FUDMA Journal of Engineering and Technology

ISSN: 3092-9385

https://sites.google.com/fudutsinma.edu.ng/fjet

Volume 1, Issue 2, 2025, 110-122

Electrochemical Analysis of *Azadirachta indica* Leaves as a Corrosion inhibitor on Mild Steel in 1 M H_2SO_4

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Abstract

Corrosion inhibition of mild steel in acidic environments is vital in several industrial applications. This study was based of the electrochemical analysis of Azadirachta indica Leaf Extract(ALE) as corrosion inhibitor on mild steel in 1mol. H_2SO_4. The Electrochemical analysis is a technique was used to study the chemical properties and reactions of substance by measuring the flow of electrical current or potential difference This process was used to determine the ions in the leaf extract and to understand the oxidation-reduction reactions and the kinetics presence in the leaf extract. . The Fourier Transform Infrared Spectroscopy (FTIR) was used to determine the functional groups present. The phytochemical analysis was used to identify and quantify the bioactive compounds that were present in the leaf extract. The chemical composition of the mild steel material was determined . The pH meter was used to determine the level of acidicity on the extract. The Scanning Electron Microscopy (SEM and Energy Dispersive Spectroscopy were used to determine the morphology and the elemental weight (%) of the mild steel . The results of the corrosion test using the Electrochemical analytical technique revealed the stability of the oxide with respect to time(sec). The potentiodynamic polarization indicates that the corrosion rate decreases with respect inhibition addition thereby mitigating the corrosion process. The result of the EIS revealed that the addition of the extract increased the diameter of the semicircle in the Nyquist plot, indicating a decrease in corrosion rate. The Bode plot revealed an increase in impedance value at high frequencies, indicating a decrease in corrosion rate. The results from FT-IR identified several key components that created a protective thin film layer that stopped the release of hydrogen ions (H^+) in the presence of acid, including C-C stretching, aromatic compounds, N-H_2 symmetric stretching vibration, N-H symmetric stretching, and others. The functional groups identified by FTIR analysis of the protective film formed by leaf extract in H_2SO_4.The hydroxyl (OH) groups, carbonyl (C=O) groups , the amines (N-H) groups and aromatic (C=C) groups, these groups possesses corrosion inhibition properties by coordinating with metal ions or forming stable complexes with the metal surface. The XRD results revealed sharp peaks indicate crystalline structure of the mild steel indicating the presence of corresponding compounds such as Fe($MgSO_4$), FeS_2, $CaCO_3$, and Fe_2O_3. The SEM / EDX revealed the morphology that exhibit smooth an uniform structures indicating the presence of inhibition while the EDX shows the elements in weight(%) The Phytochemical analysis shows the presence of Alkaloids 0.6%, Flavonoids 5.8%, Saponins 1.5%, tannins 3.6% and Phenol 7.8%. The pH values obtained indicated that Azadirachta leaf extract has 1.0 while 1M H_2SO_4 contains 0.5.The findings of potentiodynamic polarisation demonstrated that the corrosion rate dropped from 1.164e+002 to 1.3166e+004 in the 0.7g of 30mL in 1M H_2SO_4 medium and from 1.164e+002 to 1.042e+004 in the 0.9g of 30mL in H_2SO_4. The development of a physical protective layer in the mild steel was credited with the enhanced corrosion resistance of the Azadirachta indica leaf extract. The extract's chemical inertness was also cited as a factor in the mild steel's lower rate of corrosion. The findings show that Azadirachta indica leaf extract is environmentally friendly on the mild steel which serves as corrosion inhibitor in acidic settings. The results revealed that the extract has good corrosion inhibitory properties that can mitigate the corrosion process.

Keywords: *Azadirachta indica, corrosion, H_2SO_4 and electrochemical analysis.*

1.0 Introduction

Metal corrosion is a major issue in many professions, such as manufacturing of chemicals, motor vehicles and infrastructure. Because it is easy to fabricate and reasonably priced, mild steel is utilised extensively. In acidic settings, as those found in petrochemical manufacturing and preservation, it is vulnerable to corrosion. One efficient method of reducing corrosion is to utilise corrosion inhibitors. Nevertheless, a large number of traditional corrosion inhibitors are detrimental to the surroundings and harmful. Thus, research into environmentally acceptable corrosion inhibitors is becoming more and more popular. The ability of several plant extracts to reduce corrosion has been the subject of recent research. Azadirachta indica leaf extract, for instance, has been shown to suppress mild steel corrosion in H_2SO_4 solution [1]. Similarly, the bark extract of Acacia nilotica has been shown to inhibit the corrosion of mild steel in an H_2SO_4 solution [1][2]. Other plant extracts, such as those from Ocimum

Received: 06/07/2025; Revised: 15/07/2025; Accepted: 15/07/2025; Published: 08/08/2025

basilicum and Murraya koenigii. [2-5]. The corrosion inhibition mechanism of plant extracts is often attributed to the presence of phytochemicals, such as alkaloids, flavonoids, and phenolic acids. These compounds can adsorb onto the metal surface, forming a protective film that inhibits corrosion [6-8]. Materials, metals naturally deteriorate due to corrosion, which is caused by the interaction of the materials with their surroundings. Air, moisture, acids, and other corrosive materials can all speed up the process. The term "corrosion" refers to the slow disintegration or deterioration of things or materials. The irreversible degradation and destruction of steel material and its basic characteristics due to the surface's chemical or electrochemical reactivity to external elements including oxygen, moisture, and acids is another way to describe it. Usually, the term is used to describe more specialised metals like iron or steel.[9] . Corrosion occurs by chemical reactions and other interactions between a material and its environment, including those involving bacteria, dirt, hydrogen, and oxygen. One popular and obvious form of corrosion that can lead to a number of dangerous problems and situations is rust, which is produced when iron or steel breaks down in the presence of air and water [10]. Metals and other materials may also corrode if subjected to high stress or pressure [11]. Iron, zinc, and other metals with higher reactivity corrode more easily than metals with lower reactivity, such as gold, platinum, and palladium. Metal oxidation during corrosion offers an explanation to this phenomenon. The reactivity series' proclivity to oxidize decreases with depth (oxidation potentials are very low) [11-12]. Rusting and other forms of corrosion can weaken metals and other materials, causing bridge structures to deteriorate and collapse, critical pipelines to fail, and chemical plants to leak. Electrochemical reactions and corrosion of electrical systems may be even more harmful, resulting in fires, floods, and air pollution. Particularly, the estimated yearly price of metallic corrosion globally is about $2 trillion, while the annual cost of repairing corrosion-damaged structures in the United States is over $276 billion [6-8]. According to experts, 25 to 30% of corrosion might be avoided and global costs could be significantly decreased with more in-depth research into construction planning, the corrosion process, and the consequences of corrosion on the environment. [6]. The research work of corrosion mitigation is highly recognised due to the detrimental effects and high cost of commercial organic and inorganic inhibitors. Because they are easily accessible, affordable, eco-friendly, and renewable, corrosion scientists and engineers are now more strongly advocating for the adoption of green corrosion inhibitors. A basic overview of the various types of these inhibitors was provided in the research studied [13-15] . In many industries, from building materials to surface treatments for materials, corrosion inhibitors are frequently used to mitigate or at least slow the corrosion process of metals. In general, a "chemical compound that, when present in the corrosion system at a suitable concentration, decreases the corrosion rate, without significantly changing the concentration of any corrosive agent" this is considered as corrosion inhibitor. [16]. Green inhibitors are designed to have the fewest possible adverse effects on the environment. They reduce the period of time that inhibitor residues are present in ecosystems because they biodegrade frequently. Because many green inhibitors are sourced from renewable resources like plants, they are more sustainable than inhibitors based on non-renewable or harmful elements. Green inhibitors often pose fewer risks to humans and ecosystems than standard inhibitors do, allaying concerns about health and safety. A wide range of industries, including construction, oil & gas, maritime, and transportation, use green corrosion inhibitors. They are used in many different contexts to stop corrosion in metal pipes, structures, and equipment. [17].

