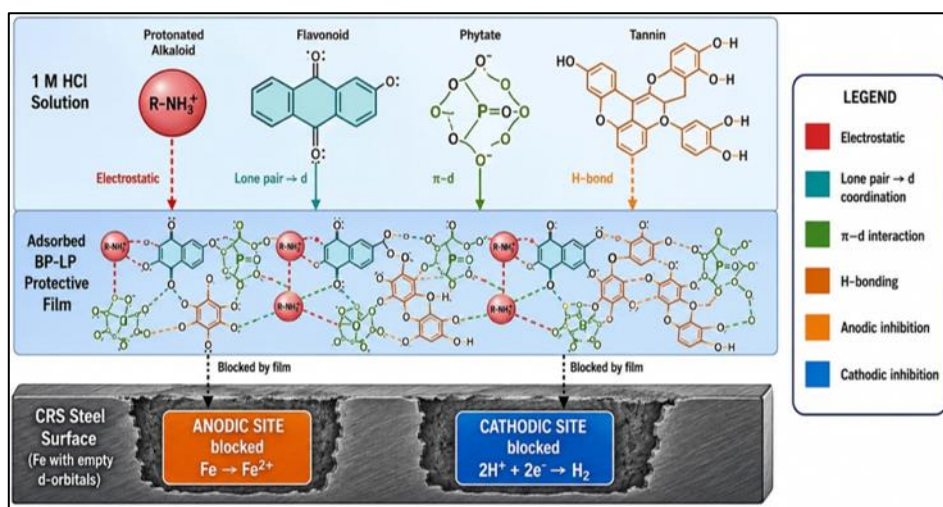


Figure 8 Proposed Adsorption Mechanism of BP-LP on 1 M HCl

4. Conclusion

The aqueous extract of *Bryophyllum pinnatum* (BP-LP), has been established as an effective green corrosion inhibitor for cold-rolled steel (CRS) in 1 M HCl. FTIR and GCMS analyses confirmed the presence of phytochemicals—tannins, alkaloids, and phenols—containing heteroatoms (O, N, P) and functional groups (N-H, C=O, aromatic C=C) that facilitate adsorption onto the CRS surface. Gravimetric measurements demonstrated that aqueous extract of BP-LP inhibits CRS corrosion, with inhibition efficiency increasing with concentration and reaching a maximum of 94%. These findings confirm that aqueous extract of BP-LP is concentration, and time dependent. low-cost, eco-friendly corrosion inhibitor with strong potential for use in acid cleaning and pickling processes in manufacturing and oil and gas industries.

Compliance with ethical standards

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Disclosure of conflict of interest

