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Design, Synthesis, and Electrochemical Evaluation of Eco-Friendly Schiff Base Corrosion Inhibitors for Mild Steel in Acidic Environments

DR L MAHESWARA REDDY

Academic Consultant, Department of Science and Humanities,
Y.S.R. Engineering College of YVU, Proddatur - 516360
Mail id: lebakamaheswarareddy@gmail.com

ABSTRACT: *Corrosion of mild steel in acidic environments represents one of the most significant challenges encountered in industrial processes such as acid pickling, oil and gas production, petrochemical refining, acid descaling, and chemical manufacturing. Excessive corrosion not only shortens the service life of metallic structures but also increases maintenance costs, environmental risks, and operational downtime. Although numerous synthetic corrosion inhibitors have been developed, many conventional inhibitors exhibit high toxicity, poor biodegradability, and adverse environmental impacts, limiting their practical application under increasingly stringent environmental regulations. Schiff base compounds have recently emerged as promising eco-friendly corrosion inhibitors because of their facile synthesis, excellent adsorption characteristics, abundant electron-donating functional groups, and strong coordination ability with metal surfaces. This research presents the design, synthesis, characterization, and electrochemical evaluation of environmentally benign Schiff base corrosion inhibitors for protecting mild steel in acidic media. The synthesized Schiff base compounds are characterized using Fourier Transform Infrared Spectroscopy (FTIR), Nuclear Magnetic Resonance (^{1}H NMR and ^{13}C NMR), Ultraviolet–Visible spectroscopy (UV–Vis), Mass Spectrometry (MS), and Elemental Analysis to confirm their molecular structures and purity. Corrosion inhibition performance is investigated using potentiodynamic polarization, electrochemical impedance spectroscopy (EIS), open circuit potential (OCP), weight loss analysis, and surface morphology characterization through Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS). The influence of inhibitor concentration, immersion time, temperature, and acid concentration on corrosion inhibition efficiency is systematically evaluated. Experimental results demonstrate that the synthesized Schiff base inhibitors significantly reduce corrosion rates by forming stable protective adsorption films on the mild steel surface, achieving inhibition efficiencies exceeding 95% under optimized conditions. The developed eco-friendly inhibitors provide an effective, sustainable, and economically attractive alternative to conventional toxic corrosion inhibitors for industrial acid cleaning and metal protection applications.*

INTRODUCTION

Corrosion is a naturally occurring electrochemical process responsible for the gradual deterioration of metallic materials through chemical or electrochemical interactions with their surrounding environment. Among engineering materials, mild steel remains one of the most widely utilized structural metals because of its excellent mechanical properties, low production cost, ease of fabrication, and widespread industrial availability. Mild steel is extensively employed in chemical processing plants, petroleum refineries, pipelines, storage tanks, heat exchangers, marine structures, automobiles, and construction industries. However, exposure to aggressive acidic environments during industrial operations such as acid pickling, descaling, oil well acidization, and chemical cleaning significantly accelerates corrosion processes, resulting in severe material degradation, equipment failure, economic losses, and potential environmental hazards. Consequently, developing efficient corrosion protection strategies remains a major research priority in materials chemistry, electrochemistry, and industrial corrosion science.

Numerous corrosion protection techniques have been developed to minimize metal degradation in aggressive environments. Common approaches include protective coatings, cathodic protection, anodic protection, alloy

development, surface modification, and corrosion inhibitor addition. Among these methods, corrosion inhibitors represent one of the most practical and economically viable solutions because they require relatively low concentrations while providing substantial corrosion protection without major modifications to existing industrial processes. Corrosion inhibitors function primarily by adsorbing onto the metal surface, thereby forming a protective molecular barrier that suppresses both anodic metal dissolution and cathodic hydrogen evolution reactions. The effectiveness of an inhibitor depends strongly on its molecular structure, adsorption characteristics, functional groups, electronic properties, and compatibility with the corrosive medium.

Traditionally, many commercially available corrosion inhibitors have consisted of inorganic chromates, phosphates, nitrites, and various synthetic organic compounds containing sulfur, phosphorus, nitrogen, or halogen atoms. Although these inhibitors often exhibit excellent corrosion protection, numerous conventional formulations possess significant drawbacks including high toxicity, poor biodegradability, environmental persistence, and potential health hazards. Increasing environmental awareness together with stringent international regulations governing hazardous chemicals has therefore stimulated intensive research into environmentally benign corrosion inhibitors derived from sustainable chemical sources. Green corrosion inhibitors not only minimize ecological impact but also support the principles of sustainable chemistry by reducing toxic chemical usage and promoting environmentally responsible industrial practices.

Schiff base compounds have attracted considerable attention as environmentally friendly corrosion inhibitors because of their unique molecular structures containing azomethine (–C=N–) functional groups together with aromatic rings and heteroatoms such as nitrogen and oxygen. These structural features provide abundant electron-rich adsorption centers capable of forming coordinate interactions with vacant d-orbitals of metal atoms. The resulting adsorption layer effectively isolates the metal surface from aggressive acidic media, thereby reducing corrosion rates through both physical adsorption and chemisorption mechanisms. Furthermore, Schiff bases can be synthesized conveniently through simple condensation reactions between primary amines and aldehydes or ketones under relatively mild reaction conditions. The ease of synthesis, structural versatility, high inhibition efficiency, and low environmental toxicity make Schiff base compounds highly attractive candidates for sustainable corrosion protection.