2.0 Materials and Methods

2.1 Materials

The Azadirachta indica leaves were sourced at the University of Nigeria, Nsukka. The chemical H_2SO_4 was purchased at Joe Chem, Chemical Shop, Nsukka. The mild steel coupons were obtained at the Forge and Fabrication Shop of the Ajaokuta Steel Company Limited, Ajaokuta, Kogi State.

2.2 Methods

Fresh healthy leaves of Azadirachta indicia were obtained in a natural condition from the Azadirachta indica tree at the University of Nigeria, Nsukka, Nigeria. The leaves were washed and dried for three (3) days under room temperature which assisted to remove moisture. Five (5) kg of the leaves were separated into different containers for easier handling. A Vitamix Series 750 Blender was used to prepare the samples where 1200g of the plant material was combined with 2.0L of 100% methanol (Me OH). Agitation techniques were used to remove the dry components for 48 hours at room temperature. The methanol was filtered, and the filtrate was then heated to 40 ^{o}C in a rotary evaporator while being vacuumed to produce aqueous extracts. [18-20].

2.2.1 Determination of Chemical composition of Mild Steel

The Mild steel sample was subjected to a SPECTRO Analytical Instrument known as Spark Analyzer where the chemical compositions of the material was determined.

2.2.2 Phytochemical Analysis

This analysis was performed to determine individual chemicals in a plant extract that are responsible for the protective benefits of the extract and the ability to inhibit corrosion such as Alkaloids, flavonoids, tannins, saponins and phenolics. These compounds interact with metal surfaces to build protective layers that either stop or slow down corrosion. The process contributes in determining which of the extract's constituents are active in preventing mild steel from corroding in acidic setting when analyzing a plant extract. [21].

2.2.3. Fourier Transform Infrared Spectroscopy (FTIR) analysis

The Shimazu FTIR Model IR Affinity-1, made in Japan, was used to perform the Fourier Transform Infrared Spectroscopy (FTIR) analysis. The instrument measured the infrared region of the electromagnetic radiation spectrum, which has a longer wavelength and lower frequency than visible light. This technique measures the absorption of infrared radiation (IR) by samples, based on the principle that bonds between different atoms absorb light at specific frequencies. The leaf extract samplewas analysed using an FTIR spectrometer, which directs IR beams at the samples and measures the absorption of infrared light at various frequencies. The spectrometer references a database of thousands of spectra identified the samples and determined its molecular identities. The experiments were conducted at the Energy Centre of the University of Nigeria, Nsukka.

2.2.4 Scanning Electron Microscopy with attached Energy Dispersive Spectroscopy. (SEM/ EDX)

The prepared samples were subjected to morphology analysis with Scanning Electron Microscopy with attached Energy Dispersive Spectroscopy. (SEM/ EDX). The mild steel samples were prepared for SEM analysis, they were sized and appropriately fitted into the chamber, and securely mounted on a specimen stub. The SEM equipment was used to examine the samples, and were tilted up to 45 degrees. The instrument was operated in a relatively high-pressure chamber with a short working distance while maintaining a low vacuum at the electron gun. This design enables charge neutralization and amplification of the secondary electron signal. For low-voltage SEM, Field Emission Gun Scanning Electron Microscopes (FEG-SEM) are ideal due to their high primary electron brightness and small spot size at low accelerating potentials. Additionally, embedding samples in resin and polishing them to a mirror-like finish to enhance imaging in backscattered electrons and quantitative X-ray microanalysis for both biological and material specimens. The instrument model was JEOL JMB which was used to determine the morphology of the samples known as the Scanning Electron Microscope.

2.2.5 Electrochemical Test

The electrochemical analyzer instrument model CHI 640 series were used to determine the electrochemical analysis of corrosion characteristics of the medium carbon steel using the Open Circuit Potential (OCP), Tafel polarization and Electrochemical Impedance Spectroscopy (EIS) methods. The methods were used to investigate the corrosion rate with varied extracts (10-30mL). The investigation of the effectiveness of the Azadirachta indica leaf extract as corrosion inhibitors on medium carbon steel in 1M H_2SO_4 solution was performed. The Corrosion rate experiments were measured with the potentiodynamic polarization tests under impingement conditions. The tests conducted with VersaSTAT 4 potentiostat using Ag/AgCl reference electrode and a platinum counter electrode. The surface of the working electrode polarized from -250 mV to +250 mV concerning the Open Circuit Potential (OCP) at a scan rate of 0.25 mV/s. Meanwhile, the OCP settled for 30 min before each experiment. The corrosion current density was determined from the Tafel plot as the intersection between the extrapolated anodic and cathodic branches of the potentials. The tests confirmed to ASTM G199–09 (2014 Standard Guide for Electrochemical Measurement). An electrochemical cell containing the potential inhibitor solutions was the electrolyte, consisting of three electrodes: the working electrode (sample), the counter electrode (graphite rod) and silver/silver chloride (Ag/AgCl) electrode, as a reference electrode. The potentiodynamic polarization method, the potential was scanned from initial E and Final E. The potential waveform applied as a function of time. The logarithm of current was recorded as a function of potential. Initial E (V) -10 + 10 Initial E - Final E (V) -10 - +10 [25]. In the case of this research work, the potential tests took place using potential parameters from -1.5 V + 1.5 V. The Open Circuit Tests run for 3600 seconds, the potentiodynamic polarization method for Tafel and the Electrochemical Impedance Spectroscopy (EIS) experiments were also run for 3600. Figure 2. shows electrochemical analyzer setup of a potentionstat, a device for regulating the voltage between RE and WE at a fixed and chosen potential with a scanning rate (vs) of 0.01

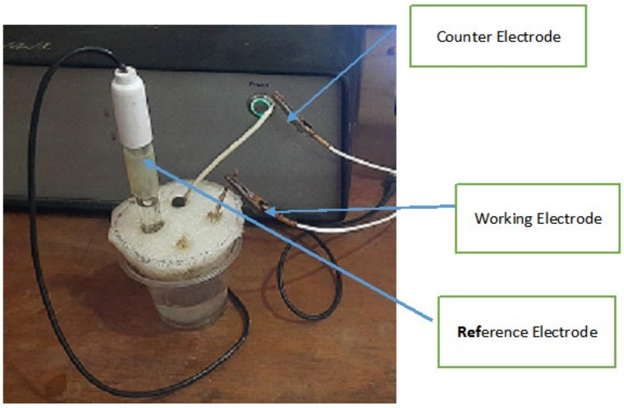


Figure 1: Set-up

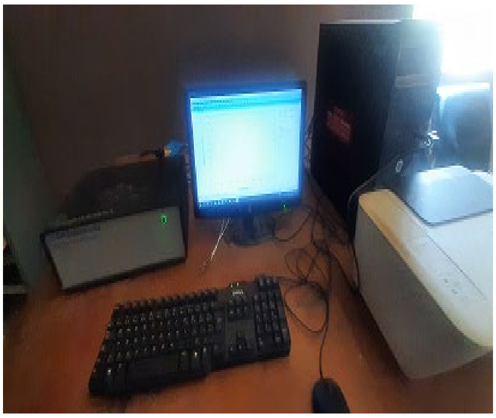


Figure 2: The corrosion cell (CH Instruments Model 600E Series)

3.0 Results and Discussion

3.1 Chemical Composition

The chemical composition of the mild steel samples was determined through the spark analytical technique. The test confirmed the presence of various elements in weight (%) as indicated in Table 1. The carbon obtained was 0.2%. This low carbon percentage was consistent with the properties of mild steel, which is known for its ductility, malleability, and relatively lower hardness compared to higher carbon steels. [22-25].