There is no conflict of interest

References

- [1] Verma C, Quraishi MA, Rhee KY. Aqueous phase polymeric corrosion inhibitors: Recent advancements and future opportunities. *Journal of Molecular Liquids*. 2022 Feb 15;348:118387.
- [2] Izionworu VO, Puyate YT, Wan WM. A study of wire croton as an inhibitor of mild steel in HCL using electrochemical–SEM–GCMS and FTIR measurements. *J New Eng Technol*. 2021;3(1):1-1.
- [3] Verma DK, Khan F. Corrosion inhibition of mild steel by extract of *Bryophyllum pinnatum* leaves in acidic solution. *Chem. Mater. Res*. 2015;7:69-76.
- [4] Zulkifli F, Haque J, Daoudi W, Ghazali MS, Izionworu VO, Al-Amiery AA, Berdimurodov E, Pradityana A, Nik WW. Cynodon dactylon extract as eco-friendly corrosion inhibitor epoxy coating addition for mild steel. *International Journal of Corrosion and Scale Inhibition*. 2024;13(4):2340-53.
- [5] Zulkifli F, Khairina S, Ghazali MS, Al-Amiery AA, Ismail N, Izionworu VO, Suriani MJ, Nik WW. Application of electrochemical impedance spectroscopy technology to evaluate passivation performance of film forming and adsorption types corrosion inhibitors. *Int. J. Corros. Scale Inhib*. 2022;11(3):1303-18.
- [6] Bandeira RM, Lima FP, Nunes MS, dos Santos EC, dos Santos Júnior JR, de Matos JM, Feitosa CM, Rai M, Bhattarai S, Das Mulmi D. The green plant-based corrosion inhibitors—a sustainable strategy for corrosion protection. *Surface Science and Technology*. 2025 Dec;3(1):19.
- [7] Onuegbu VI, Alabi I. Characterisation of Sawdust from *Entandrophragma Cylindricum* (Sapele), *Diospyrusscrassiflora* (Ebony), *Triplochitonscleroxylon* (Obeche) and *Chlorophora Excelsa* (Iroko) Woods. *Int. J. Sci. Eng. Res*. 2018;9:1569-76.
- [8] Răuță DI, Matei E, Avramescu SM. Recent development of corrosion inhibitors: types, mechanisms, electrochemical behavior, efficiency, and environmental impact. *Technologies*. 2025 Mar 5;13(3):103.
- [9] Izionworu VO, Byadi S, Arukalam IO, Nik WM. Inhibitive mechanism of acid corrosion of cold-rolled steel by polyethylene glycol via experimental, computational and surface analytical approaches. *Journal of Bio-and Tribo-Corrosion*. 2022 Mar;8(1):14.
- [10] Haque J, Verma C, Srivastava V, Nik WW. Corrosion inhibition of mild steel in 1M HCl using environmentally benign *Thevetia peruviana* flower extracts. *Sustainable Chemistry and Pharmacy*. 2021 Apr 1;19:100354.
- [11] Ahmed MA, Amin S, Mohamed AA. Current and emerging trends of inorganic, organic and eco-friendly corrosion inhibitors. *RSC advances*. 2024;14(43):31877-920.