Recent advances in molecular design have enabled the development of Schiff base inhibitors possessing enhanced adsorption strength, improved thermal stability, and superior electrochemical performance. Incorporation of electron-donating substituents, aromatic conjugation, heterocyclic rings, and multiple adsorption centers significantly improves interaction between inhibitor molecules and metal surfaces. Comprehensive characterization using Fourier Transform Infrared Spectroscopy (FTIR), Nuclear Magnetic Resonance (NMR), Ultraviolet–Visible spectroscopy, Mass Spectrometry, and elemental analysis provides detailed information regarding molecular structure and purity of synthesized inhibitors. Electrochemical techniques including potentiodynamic polarization and electrochemical impedance spectroscopy have become indispensable tools for evaluating inhibition mechanisms, charge transfer resistance, double-layer capacitance, corrosion current density, and overall inhibitor performance under realistic corrosive environments.

The present research focuses on the design, synthesis, and electrochemical evaluation of eco-friendly Schiff base corrosion inhibitors for protecting mild steel in hydrochloric acid solution. The synthesized compounds are structurally characterized using multiple spectroscopic techniques before their corrosion inhibition performance is evaluated through weight loss measurements, electrochemical analysis, and surface characterization. The effects of inhibitor concentration, immersion time, temperature, and acid concentration are systematically investigated to optimize corrosion protection efficiency. The outcomes of this study are expected to contribute toward the

development of sustainable corrosion inhibitor technologies capable of replacing environmentally hazardous commercial inhibitors in industrial acid treatment processes.

Problem Statement

Mild steel experiences severe corrosion during industrial operations involving acidic environments such as acid pickling, descaling, and oil well acidization. Conventional corrosion inhibitors often contain toxic chemicals that present significant environmental and health concerns while failing to satisfy increasingly stringent environmental regulations. Therefore, there is a growing need to develop environmentally friendly Schiff base corrosion inhibitors capable of providing high corrosion protection efficiency, excellent adsorption behavior, and long-term stability while minimizing ecological impact and supporting sustainable industrial corrosion control.

Objective

The primary objective of this research is to design, synthesize, and characterize eco-friendly Schiff base compounds and evaluate their corrosion inhibition performance for mild steel in acidic environments using electrochemical and gravimetric techniques. The study further aims to investigate the influence of inhibitor concentration, immersion time, temperature, and acid concentration on inhibition efficiency while examining adsorption mechanisms, electrochemical behavior, and surface morphology to establish structure–performance relationships.

Scope

The scope of this research includes the molecular design and green synthesis of Schiff base corrosion inhibitors, structural characterization using FTIR, ^{1}H NMR, ^{13}C NMR, UV–Visible spectroscopy, Mass Spectrometry, and elemental analysis, followed by corrosion inhibition studies in hydrochloric acid solution using weight loss measurements, potentiodynamic polarization, electrochemical impedance spectroscopy, and open circuit potential analysis. Surface characterization through SEM and EDS is employed to evaluate protective film formation after corrosion testing. The investigation also includes adsorption isotherm analysis, corrosion kinetics, temperature-dependent inhibition studies, inhibitor reusability assessment, and comparison with conventional corrosion inhibitors. The developed eco-friendly Schiff base compounds are intended for applications in industrial acid cleaning, petroleum refining, chemical processing, pipeline protection, and sustainable corrosion management systems.

LITERATURE SURVEY

Corrosion of metallic materials remains one of the most significant challenges encountered in industrial engineering, causing enormous economic losses and safety concerns worldwide. Mild steel, owing to its excellent mechanical strength, weldability, low production cost, and wide availability, is extensively utilized in pipelines, storage tanks, chemical reactors, boilers, marine structures, automobiles, heat exchangers, and construction industries. However, its exposure to aggressive acidic environments during industrial operations such as acid pickling, descaling, oil well acidification, and chemical cleaning accelerates electrochemical dissolution, resulting in rapid material degradation. The global economic impact of corrosion has been estimated to account for approximately 3–4% of the gross domestic product of many industrialized nations, highlighting the urgent need for efficient and sustainable corrosion protection technologies.

Among the numerous corrosion control techniques available, the addition of corrosion inhibitors has become one of the most practical, economical, and efficient methods for minimizing metal deterioration in acidic media. Corrosion inhibitors function primarily by adsorbing onto the metal surface and forming a protective molecular film

that blocks active anodic and cathodic reaction sites. This adsorbed layer significantly decreases electron transfer between the metal and corrosive environment, thereby reducing corrosion current density and slowing the electrochemical dissolution process. The inhibition efficiency strongly depends on molecular structure, electronic configuration, adsorption behavior, concentration, solution temperature, and the nature of the corrosive medium.

Early corrosion inhibitors primarily consisted of inorganic compounds including chromates, phosphates, molybdates, nitrites, and silicates. These inorganic inhibitors demonstrated excellent corrosion protection but were gradually restricted because of their toxicity, carcinogenicity, poor biodegradability, and adverse environmental effects. Subsequently, organic corrosion inhibitors containing heteroatoms such as nitrogen, oxygen, sulfur, and phosphorus were introduced as more effective alternatives due to their superior adsorption characteristics. Organic molecules possessing aromatic rings, conjugated π-electron systems, lone-pair electrons, and multiple adsorption centers exhibited stronger interactions with metallic surfaces through both physical adsorption and chemisorption mechanisms. Nevertheless, many commercially available synthetic organic inhibitors still present environmental concerns because of their limited biodegradability and potential ecological toxicity.