Table 1: Chemical compositions of mild steel

%C	%	% C	%Mn	%S	% P	%Cr	%Ni	%Cr	%Mo	%Al	%Cu	%Co	%V	%Ti
0.2	0.58	0.2	0.58	0.0013	0.0074	0.051	0.034	0.1	0.0069	0.129	0.54	0.013	<0.0010	0.0021
%W	%Pb	%W	%Mg	% B	%Sn	%Zn	%As	%Bi	%Ca	%Ce	%Zr	%La	Nb	%Fe
0.0094	0.038	0.0094	0.014	0.0016	0.0045	>0.036	0.0036	<0.0020	>0.016	0.025	<0.0015	0.062	<0.0040	<96.081

3.2 Phytochemical Analysis

Table 2 shows the identified and quantified bioactive compounds that are present in Azadirachta indica leaf extract

Table 2: Azadirachta indica leaf extract's essential phytochemicals

Phytochemical	**Alkaloids (wt%)**	**Flavonoids (wt%)**	**Saponins (wt%)**	**Tannins (wt%)**	**Phenol (wt%)**
Composition (mg/L)	0.6	5.8	1.5	3.6	7.8

3.3 pH Value

The Azadirachta indica leaf extract acts as a base, slightly increasing the pH of acidic solutions by neutralizing corrosive species. In a 1M H_2SO_4 solution, the pH values are indicated in Table 3. The pH measures the acidity/alkalinity based on H^+ ion concentration. [26]. The pH values of the materials utilised in the study are displayed in Table 3.

Table 3: The pH values

pH	**Azadirachta indica extract**	**1 mol of H_2SO_4**
Value	1.0	0.5

3.4 Fourier Transform Infrared Spectroscopy (FTIR)

FTIR analysis of the protective film formed by Azadirachta indica leaf extract in 1mol H_2SO_4 showed hydroxyl, carbonyl, amine, sulfonate, sulfate, aromatic, and aliphatic groups. By generating stable and protective complexes that prevent corrosion, these functional groups indicate that the resulting extract compounds adsorbed onto the mild steel surface through hydrophobic interactions, π-π stacking, electrostatic interactions, and hydrogen bonding.

Received: 06/07/2025; Revised: 15/07/2025; Accepted: 15/07/2025; Published: 08/08/2025

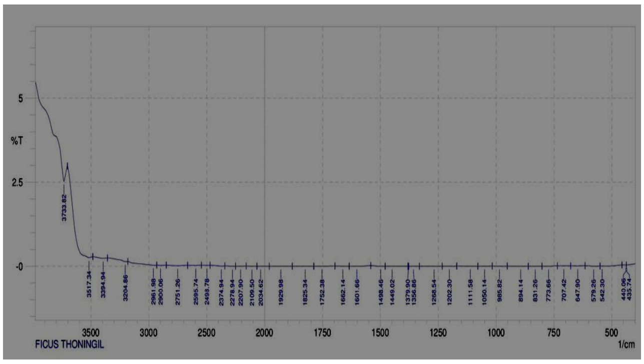


Figure 5 FTIR of Azadirachta indica leaf extract

The FT-IR identified several key components that created a protective thin film layer that stopped the release of hydrogen ions (H^+) in the presence of acid, including C-C stretching, aromatic compounds, N-H_2 symmetric stretching vibration, N-H symmetric stretching, and others. The functional groups identified by FTIR analysis of the protective film formed by leaf extract in H_2SO_4 [27]. The hydroxyl (OH) groups, found in alcohols, phenols, and carboxylic acids, are known to possess corrosion inhibition properties by forming hydrogen bonds with the metal surface or donating electrons to the metal ions. The carbonyl (C=O) groups, found in aldehydes, ketones, carboxylic acids, esters, and amides, are known to possess corrosion inhibition properties by coordinating with metal ions or forming stable complexes with the metal surface. The amines (N-H) groups, found in amines, amides, and anilines, are known to possess corrosion inhibition properties by coordinating with metal ions or forming stable complexes with the metal surface. The aromatic (C=C) groups, found in aromatic compounds such as phenols and anilines, are known to possess corrosion inhibition properties by adsorbing onto the metal surface through π-π stacking or donating electrons to the metal ions.

3.5 Scanning Electron Microscopy (SEM) Energy Dispersive Spectroscopy(EDS)

The SEM/EDX results for 0.9g Azadirachta indica leaf extract on Mild Steel in 10mL and 30mL of H_2SO_4. Figure 6: SEM/EDX of Azadirachta indica extract at 0.9 H_2SO_4 10mL [28]. Figure 7: SEM/EDX of Azadirachta indica extract at 0.9 H_2SO_4 30mL [28]. SEM Analysis revealed smooth, uniform surface indicating effective corrosion inhibition. The thin film was formed as even layer on mild steel indicating the presence of the extract. Fewer pits and crevices were observed indicating reduced localized corrosion. The surface protection shows protective layer reducing mild steel reactivity according to [28]. EDX Analysis revealed the presence elementin weigh (%) compositions as follows : 65.50%Fe, 12.%O, 4.20%C, 3.20%S, 3.20%Mg, 4.30Mn%. Plate 2 shows the SEM of 0.9g of Azadirachta indica leaf extract immersed in 30mL of 1mol H_2SO_4 , while Figure 7 shows the EDX of 0.9g Azadirachta indica leaf extract immersed in 30mL of H_2SO_4 .[28] SEM Analysis shows smooth and uniform surface structure indicating effective corrosion inhibition. There was even layer protection on the mild steel. Fewer pits and crevices, suggesting reduced localized corrosion and protective layer reducing mild steel reactivity. EDX Analysis revealed the presence of the following elements in wt.% 65.35%Fe, 12.20%O, 0.20%C, 3.2%S, 4.3% Mg and 4.30 %Mg. The 10mL solution has a higher carbon content (4.20%) compared to the 30mL solution (0.20%), there was an indication of higher Mn in 30mL (4.3%) as compared to 10mL (3.20%). The SEM/EDX analysis demonstrates that the leaf extract forms a protective layer on mild steel in both 10 mL and 30 mL H_2SO_4 respectively therefore indicating effectiveness in reducing corrosion and pit formed.