- [12] Verma C, Ebenso EE, Bahadur I, Quraishi MA. An overview on plant extracts as environmental sustainable and green corrosion inhibitors for metals and alloys in aggressive corrosive media. *Journal of molecular liquids*. 2018 Sep 15;266:577-90.
- [13] Kolo AM, Idris S, Bamishaiye OM. Corrosion inhibition potential of ethanol extract of *Bryophyllum pinnatum* leaves for zinc in acidic medium. *Edelweiss Appl Sci Technol*. 2018;1(2):17-24.
- [14] Loto CA, Joseph OO, Loto RT, Popoola AP. Inhibition effect of *Vernonia amygdalina* extract on the corrosion of mild steel reinforcement in concrete in 3.5 M NaCl environment. *International Journal of Electrochemical Science*. 2013 Sep 1;8(9):11087-100.
- [15] Medini F, Fellah H, Ksouri R, Abdelly C. Total phenolic, flavonoid and tannin contents and antioxidant and antimicrobial activities of organic extracts of shoots of the plant *Limonium delicatulum*. *Journal of Taibah University for science*. 2014 Jul 1;8(3):216-24.
- [16] Dewi AL, Siregar VD, Kusumayanti H. Effect of Extraction Time on Tannin Antioxidant Level and Flavonoid on Pandan Wangi Leaf (*Pandanus amaryllifolius* Roxb) Using Hydrothermal Extractor. In *Journal of Physics: Conference Series* 2019 Sep 1 (Vol. 1295, No. 1, p. 012066). IOP Publishing.
- [17] Agidew MG. Phytochemical analysis of some selected traditional medicinal plants in Ethiopia. *Bulletin of the National Research Centre*. 2022 Apr 1;46(1):87.
- [18] Darkwah WK, Ao Y, Adinortey MB, Weremfo A, Abrokwa FK, Afriyie E. Total phenolic, flavonoid and alkaloid contents, oxidative DNA damage protective and antioxidant properties of methanol and aqueous extracts of *Dissotis rotundifolia* whole plant. *Free Radic Antioxid*. 2018 Apr 1;8(2):82-8.
- [19] Lahare RP, Yadav HS, Bisen YK, Dashahre AK. Estimation of total phenol, flavonoid, tannin and alkaloid content in different extracts of *Catharanthus roseus* from Durg district, Chhattisgarh, India. *Scholars Bulletin*. 2021;7(1):1-6.
- [20] Sharma T, Gamit R, Acharya R, Shukla VJ. Quantitative estimation of total tannin, alkaloid, phenolic, and flavonoid content of the root, leaf, and whole plant of *Byttneria herbacea* Roxb. *AYU (An international quarterly journal of research in Ayurveda)*. 2021 Jul 1;42(3):143-7.
- [21] ASTM G. G 31-72, "Standard Practice for Laboratory Immersion Corrosion Testing of Metals," ASTM Int., vol. 72,
- [22] Onuegbu IV, Peter UC, Emmanuel OE. Inhibition of mild steel corrosion in acidic medium using theobroma cacao pod. *International Journal of Science and Engineering*. 2020;11(3):255-65.
- [23] Izionworu VO, Ikenyiri PN, Chie-Amadi GO. Evaluation of *Codiaeum Variegatum* Brilliantissima-Zanzibar as an Inhibitor of Mild Steel Corrosion in 1 M HCl Using Gravimetric Method. *Journal of Newviews in Engineering and Technology (JNET)*. 2021 Mar;3(1).
- [24] Eziuka JE, Onyeachu BI, Njoku DI, Nwanonenyi SC, Chidiebere MA, Oguzie EE. Elucidating the inhibition behaviour of *Pterocarpussantalinoides* leaves extract on mild steel corrosion in H₂SO₄ solution–GC-MS, FTIR, SEM, Experimental and computational approach. *Moroccan Journal of Chemistry*. 2023 May 2;11(3):J-Chem.
- [25] Sesia R, Spriano S, Sangermano M, Ferraris S. Natural polyphenols and the corrosion protection of steel: recent advances and future perspectives for green and promising strategies. *Metals*. 2023 Jun 3;13(6):1070.
- [26] Assad H, Kumar A. Understanding functional group effect on corrosion inhibition efficiency of selected organic compounds. *Journal of Molecular Liquids*. 2021 Dec 15;344:117755.
- [27] Alkaloid (2019). Retrieved from <https://en.wikipedia.org/wiki/Alkaloid>. April 2nd, 2019
- [28] Flavonoid (2019). Retrieved from Wikipedia, the free encyclopedia <https://en.wikipedia.org/wiki/Flavonoid>. April 2nd, 2019 and 10th July, 2026.
- [29] Ismail N, Mujad SM, Zulkifli MF, Izionworu VO, Ghazali MJ, Nik WM. A review on application of marine algae as green corrosion inhibitors in acid medium. *Vietnam Journal of Chemistry*. 2022 Aug;60(4):409-16.
- [30] Kumar UP, He BB. Synergistic impact of phytic acid and sodium phosphate on the corrosion inhibition of additively manufactured 304L steel in a 3.5 wt% NaCl medium. *Journal of Materials Science*. 2025 Jul;60(26):11092-111.
- [31] Liu Y, Zhou X, Guan X, Shi J. Synergistic inhibition mechanism of phosphate and phytic acid on carbon steel in carbonated concrete pore solutions containing chlorides. *Corrosion Science*. 2022 Nov 1;208:110637.

- [32] Nik WW, Ravindran K, Al-Amiery AA, Izionworu VO, Fayomi OS, Berdimurodov E, Daoudi W, Zulkifli F, Dhande DY. Piper betle extract as an eco-friendly corrosion inhibitor for aluminium alloy in hydrochloric acid media. *Int. J. Corros. Scale Inhib.* 2023;12(3):948-60.
- [33] Biswas A, Pal S, Udayabhanu G. Experimental and theoretical studies of xanthan gum and its graft co-polymer as corrosion inhibitor for mild steel in 15% HCl. *Applied surface science.* 2015 Oct 30;353:173-83.
- [34] Azeez S, Shenbagaraman R. Fourier transform infrared spectroscopy in characterization of bionanocomposites. *In Characterization Techniques in Bionanocomposites* 2025 Jan 1 (pp. 209-227). Woodhead Publishing.

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