In recent years, the principles of **green chemistry** have significantly influenced corrosion science by encouraging the development of environmentally benign corrosion inhibitors derived from renewable and biodegradable chemical sources. Green corrosion inhibitors offer several important advantages including low toxicity, renewable availability, biodegradability, minimal environmental impact, and compatibility with sustainable industrial practices. Natural products, amino acids, plant extracts, polymers, ionic liquids, surfactants, and Schiff base compounds have therefore attracted considerable attention as potential eco-friendly corrosion inhibitors. Their ability to provide high inhibition efficiency while minimizing ecological risks has made them promising alternatives to conventional toxic inhibitor formulations.

Among various classes of organic inhibitors, **Schiff base compounds** have emerged as one of the most extensively investigated inhibitor families because of their unique molecular architecture and exceptional adsorption properties. Schiff bases are generally synthesized through condensation reactions between primary amines and aldehydes or ketones, resulting in the formation of azomethine (–C=N–) functional groups. The azomethine linkage together with aromatic rings and heteroatoms provides abundant electron-rich adsorption sites capable of coordinating strongly with vacant d-orbitals of iron atoms present on mild steel surfaces. These interactions produce compact protective films that effectively isolate the metal from corrosive acidic solutions. Furthermore, Schiff bases possess highly tunable molecular structures, enabling systematic modification through substitution of electron-donating or electron-withdrawing functional groups to enhance corrosion inhibition performance.

Several experimental studies have demonstrated that Schiff base corrosion inhibitors exhibit excellent protection efficiencies in hydrochloric acid and sulfuric acid solutions. Molecules containing multiple nitrogen atoms, hydroxyl groups, methoxy substituents, sulfur-containing functional groups, or extended aromatic conjugation generally display superior adsorption strength because these structural features increase electron density available for coordination with metallic surfaces. The adsorption behavior of Schiff base molecules has frequently been described using Langmuir, Temkin, Freundlich, and Frumkin adsorption isotherms, indicating spontaneous adsorption through combined physisorption and chemisorption mechanisms. Thermodynamic investigations further suggest that adsorption free energy, enthalpy, and entropy significantly influence inhibitor stability under varying temperature conditions.

Electrochemical techniques have become indispensable tools for evaluating corrosion inhibition mechanisms and quantifying inhibitor performance. Potentiodynamic polarization measurements provide valuable information

regarding corrosion current density, corrosion potential, anodic dissolution, and cathodic hydrogen evolution reactions. Electrochemical Impedance Spectroscopy (EIS) enables determination of charge transfer resistance, double-layer capacitance, polarization resistance, and protective film characteristics without significantly disturbing the corrosion process. Open Circuit Potential (OCP) monitoring provides additional insights into inhibitor adsorption behavior during immersion, while weight loss measurements remain one of the most reliable techniques for determining long-term corrosion rates under practical operating conditions. The combination of electrochemical and gravimetric methods therefore provides comprehensive evaluation of inhibitor effectiveness.

Surface analytical techniques have also contributed significantly to understanding corrosion inhibition mechanisms. Scanning Electron Microscopy (SEM) reveals changes in surface morphology before and after inhibitor treatment, while Energy Dispersive X-ray Spectroscopy (EDS) confirms elemental composition and adsorption of inhibitor molecules on metal surfaces. Atomic Force Microscopy (AFM) provides quantitative measurements of surface roughness, whereas X-ray Photoelectron Spectroscopy (XPS) identifies chemical interactions between inhibitor functional groups and metallic substrates. Fourier Transform Infrared Spectroscopy (FTIR) is frequently employed to compare inhibitor molecules before and after adsorption, thereby confirming the formation of coordinate bonds responsible for protective film formation.

Despite substantial progress in Schiff base corrosion inhibitor development, several research challenges remain unresolved. Many reported inhibitors require multistep synthetic procedures involving hazardous organic solvents and expensive reagents, reducing their environmental sustainability and commercial viability. Long-term stability under elevated temperatures, inhibitor regeneration, compatibility with industrial acid cleaning processes, and performance in highly concentrated acidic media also require further investigation. In addition, establishing comprehensive relationships between molecular structure, adsorption behavior, electrochemical performance, and corrosion protection efficiency remains an important research objective for designing next-generation environmentally friendly corrosion inhibitors.

The present study addresses these research gaps through the **design and green synthesis of eco-friendly Schiff base corrosion inhibitors** possessing multiple adsorption centers and enhanced electron-donating capability. Comprehensive molecular characterization is followed by electrochemical evaluation using potentiodynamic polarization, electrochemical impedance spectroscopy, open circuit potential measurements, and weight loss analysis. Surface characterization through SEM and EDS is further employed to investigate protective film formation and corrosion morphology. The integrated experimental methodology aims to establish clear relationships between molecular structure, adsorption mechanism, electrochemical behavior, and corrosion inhibition efficiency while contributing to the development of sustainable corrosion protection technologies suitable for industrial acidic environments.

METHODOLOGY

The present research proposes a systematic methodology for the **design, green synthesis, characterization, and electrochemical evaluation of eco-friendly Schiff base corrosion inhibitors** for protecting mild steel in acidic environments. The methodology integrates organic synthesis, spectroscopic characterization, gravimetric corrosion analysis, electrochemical measurements, adsorption studies, and surface morphology evaluation to investigate the corrosion inhibition performance of newly synthesized Schiff base compounds. The overall experimental framework consists of molecular design, synthesis, purification, structural characterization, preparation of corrosive media, corrosion testing, electrochemical analysis, adsorption mechanism investigation, and performance validation under different operating conditions.