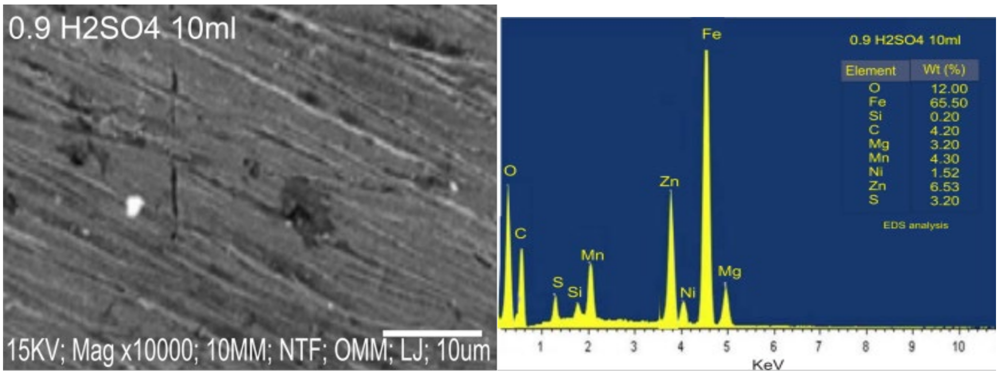


Figure 6: SEM/EDX of Azadirachta indica extract at 0.9 H_2SO_4 10mL

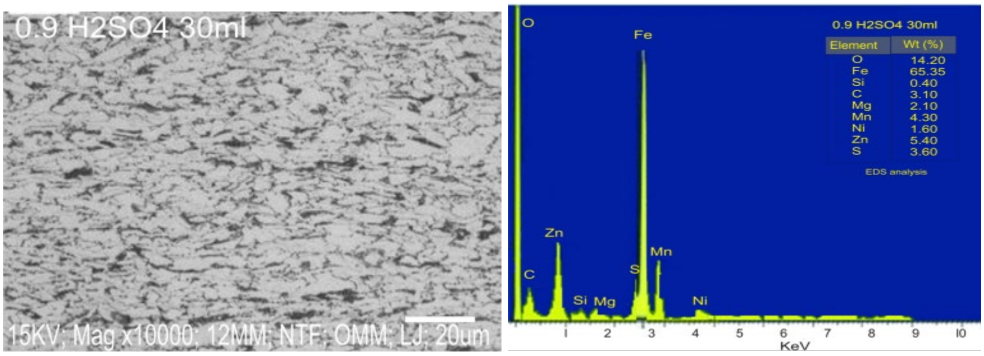


Figure 7 SEM/EDX of the Mild Steel substrate of 0.9g ALE of 30Ml in $1MH_2SO_4$

3.6 X-ray Diffraction (XRD)

The XRD analysis of leaf extract as a green corrosion inhibitor for mild steel in 10ml and 30ml H_2SO_4 reveals differences in its crystalline structure and corrosion inhibition properties.

In 10mL H_2SO_4: the crystalline structure formed sharp peaks indicating the presence corresponding compounds such as $Fe(MgSO_4)$, FeS_2, $Fe(ZnSO_4)$, $CaCO_3$, Fe_2O_3, CO_2CrO_4, Mn $(Fe)SiO_4$, Al(Mn.Fe). The corrosion inhibition formed a protective crystalline layer,reducing corrosion rates. The sulfur compounds revealed that there was the formation of a sulfide layer enhancing protection. In 30mL H_2SO_4: A sharp peaks formed indicating the presence of crystalline structure. The corresponding peaks include FeS_2, SiO_2 $(ZnSO_4)$, Al (Mn.Fe), Ca (Mn), Fe_2O_3, Zn (Fe) SiO_4, $MgSO_4$. A broad halo revealed the presence of an amorphous structure, lacking distinct peaks. [21].

There was an increased in the level acidity which was disrupted the crystalline structure, leading to an amorphous phase. The presence of sulfur revealed that there was a disordered form, which contributed to protection process. it forms an amorphous layer, both effectively inhibiting corrosion but adapting differently to the acidity levels. Figure 8 shows the XRD of 0.7g of Azadirachta indica leaf extract of 10mL in 1mol H_2SO_4 10ml, while Figure 9 shows the XRD of 0.9g Azadirachta indica leaf extract of 30mL in 1mol H_2SO_4.

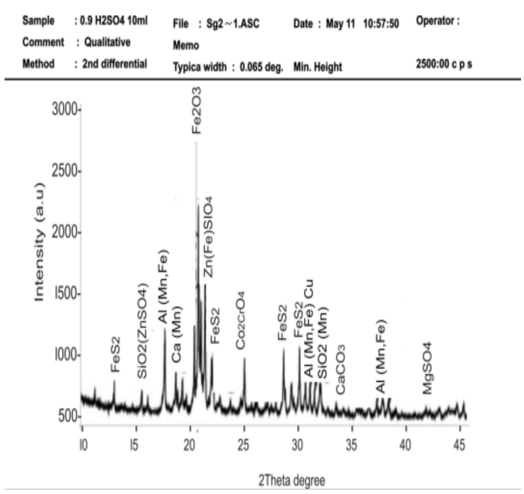


Figure 8 XRD of Azadirachta indica extract at 0.9 H_2SO_4 10 ml

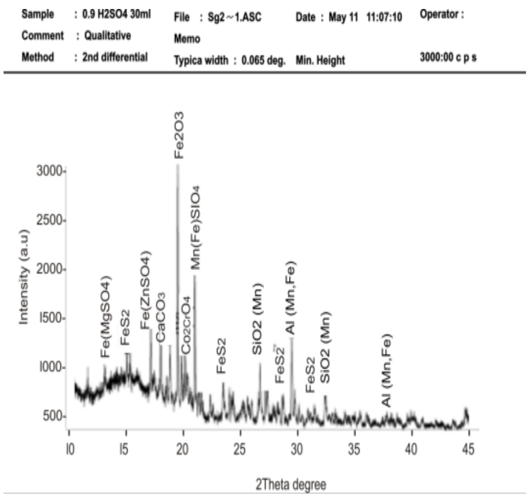


Figure 9 XRD of Azadirachta indica extract 0.9 H_2SO_4 30 ml

3.7 Electrochemical Analysis Results

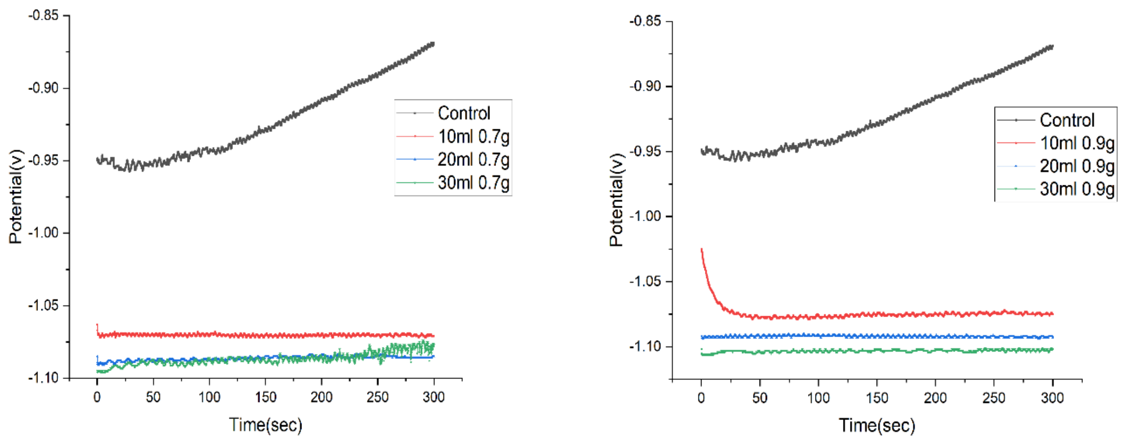
3.7.1 Open Circuit Potential (OCP) Result

The Open Circuit Potential (OCP) is a crucial parameter in corrosion studies, as it provides insight into the corrosion behavior of a material in a specific environment. In the context of the investigation of Azadirachta indica as a corrosion inhibitor on mild steel in 1mL H_2SO_4, the OCP values for different concentrations and exposure times are discussed as follows:

(a)Control (0% inhibitor): The OCP value for the control sample (without inhibitor) was more negative, indicating a higher tendency for corrosion to take place. [1]. This is because the acidic environment of 1M H_2SO_4 promotes the dissolution of iron from the mild steel surface.

(b)10mL of 0.7g Azadirachta indica in 1M H_2SO_4: The addition of 0.7g of Azadirachta indica inhibitor to 10mL of 1M H_2SO_4 solution shifted the OCP value to a more positive potential, indicating a decrease in corrosion rate.[3]. This is due to the adsorption of inhibitor molecules on the mild steel surface, blocking the active sites for corrosion.