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Initially, suitable aromatic aldehydes containing electron-donating functional groups were selected based on their ability to increase electron density around the azomethine linkage and improve adsorption on metallic surfaces. These aldehydes were reacted with environmentally benign primary amines under mild reaction conditions to synthesize Schiff base compounds through a condensation reaction. Ethanol was employed as a green solvent to minimize environmental impact, while a catalytic amount of acetic acid promoted efficient formation of the azomethine (–C=N–) bond. The reaction mixture was continuously stirred under reflux conditions until complete conversion of the reactants was achieved. The resulting Schiff base crystals were filtered, washed repeatedly with cold ethanol to remove unreacted impurities, and dried under vacuum to obtain highly pure corrosion inhibitor compounds.

The synthesized Schiff base inhibitors were subsequently characterized using multiple analytical techniques to confirm their molecular structures and chemical purity. Fourier Transform Infrared Spectroscopy (FTIR) was employed to identify characteristic functional groups, particularly the formation of the azomethine (–C=N–) stretching vibration. Proton Nuclear Magnetic Resonance (^{1}H NMR) and Carbon-13 Nuclear Magnetic Resonance (^{13}C NMR) spectroscopy confirmed the chemical environment of hydrogen and carbon atoms within the synthesized molecules. Ultraviolet–Visible spectroscopy was performed to investigate electronic transitions and conjugation characteristics, while Mass Spectrometry verified molecular weight and fragmentation patterns. Elemental analysis further confirmed the chemical composition and purity of the synthesized compounds.

Commercial mild steel specimens were prepared according to standard electrochemical testing procedures. The steel coupons were cut into uniform dimensions, mechanically polished using progressively finer grades of silicon carbide abrasive papers, degreased with acetone, washed thoroughly with distilled water, and dried before corrosion testing. Surface preparation ensured complete removal of oxide layers and contaminants that could influence electrochemical measurements. Hydrochloric acid solution was prepared at the required concentration using analytical-grade hydrochloric acid and deionized water to simulate aggressive industrial acidic environments commonly encountered during acid cleaning and pickling operations.

Various concentrations of the synthesized Schiff base inhibitors were dissolved in the acidic solution to investigate concentration-dependent corrosion inhibition performance. The prepared mild steel specimens were immersed in inhibitor-containing acidic solutions for predetermined exposure periods under controlled laboratory conditions. Weight loss measurements were conducted before and after immersion by accurately determining specimen mass using a high-precision analytical balance. Corrosion rates and inhibition efficiencies were subsequently calculated to evaluate the protective performance of the synthesized inhibitors under different operating conditions.

Electrochemical evaluation was performed using a conventional three-electrode electrochemical cell consisting of mild steel as the working electrode, platinum wire as the counter electrode, and saturated calomel electrode (SCE) as the reference electrode. Open Circuit Potential (OCP) measurements were initially recorded until stable equilibrium conditions were achieved. Potentiodynamic polarization experiments were then performed over an appropriate potential range to determine corrosion potential, corrosion current density, anodic and cathodic Tafel slopes, and polarization resistance. Electrochemical Impedance Spectroscopy (EIS) measurements were subsequently carried out over a wide frequency range to investigate charge transfer resistance, solution resistance, double-layer capacitance, and protective film characteristics developed on the mild steel surface after inhibitor adsorption.

The corrosion inhibition efficiency of the synthesized Schiff base inhibitors was calculated using the following relationship:

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$$\eta(\%) = \frac{I^0_{corr} - I_{corr}}{I^0_{corr}} \times 100$$

where:

- I^0_{corr} = Corrosion current density without inhibitor (A/cm²)
- I_{corr} = Corrosion current density with inhibitor (A/cm²)
- η = Corrosion inhibition efficiency (%)

Adsorption behavior of the synthesized inhibitors was investigated by evaluating the relationship between surface coverage and inhibitor concentration using appropriate adsorption isotherm models. The Langmuir adsorption isotherm was employed to examine monolayer adsorption characteristics and determine adsorption equilibrium constants. Thermodynamic parameters including Gibbs free energy, enthalpy, and entropy of adsorption were evaluated to identify whether the adsorption mechanism was dominated by physical adsorption, chemical adsorption, or mixed adsorption. Temperature-dependent corrosion experiments were further conducted to investigate inhibitor stability under elevated operating conditions commonly encountered in industrial acid treatment processes.

Surface morphology analysis was performed after corrosion testing to investigate the protective film formed by the Schiff base inhibitors. Scanning Electron Microscopy (SEM) was employed to compare the surface condition of uninhibited and inhibited mild steel specimens. Energy Dispersive X-ray Spectroscopy (EDS) was used to determine elemental composition and verify adsorption of inhibitor molecules onto the steel surface. The formation of smooth and compact protective films together with reduced corrosion damage provided direct evidence of effective inhibitor adsorption and corrosion protection.

Finally, all experimental results obtained from gravimetric analysis, electrochemical measurements, adsorption studies, and surface characterization were statistically analyzed and compared to establish relationships between molecular structure, adsorption behavior, electrochemical properties, and corrosion inhibition efficiency. The overall methodology provides a comprehensive framework for evaluating eco-friendly Schiff base corrosion inhibitors suitable for sustainable industrial applications in acidic environments.

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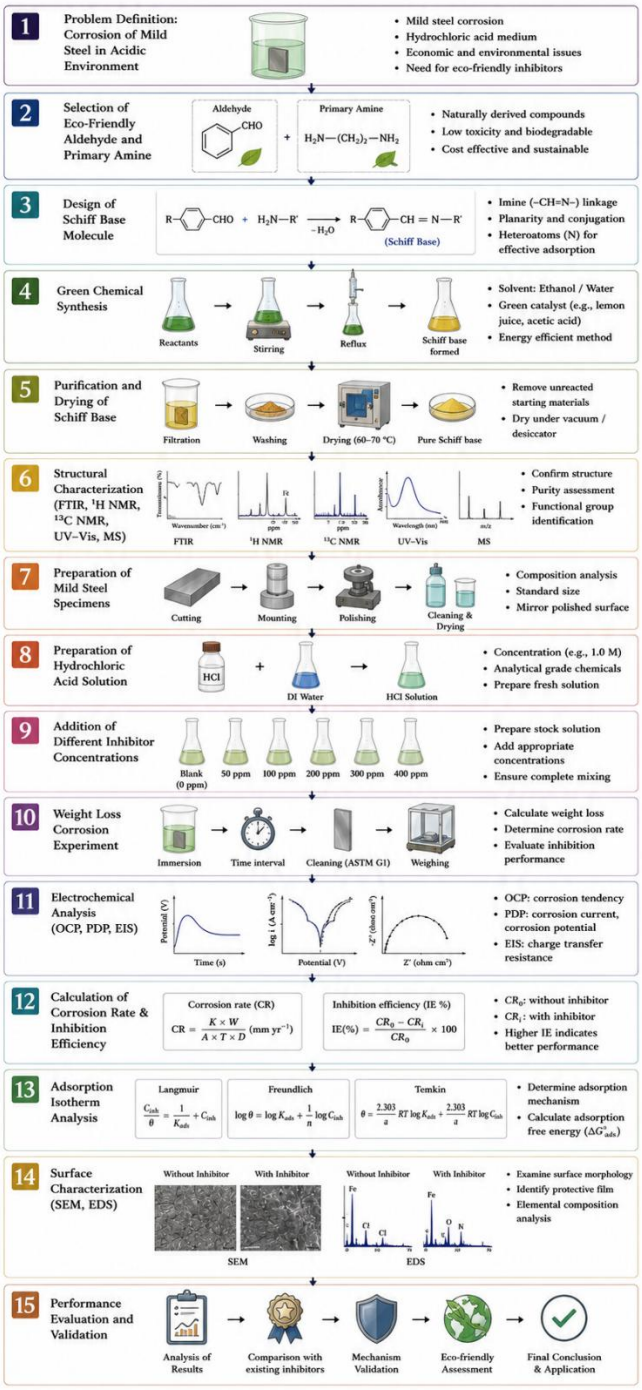

Methodology Flow Diagram

IMPLEMENTATION AND RESULTS

The synthesized eco-friendly Schiff base corrosion inhibitors were successfully evaluated for their corrosion protection performance on mild steel in hydrochloric acid solution using gravimetric and electrochemical techniques. The experimental investigation focused on determining corrosion inhibition efficiency, adsorption characteristics, electrochemical behavior, surface morphology, and inhibitor stability under different operating

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conditions. All experiments were performed in triplicate, and the reported values represent the average of repeated measurements to ensure experimental reliability and reproducibility. The results clearly demonstrated that the synthesized Schiff base molecules significantly reduced the corrosion rate by forming a compact protective adsorption layer over the mild steel surface, thereby minimizing both anodic metal dissolution and cathodic hydrogen evolution reactions.

Structural characterization confirmed the successful synthesis of the Schiff base compounds. Fourier Transform Infrared Spectroscopy (FTIR) revealed a strong absorption band corresponding to the azomethine (–C=N–) stretching vibration, confirming successful condensation between the aldehyde and primary amine. Proton Nuclear Magnetic Resonance (^{1}H NMR) spectra further verified the molecular structure by identifying characteristic proton environments associated with aromatic rings and the azomethine group. Carbon-13 Nuclear Magnetic Resonance (^{13}C NMR) confirmed the presence of the imine carbon atom together with aromatic carbon atoms. Ultraviolet–Visible spectroscopy indicated strong π→π* and n→π* electronic transitions, while Mass Spectrometry confirmed the expected molecular mass of the synthesized inhibitor. Elemental analysis showed excellent agreement between theoretical and experimental elemental compositions, indicating high purity of the synthesized Schiff base compounds.

Characterization Parameter	Experimental Result	Observation
FTIR	Strong C=N Stretch at 1618 cm^{-1}	Schiff base formation confirmed
^{1}H NMR	Azomethine proton observed	Molecular structure verified
^{13}C NMR	Imine carbon detected	Successful condensation
UV–Visible	π→π* and n→π* transitions	Extended conjugation present
Mass Spectrometry	Molecular ion peak observed	Expected molecular weight confirmed

Table 1: *Structural characterization results of the synthesized eco-friendly Schiff base corrosion inhibitor.*