(c)10mL of 0.9g Azadirachta indica in 1M H_2SO_4 : Increasing the concentration of Azadirachta indica inhibitor to 0.9g in 10mL of 1M H_2SO_4 solution further shifted the OCP value to a more positive potential, indicating a greater decrease in corrosion rate.[5]. This was due to the increased adsorption of inhibitor molecules on the mild steel surface.
(d) 20mL of 0.7g Azadirachta indica in 1M H_2SO_4: Increasing the exposure time(sec) in 20mL while maintaining the same concentration of 0.9g Azadirachta indica inhibitor in 1M H_2SO_4 solution resulted in a slight decrease in the OCP value, indicating a slight decrease in corrosion rate.[5]. This was due to the prolonged exposure of the mild steel surface to the corrosive environment.
(e) 20mL of 0.7g Azadirachta indica in 1M H_2SO_4: However, increasing the concentration of Azadirachta indica inhibitor to 0.7g in 20mL of 1mol H_2SO_4 solution further shifts the OCP value to a more positive potential, indicating a sustained or increased decrease in corrosion rate.[5].
(f) 30mL of 0.9g Azadirachta indica in 1M H_2SO_4: Further increase in the concentration of the leaf extract shows stability while maintaining the same concentration of 0.9g Azadirachta indica inhibitor in 1M H_2SO_4 solution resulted indicated a decrease in the OCP value, indicating a greater decrease in corrosion rate. [8].
(g) 30mL of 0.7g Azadirachta indica in 1M H_2SO_4: However, increasing the concentration of Azadirachta indica inhibitor to 0.7g in 30mL in1M H_2SO_4 solution was maintained which shifted the OCP value to a more positive potential, indicating a sustained or increased decrease in corrosion rate.[8]. The OCP values for the different concentrations and exposure times of the mild steel in the inhibitor in 1M H_2SO_4 solution indicate that the inhibitor was effective in reducing the corrosion rate of mild steel. The results also indicate that increasing the concentration of the inhibitor and decreasing the exposure time leads to a greater decrease in corrosion rate. Figure 10 (a) and (b) shows the OCP behaviour of the mild steel in 0.9g of the extract in 10, 20 and 30 mL 1M of H_2SO_4.



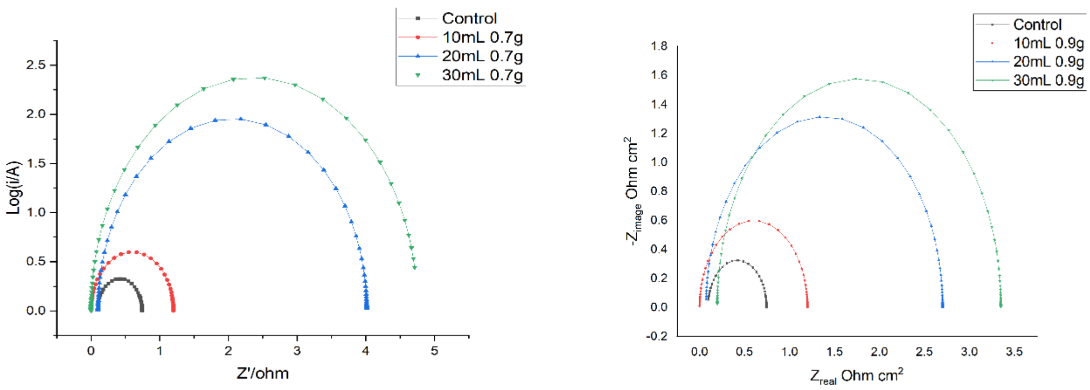
(a) (b)
Figure 10: OCP 0.7g and 0.9g ALE of 10, 20 and 30 mL in 1MH_2SO_4

3.7.2 Electrochemical Impedance Spectroscopy (EIS)

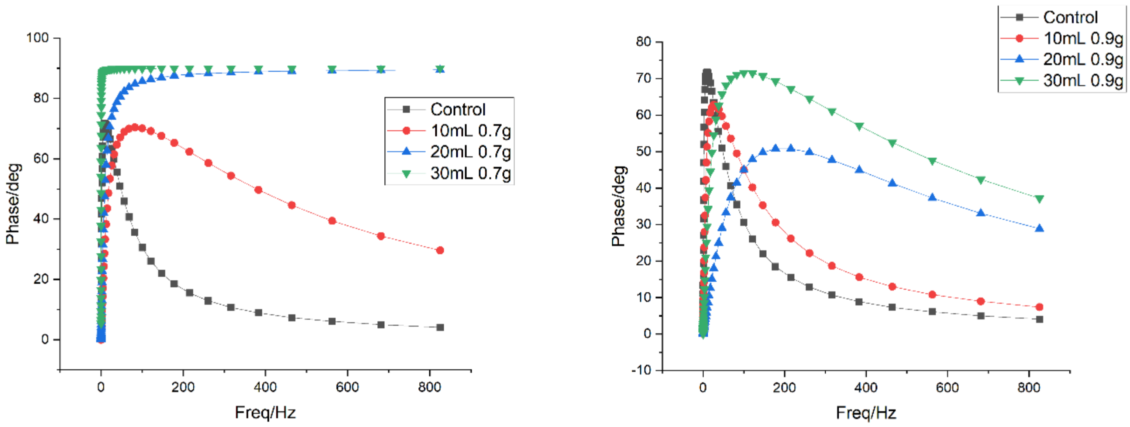
The Electrochemical Impedance Spectroscopy (EIS) is a powerful tool for investigating the corrosion behaviour of materials. In the process of the investigation of Azadirachta indica as a corrosion inhibitor on mild steel in 1M H_2SO_4, the EIS results for different concentrations and exposure times are discussed as follows:
(i)Control (0% inhibitor): The EIS spectrum for the control sample (without inhibitor) showed a small semicircle in the Nyquist plot, indicating a high corrosion rate. [8]. The Bode plot showed a low impedance value at high frequencies, indicating a high corrosion rate.
(ii) 10 mL of 0.7 g Azadirachta indica in 1M H_2SO_4: The addition of 0.7 g of Azadirachta indica inhibitor to 10 mL of 1M H_2SO_4 solution increased the diameter of the semicircle in the Nyquist plot, indicating a decrease in corrosion rate. [8]. The Bode plot showed an increase in impedance value at high frequencies, indicating a decrease in corrosion rate.
(iii)10 mL of 0.9 g Azadirachta indica in 1M H_2SO_4: Increasing the concentration of Azadirachta indica inhibitor to 0.9 g in 10 mL of 1M H_2SO_4 solution it further increased the diameter of the semicircle in the Nyquist plot, indicating a greater decrease in corrosion rate. [8]. The Bode plot showed a further increase in impedance value at high frequencies, indicating a greater decrease in corrosion rate.
(iv) 20 mL of 0.7 g Azadirachta indica in 1M H_2SO_4: Increasing the exposure time(sec) in 20 mL while maintaining the same concentration of 0.7 g Azadirachta indica inhibitor in 1M H_2SO_4 solution resulted in a decrease in the diameter of the semicircle in the Nyquist plot, indicating a slight increase in corrosion rate. [8]. The Bode plot indicated a slight decrease in impedance value at high frequencies, indicating a slight increase in corrosion rate.