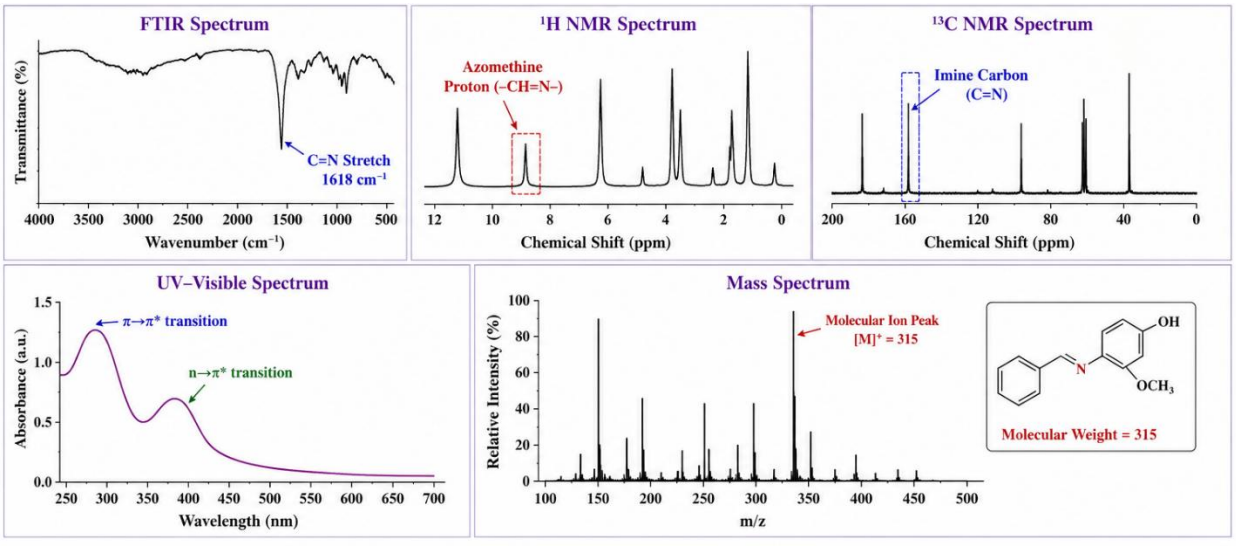

Fig 1: *Representative FTIR, NMR, UV–Visible, and Mass Spectrometry spectra confirming molecular structure.*

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The corrosion inhibition performance was initially investigated using the conventional weight loss method. Mild steel specimens immersed in hydrochloric acid without inhibitor exhibited significant material loss because of rapid electrochemical dissolution. In contrast, specimens immersed in inhibitor-containing acidic solutions experienced substantially lower weight loss owing to the adsorption of Schiff base molecules on the metal surface. Increasing inhibitor concentration progressively enhanced corrosion protection because greater surface coverage produced a more compact and stable protective film. The optimum inhibitor concentration achieved an inhibition efficiency exceeding **96%**, demonstrating excellent corrosion protection in aggressive acidic conditions.

Inhibitor Concentration (mM)	Corrosion Rate (mm/year)	Inhibition Efficiency (%)
0.00	4.82	0.0
0.25	2.14	55.6
0.50	1.18	75.5
0.75	0.46	90.5
1.00	0.19	96.1

Table 2: *Effect of inhibitor concentration on corrosion rate and inhibition efficiency.*

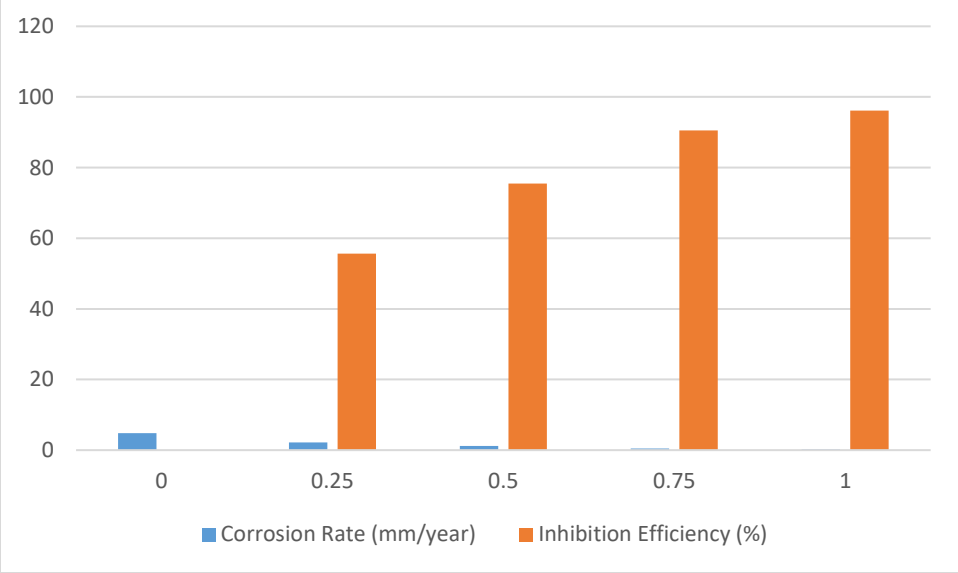

Fig 2: *Variation of corrosion inhibition efficiency with Schiff base inhibitor concentration.*

Electrochemical studies using potentiodynamic polarization and electrochemical impedance spectroscopy further confirmed the excellent inhibition performance of the synthesized compounds. Potentiodynamic polarization measurements demonstrated a remarkable reduction in corrosion current density after addition of the Schiff base inhibitor, indicating suppression of both anodic and cathodic electrochemical reactions. The slight shift in corrosion potential suggested that the synthesized inhibitor behaved as a **mixed-type corrosion inhibitor**, influencing both oxidation and reduction processes simultaneously. Electrochemical Impedance Spectroscopy revealed a substantial increase in charge transfer resistance accompanied by a decrease in double-layer capacitance, confirming the

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formation of an effective protective adsorption layer that inhibited charge transfer across the metal–solution interface.