Received: 06/07/2025; Revised: 15/07/2025; Accepted: 15/07/2025; Published: 08/08/2025

(v) 20 mL of 0.9 g Azadirachta indica in 1M H_2SO_4 : However, increasing the concentration of Azadirachta indica inhibitor to 0.9 g in 20 mL of 1M H_2SO_4 solution maintained and further increase the diameter of the semicircle in the Nyquist plot, indicating a sustained or greater decrease in corrosion rate [8].
(vi) 30 mL of 0.7 g Azadirachta indica in 1M H_2SO_4 :Further increasing the exposure time(sec) in 30 mL while maintaining the same concentration of 0.7 g Azadirachta indica inhibitor in 1M H_2SO_4 solution resulted in a more significant decrease in the diameter of the semicircle in the Nyquist plot, indicating a greater decrease in corrosion rate. [8].
(vii) 30 mL of 0.9 g Azadirachta indica in 1M H_2SO_4 : However, increasing the concentration of Azadirachta indica inhibitor to 0.9 g in 30 mL of 1 M H_2SO_4 solution further increased the diameter of the semicircle in the Nyquist plot, indicating a sustained or greater decrease in corrosion rate. [8]. The EIS results indicate that Azadirachta indica is an effective corrosion inhibitor for mild steel in 1M H_2SO_4 solution. The results also indicate that increasing the concentration of the inhibitor and decreasing the exposure time can lead to a greater decrease in corrosion rate. Figure 11 shows the EIS behaviour of the mild steel in various 10, 20 and 30 mL of 1M in H_2SO_4. Figure 12: Bode plot behaviour of the mild steel in various concentration of the leaf extract in 1M of H_2SO_4. Figure 13 shows the circuit of EIS of the Control Sample and Table 4: values of the sample obtained from various Circuits



(a) (b)
Figure 11: EIS 0.7g and 0.9g ALE of 10, 20 and 30mL in 1MH_2SO_4



(a) (b)
Figure 12: EIS 0.7g and 0.9g ALE of 10, 20 and 30mL in 1 M H_2SO_4

Received: 06/07/2025; Revised: 15/07/2025; Accepted: 15/07/2025; Published: 08/08/2025

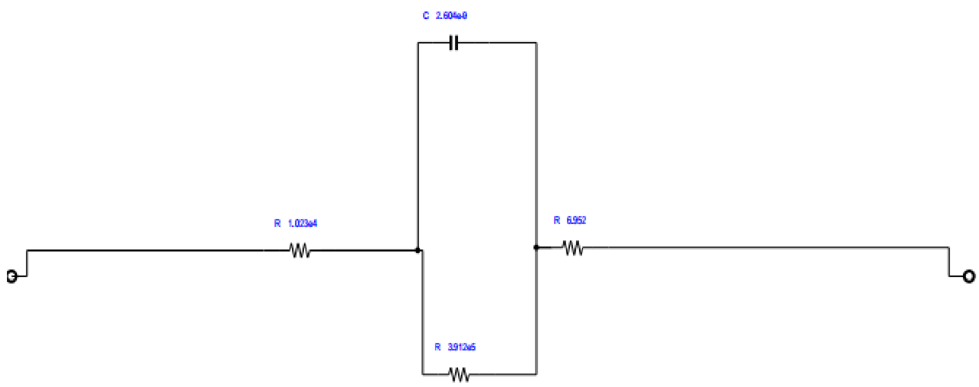


Figure 13: The circuit of EIS of the control sample

Table 4: Values of the sample obtained from various circuits

S/N	Sample	Resistor (R)	Capacitor (C)	Resistor (R)	Resistor (R)
1	Control	0.01	1.754e-9	1.19e5	0.01
2	0.7 g of 10 mL in 1 M H_2SO_4	0.01	3.142e-8	4.753e5	0.01
3	0.9 g of 10 mL in 1 M H_2SO_4	6.256	3.539e-10	799.8	2631e5
4	0.7 g of 20 mL in 1 M H_2SO_4	1,02e4	2,6-5e-9	6.952	3.912e5
5	0.9 g of 20 mL in 1 M H_2SO_4	1.145e4	7.573e-10	8081	3.153e5
6	0.7 g of 30 mL in 1 M H_2SO_4	1051	3.201e-9	3.412e-4	0.01
7	0.9 g of 30 mL in 1 M H_2SO_4	0.01	8.135e-10	7,30te4	0.01

1. Resistance (R): Significant variation in the results between samples suggests variations in the electrochemical system's resistance.
2. The capacitance values of the second capacitor (C) likewise fluctuate, indicating variations in the double-layer capacitance or other capacitive processes.
3. Resistor (R): There are notable fluctuations in the second resistor values, which may be associated with resistive processes or charge transfer resistance.
4. Resistor (R): Without additional information, it is unclear what the units or significance of the fourth column, which seems to be another resistor value, are.

The results revealed that there was an increased in resistance of sample with higher concentrations (0.9g) of 30mL in 1MH_2SO_4 which show higher resistance values. The capacitance values varied significantly across samples, which related to changes in the electrochemical interface and double-layer capacitance. The 30mL sample show distinct resistance and capacitance in values compared to the 10mL and 20mL samples. The variations in the circuit element values indicate that the electrochemical behaviour of the samples were influenced by the concentration and volume of the solution. These changes related to differences in corrosion rates, electrochemical reactions, or other processes occurring at the electrode-solution interface.

3.7.3 Potentiodynamic Polarization (Tafel Plots)

The corrosion rate of mild steel also decreased with increasing extract concentration in 1M H_2SO_4 .According to the Tafel plot analysis, the results revealed that the leaf extract has a stronger corrosion tendency to mitigate corrosion processes . The Tafel plots for the investigation of Azadirachta indica as a corrosion inhibitor on mild steel in 1M H_2SO_4 provides valuable insights into the corrosion behaviour. The control sample without Azadirachta indica inhibitor showed a higher corrosion rate, as indicated by a higher corrosion rate in the Tafel plot. The anodic and cathodic Tafel slopes are higher, indicating a higher corrosion rate. The potentiodynamic polarisation results for a range of samples are shown in the Table 5.

Table 5 : Anodic and cathodic slope and other parameters

sample	Cat Slp (1/V)	Ano Slp (1/V)	Cat Int (log i)	Ano Int (log i)	Lin Pol R (ohm)	Corr i (A)	Rate (mil/year)	Rate (Angs/min)	Rate (gram/hr)
control	4.706	6.53	-4.11	-4.24	259	1.49E-04	1.16E+02	5.62E+01	1.82E-04

Received: 06/07/2025; Revised: 15/07/2025; Accepted: 15/07/2025; Published: 08/08/2025

10ml 0.7	6.612	8.043	-2.589	-2.253	8	3.92E-03	3.05E+03	1.47E+03	4.78E-03
10ml 0.9	7.324	7.608	-2.745	-2.274	10	2.81E-03	2.19E+03	1.06E+03	3.43E-03
20ml 0.7	7.296	7.653	-3.265	-3.265	39	7.43E-04	5.79E+02	2.80E+02	9.07E-04
20ml 0.9	5.551	5.989	-2.167	-1.741	3	1.34E-02	1.05E+04	5.06E+03	1.64E-02
30ml 0.7	5.771	5.79	-2.086	-1.644	2	-1.644	1.32E+04	6.36E+03	2.06E-02
30ml 0.9	5.592	6.242	2.107	1.737	3	1.34E-02	1.04E+04	5.03E+03	1.63E-02

The cathodic polarisation curve's slope, or cathodic slope (Cat Slp), revealed the kinetics of the cathodic reaction. The anodic polarisation curve's slope, or anodic slope (Ano Slp), shows the kinetics of the anodic reaction. The cathodic polarisation curve's intercept with respect to the exchange current density. The exchange current density and the anodic intercept (Ano Int), or the intercept of the anodic polarisation curve, are connected. The Linear Polarisation Resistance, or Lin Pol R, measured the corrosion resistance which provide greater values indicating a stronger resistance. The Corrosion Current (Corr I measured the corrosion rate which was greater in values and indicated higher corrosion rates. The corrosion rate expressed in a variety of units, including meters per year, angstroms per minute, and grammes per hour. The results show that the corrosion process is provided by the results of the potentiodynamic polarisation tests. The concentration and volume of the solution impacted on the electrochemical reactions and corrosion processes, as shown by slope values, corrosion current, and rate changes. These findings were used to enhance material performance and improve corrosion reduction circumstances.

(i)10 mL of 0.7 g Azadirachta indica in 1M H_2SO_4: The addition of 0.7 g of Azadirachta indica inhibitor to 10 mL of 1M H_2SO_4 solution indicated a shift of the Tafel plot to lower current densities, indicating a decrease in corrosion rate. [5]The anodic and cathodic Tafel slopes decreased, indicating a decrease in corrosion rate.

(iii)10 mL of 0.9 g Azadirachta indica in 1 M H_2SO_4: Increasing the concentration of Azadirachta indica inhibitor to 0.9 g in 10 mL of 1 M H_2SO_4 solution shifted the Tafel plot to lower current densities further, indicating a greater decrease in corrosion rate. [2]. The anodic and cathodic Tafel slopes are also decrease further, indicating a greater decrease in corrosion rate.

(iv) 20 mL of 0.7g Azadirachta indica in 1M H_2SO_4: Increasing the H_2SO_4 concentration to 20 mL while maintaining the same concentration of 0.7g Azadirachta indica inhibitor resulted in a slight increase in corrosion rate, as indicated by a higher current density in the Tafel plot. Singh & Quraishi (2019). The anodic and cathodic Tafel slopes increased, indicating an increase in the corrosion rate.

(v) 20 mL of 0.9 g Azadirachta indica in 1M H_2SO_4 : However, increasing the concentration of Azadirachta indica inhibitor to 0.9 g in 20 mL in 1M H_2SO_4 solution maintained a decrease in the corrosion rate, as indicated by a lower current density in the Tafel plot. [8].

(vi)30 mL of 0.7 g Azadirachta indica in 1M H_2SO_4 : Further increasing the H_2SO_4 concentrate to 30 mL while maintaining the same concentration of 0.7 g Azadirachta indica inhibitor was utilized, resulting in a more significant increase in corrosion rate, as indicated by a higher current density in the Tafel plot.

(vii)30 mL of 0.9 g Azadirachta indica in 1M H_2SO_4 : However, increasing the concentration of Azadirachta indica inhibitor to 0.9 g in 30 mL of 1M H_2SO_4 solution maintained a further decrease in the corrosion rate, as indicated by a lower current density in the Tafel plot.

The Tafel plots indicate that Azadirachta indica is an effective corrosion inhibitor for mild steel in 1 M H_2SO_4 solution. The results also indicate that increasing the concentration of the inhibitor leads to a greater decrease in corrosion rate. Figure 14: Tafel behaviour of the mild steel in various 10, 20 and 30mL of 0.7g and 0.9g 1M H_2SO_4.

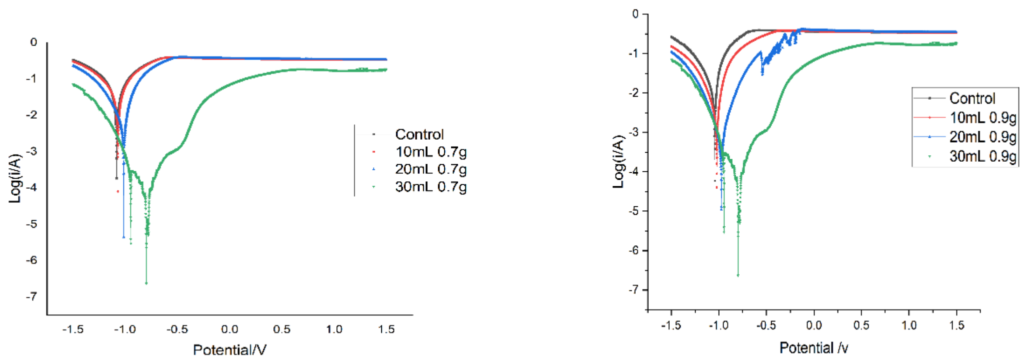


Figure 14: Tafel behaviour of the mild steel in various concentrations of the extract in 1M H_2SO_4

Received: 06/07/2025; Revised: 15/07/2025; Accepted: 15/07/2025; Published: 08/08/2025

4.0 Conclusion

The findings imply that the extract from Azadirachta indica forms a protective layer that prevents corrosion by adhering to the mild steel surface.

1. The chemical compositions of the mild steel were determined and the revealed that it consists 0.2%C and other relevant elements
2. The pH value obtained from the leaf extract was 1 while H_2SO_4 was 0.5.
3. The compounds present in the extract from phytochemicals analysis indicates that it contains alkaloids at 0.6%, flavonoids at 5.8%, Saponins at 1.5% , Tannins at 3.6% and Phenol at 7.8% . These compounds are responsible for the corrosion inhibition on the mild steel, thereby mitigating the corrosion process.
4. The FTIR analysis revealed the functional groups that were present such asOH, (C=O),(N-H)and (C=C). These groups processes corrosion inhibition properties that adsorbed onto the metal surface through π-π stacking or donating electrons to the metal ions.
5. The SEM /EDX indicated the morphology with smooth and uniform structure that shows the presence of the leaf extract , while the EDX shows the elements in weight (%) for 0.7 and 0.9g of the extract in 10, 20 and 30mL in 1MH_2SO_4.
6. The XRD analysis of leaf extract as a green corrosion inhibitor for mild steel in 10ml and 30ml H_2SO_4 reveals differences in its crystalline structure and corrosion inhibition properties.The XRD results for 0.7g of 10mL and 30mL in H_2SO_4 where the crystalline structure formed sharp peaks indicating the presence corresponding compounds such as Fe($MgSO_4$), FeS_2, Fe($ZnSO_4$), $CaCO_3$, Fe_2O_3, CO_2CrO_4, Mn (Fe)SiO_4, Al(Mn.Fe). The corrosion inhibition formed a protective crystalline layer, reducing corrosion rates. The sulfur compounds revealed that there was the formation of a sulfide layer enhancing protection. Similarly, the XRD result for 0.9g of 10 mL and 30mL in H_2SO_4 with the corresponding peaks include FeS_2, SiO_2 (ZnSO4), Al (Mn.Fe), Ca (Mn), Fe_2O_3, Zn (Fe) SiO_4, $MgSO_4$. A broad halo revealed the presence of an amorphous structure, lacking distinct peaks. [21]
7. The OCP, EIS and PDP measurements were conducted using a potentiostat. The charge transfers resistance (Rct) was computed by utilising the Nyquist plot to analyse the EIS spectra. The extract functions as a mixed-type inhibitor, according to the OCP, EIS and PDP data. In the presence of the inhibitor, the charge transfers resistance (Rct) significantly increases, as indicated by the Nyquist and the Bode plots, which also demonstrates a decrease in the rate of corrosion. As the inhibitor concentration increases, the PDP curves demonstrate a drop in the corrosion current density (i_{corr}) . The findings of potentiodynamic polarisation demonstrated that the corrosion rate dropped from 1.164e+002 to 1.3166e+004 in the 0.7g of 30mL in 1M H_2SO_4 medium and from 1.164e+002 to 1.042e+004 in the 0.9g of 30mL in H_2SO_4. The development of a physical protective layer in the mild steel was credited with the enhanced corrosion resistance of the *Azadirachta indica* leaf extract. The extract's chemical inertness was also cited as a factor in the mild steel's lower rate of corrosion
8. The study's findings show that Azadirachta indica extract prevents mild steel from corroding in 1mol H_2SO_4 with varied concentration of the extract.The extract functions as a mixed-type inhibitor. lude OCP, EIS and PDP plots. The Azadirachta indica shows promise as an environmentally friendly mild steel corrosion inhibitor in acidic settings and contribute to mitigating the corrosion process for efficient and effective performances.

Acknowledgements

The authors appreciate and thank TETFund for supporting research project no. (TETF /DR& D/CE/ UNI/ NSUKKA /BR/2024 /VOL.IB).

Conflict of interest

No conflicts of interest are disclosed by the authors.

References

[1] Singh, A. K., & Quraishi, M. A. Corrosion inhibition of mild steel in acidic media by some plant extracts: A review. Journal of Materials and Environmental Science,2019 10(2), 151-163.