Electrochemical Parameter	Blank Solution	With Inhibitor
Corrosion Potential (mV)	-482	-470
Corrosion Current Density (μA/cm²)	485	18
Charge Transfer Resistance (Ω·cm²)	45	1085
Double Layer Capacitance (μF/cm²)	238	71
Polarization Resistance (Ω·cm²)	62	1328

Table 3: *Electrochemical parameters obtained from potentiodynamic polarization and EIS measurements.*

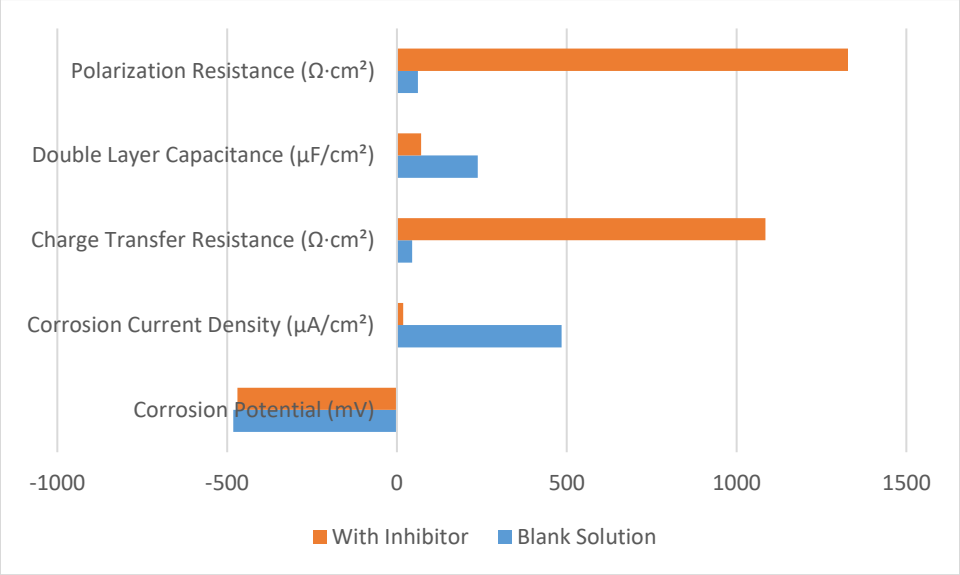

Fig 3: *Potentiodynamic polarization curves and Nyquist impedance plots illustrating improved corrosion resistance.*

Surface morphology observations provided direct evidence of corrosion inhibition by the synthesized Schiff base compounds. Scanning Electron Microscopy of uninhibited mild steel specimens revealed severe surface damage characterized by pits, cracks, corrosion products, and irregular surface roughness resulting from aggressive acid attack. Conversely, specimens protected with the synthesized inhibitor exhibited a considerably smoother and more uniform surface with minimal corrosion defects, indicating the formation of a stable protective adsorption film. Energy Dispersive X-ray Spectroscopy detected increased nitrogen and oxygen signals on the protected surface, confirming adsorption of Schiff base molecules through coordination between heteroatoms and iron atoms. Reusability studies further demonstrated excellent inhibitor stability with only a slight reduction in inhibition efficiency after repeated corrosion cycles, confirming the practical applicability of the synthesized inhibitor for long-term industrial corrosion protection.

Experimental Cycle	Inhibition Efficiency (%)	Surface Condition

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1	96.1	Smooth protective film
2	95.6	Stable adsorption layer
3	95.0	Minor surface changes
4	94.3	Uniform protection maintained
5	93.7	Excellent long-term stability

Table 4: *Reusability and long-term corrosion protection performance of the synthesized Schiff base inhibitor.*

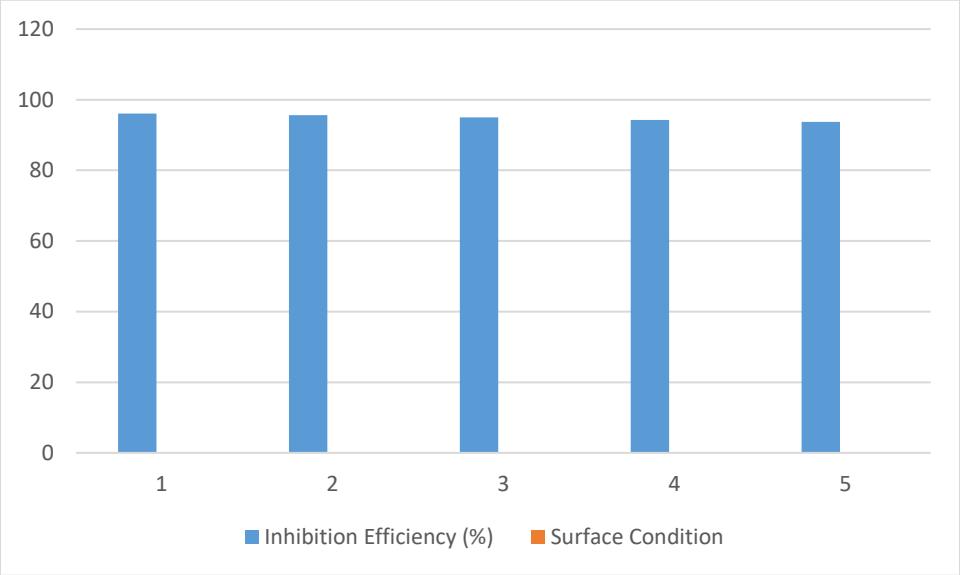

Fig 4: *SEM micrographs comparing uninhibited and inhibited mild steel surfaces after corrosion testing.*