[2] Kumar, S., & Quraishi, M. A. Corrosion inhibition of mild steel in acidic media by Azadirachta indica bark extract. Journal of Adhesion Science and Technology, 2018 32(10), 1039-1053.

[3] Bard, A. J., & Faulkner, L. R. Electrochemical Methods: Fundamentals and Applications. John Wiley & Sons. 2001.

[4] Hussein, L. B. K. A., Mater, A. A. A., Clinic, H. K. M., Alanbar, D. M. F. K., & Ali, S. M. F. The Role of Rusts in Corrosion and Corrosion Protection of Iron and Steel. Journal of Medical Genetics and Clinical Biology, 20241(8), 229–233. (link unavailable) .

[5] Sharma, S. K., Sharma, S. K., & Quraishi, M. A. Investigation of Azadirachta indica leaves extract as a corrosion inhibitor for mild steel in 1 M H_2SO_4. Journal of Environmental Chemical Engineering, 2020 8(4), 103944.

[6] Răuță, D.-I., Matei, E., & Avramescu, S.-M. Recent Development of Corrosion Inhibitors:Types, Mechanisms, Electrochemical Behavior, Efficiency, and Environmental Impact. Technologies, 2025 13(3), 103

[7] Marko Chigondo and Fidelis Chigondo Recent Natural Corrosion Inhibitors for Mild Steel: An Overview Hindawi Publishing Corporation , Journal of Chemistry , Volume Article ID 6208937, 7 2016 pages http://dx doi .org/10.1155/2016/6208937

[8] Tetyana Kalyn,Olga Fomicheva,Halyna Hrytsuliak, Yury Voloshyn, Tetiana Hoisan(2025) Environmentally friendly corrosion inhibitors: a modern alternative to traditional methods of

[9] protecting metal structures International Science Journal of Engineering & Agriculture 2025;4(3):66-80, https://isg-journal.com/isjeadoi: 10 .46299/j.isjea.20250403.06, ISSN: 2720-6319.

[10] Bhoomika R. Holla a a , R. Mahesh b , ** , H.R. Manjunath Plant extracts as greencorrosion inhibitors for different kinds of steel: A review Heliyon journal homepage 2024

[11] Abd El Maksoud, S., & Fouda, A. E. A. researched "Furosemide drug as a corrosion inhibitor for carbon steel in 1.0 M hydrochloric acid" in Scientific Reports 2024

[12] Sharma, S. K., & Quraishi, M. A. Investigating the efficacy of Azadirachta indica (neem) leaf on mild steel corrosion in acidic media. International Journal of Industrial Chemistry, 2020 10(1), 31-47.

[13] Guillen, E.; Terrones, H.; de Terrones, T.C.; Simirgiotis, M.J.; Hájek, J.; Cheel, J.; Sepulveda, B.; Areche, C. Microwave-Assisted Extraction of Secondary Metabolites Using Ethyl Lactate Green Solvent from *Ambrosia arborescens*: LC/ESI-MS/MS and Antioxidant Activity. 2024 *Plants 13*, 1213. https://doi.org/10.3390/ plants13091213

[14] Cifuentes-Araya, N.; Simirgiotis, M.; Sepúlveda, B.; Areche, C.Green Separation by Using Nanofiltration of *Tristerix tetrandus* Fruits and Identification of Its Bioactive Molecules through MS/MS Spectrometry. *Plants 2024* , *13*, 1521. https://doi.org/10.3390/ plants13111521

[15] Imcharoen, U.; Rachtanapun, P.; Thipchai, P.; Sae Eng, R.;Chinvorarat, S.; Jearanaisilawong, P. Effects of Steam Explosion on Curcumin Extraction from Fresh Turmeric Chips. *Plants* **2024**, *13*, 3417. https://doi.org/10.3390/ plants13233417

[16] N.; Krishna, S.B.N.; Gqaleni, N.; Ngcobo, M. Extraction and Processing of Bioactive Phytoconstituents from Widely Used South African Medicinal Plants for the Preparation of Effective Traditional Herbal Medicine Products: A Narrative Review. *Plants* **2025**, *14*, 206. https://doi.org/10.3390/ plants14020206

[17] Shyamal Majumdar(2017) and others, who published a book titled "Penghijauan Pendidikan dan Latihan Teknikal Serta Vokasional: Panduan untuk Institusi" Journal of Food Science and Technology or Phytochemistry 2017

[18] Suresh Kumar* and Veda Krishnan,(2017 Phytochemistry and Functional Food: The Needs of

[19] Healthy Life Journal of a e Phytochemistry & Biochemistry y & Research Article Commentary Phytochemistry Biochem 2017

[20] Riffi, O., Salim, R., Ech-chihbi, E., Taleb, M., Fliou, J., & Elhourri, M. et al. Experimental and Quantum Studies of Dysphania ambrosioides (L.) as Ecological Corrosion Inhibitor for Mild Steel in Hydrochloric Acid Environment. Journal of Bio- and Tribo-Corrosion, 8(4), 2022. (link unavailable)

[21] Faustin, M., Maciuk, A., Salvin, P., Roos, C., & Lebrini, M. (2015). Corrosion inhibition of C38 steel by alkaloids extract of Geissospermum laeve in 1 M hydrochloric acid: Electrochemical and phytochemical studies. Corrosion Science, 92, 287-300. (link unavailable)

[22] Zhang, Q. H., Hou, B. S., Li, Y. Y., Zhu, G. Y., Liu, H. F., & Zhang, G. A.. Effective corrosion inhibition of mild steel by eco-friendly thiourea functionalized glucosamine derivatives in acidic solution. Journal of Colloid and Interface Science,2021 585, 355-367. (link unavailable)

[23] Macdonald, D. D. Application of electrochemical impedance spectroscopy in electrochemistry and corrosion science. Techniques for Characterization of Electrodes and Electrochemical Processes, 1992 515-580. (link unavailable)

[24] Orazem, M. E., & Tribollet, B. (2008). Electrochemical Impedance Spectroscopy. John Wiley & Sons.

[25] Lasia, A. Electrochemical Impedance Spectroscopy and its Applications. Springer.

[26] Faustin, M., Maciuk, A., Salvin, P., Roos, C., & Lebrini, M. (2015). Corrosion inhibition of C38 steel by alkaloids extract of Geissospermum laeve in 1 M hydrochloric acid: Electrochemical and phytochemical studies. Corrosion Science, 2014 92, 287-300. (link unavailable).

[27] Zhang, Q. H., Hou, B. S., Li, Y. Y., Zhu, G. Y., Liu, H. F., & Zhang, G. A. Effective corrosion inhibition of mild steel by eco-friendly thiourea functionalized glucosamine derivatives in acidic solution. Journal of Colloid and Interface Science, 2021 585, 355-367. (link unavailable).

[28] Amer F. Noori, Nader M. Moustafa, and Katea L. Hamid published "Microbial Corrosion Study Using Tafel Principles of Polarization" in IOP Conference Series: Materials Science and Engineering, exploring the application of Tafel principles in microbial corrosion studies 2020
[29] Satoru Yamamoto, Kenkichi Tashiro, and Masaru Abe presented "A Novel Corrosion Rate Monitoring Method for Steel in Soil Based on Tafel Extrapolation Method" at 2021 CORROSION
[30] José Enrique Ramón, Isabel Martínez, José Manuel Gandía-Romero, and Juan Soto published "Improved Tafel-Based Potentiostatic Approach for Corrosion Rate Monitoring of Reinforcing Steel" in Journal of Nondestructive Evaluation, 2022 DOI: 10.1007/s10921-022-00903-z.

Received: 06/07/2025; Revised: 15/07/2025; Accepted: 15/07/2025; Published: 08/08/2025