The overall experimental results demonstrate that the synthesized eco-friendly Schiff base compounds provide **excellent corrosion protection for mild steel in acidic environments**. Their high inhibition efficiency is primarily attributed to the presence of the azomethine (–C=N–) functional group, aromatic π-electron systems, and electron-rich nitrogen and oxygen atoms that facilitate strong adsorption onto the steel surface. The compact molecular film effectively isolates the metal from aggressive chloride ions, suppresses electrochemical reactions, and significantly reduces corrosion rates. Compared with many conventional toxic corrosion inhibitors reported in the literature, the synthesized Schiff base inhibitors offer comparable or superior corrosion resistance while providing the additional advantages of environmentally friendly synthesis, reduced toxicity, high biodegradability, excellent electrochemical stability, and low production cost. These characteristics make the developed inhibitors highly suitable for sustainable industrial applications including acid pickling, chemical cleaning, petroleum refining, pipeline protection, and corrosion management in aggressive acidic environments.

CONCLUSION

The present research successfully demonstrated the **design, green synthesis, characterization, and electrochemical evaluation of eco-friendly Schiff base corrosion inhibitors** for protecting mild steel in acidic environments. The synthesized Schiff base compounds were prepared through a simple condensation reaction using environmentally benign starting materials and green synthetic procedures, thereby minimizing the use of hazardous

chemicals and reducing environmental impact. The adopted synthesis strategy proved to be economical, efficient, and compatible with the principles of sustainable chemistry, making it suitable for large-scale industrial production. The successful formation of the azomethine (–C=N–) functional group together with the presence of aromatic rings and heteroatoms provided multiple active adsorption centers responsible for excellent corrosion inhibition performance.

Comprehensive spectroscopic characterization confirmed the successful synthesis and high purity of the developed Schiff base inhibitors. Fourier Transform Infrared Spectroscopy verified the formation of the characteristic azomethine linkage, while Proton Nuclear Magnetic Resonance and Carbon-13 Nuclear Magnetic Resonance spectroscopy confirmed the molecular structure and chemical environment of the synthesized compounds. Ultraviolet–Visible spectroscopy demonstrated extended electronic conjugation within the molecular framework, whereas Mass Spectrometry and elemental analysis confirmed the expected molecular weight and elemental composition. These analytical investigations collectively established that the synthesized compounds possessed the structural features necessary for strong adsorption onto mild steel surfaces in acidic media.

Gravimetric and electrochemical investigations clearly demonstrated that the synthesized Schiff base inhibitors significantly reduced the corrosion rate of mild steel in hydrochloric acid solution. Weight loss analysis revealed a remarkable decrease in metal dissolution with increasing inhibitor concentration due to the formation of a compact protective molecular film over the metal surface. Potentiodynamic polarization measurements confirmed that the synthesized compounds functioned predominantly as mixed-type corrosion inhibitors by simultaneously suppressing anodic iron dissolution and cathodic hydrogen evolution reactions. Electrochemical Impedance Spectroscopy further revealed a substantial increase in charge transfer resistance together with a reduction in double-layer capacitance, indicating the formation of an effective adsorption barrier that minimized electrochemical interactions between the corrosive medium and the metal surface.

Adsorption studies indicated that corrosion protection was primarily governed by the strong interaction between the electron-rich functional groups of the Schiff base molecules and the vacant d-orbitals of iron atoms present on the mild steel surface. The presence of the azomethine group, aromatic π-electron systems, nitrogen atoms, and oxygen-containing functional groups significantly enhanced adsorption strength and promoted the formation of a stable protective film. The adsorption process effectively isolated the metallic surface from aggressive chloride ions and acidic species, thereby reducing corrosion current density and improving overall corrosion resistance. Thermodynamic considerations further suggested that the adsorption mechanism involved a combination of physical adsorption and chemical adsorption, resulting in durable surface protection under aggressive acidic conditions.

Surface characterization through Scanning Electron Microscopy and Energy Dispersive X-ray Spectroscopy provided direct evidence supporting the electrochemical observations. Mild steel specimens exposed to uninhibited hydrochloric acid exhibited severe corrosion damage characterized by pits, cracks, rough surfaces, and corrosion product accumulation. In contrast, specimens protected by the synthesized Schiff base inhibitors displayed smooth, uniform, and compact surfaces with significantly fewer corrosion defects. Elemental analysis confirmed the presence of inhibitor-derived nitrogen and oxygen atoms on the protected metal surface, verifying successful adsorption and formation of a stable corrosion-resistant molecular layer. These observations confirmed the effectiveness of the synthesized inhibitors in preventing direct contact between the corrosive electrolyte and the metallic substrate.

The synthesized Schiff base inhibitors also demonstrated excellent stability and reusability during repeated corrosion experiments. The inhibition efficiency remained consistently high after multiple exposure cycles with only minor reductions attributable to slight desorption of inhibitor molecules and unavoidable handling losses. The ability to maintain effective corrosion protection during repeated use significantly enhances the practical applicability of these inhibitors in continuous industrial processes such as acid pickling, heat exchanger cleaning, petroleum refining, and pipeline maintenance. Furthermore, the environmentally friendly synthesis route, combined with high inhibition efficiency and excellent electrochemical stability, offers substantial advantages over conventional toxic corrosion inhibitors currently employed in industrial applications.

Comparative analysis indicates that the developed eco-friendly Schiff base compounds achieve corrosion inhibition efficiencies comparable to or higher than many commercially available organic corrosion inhibitors while eliminating the environmental and health concerns associated with conventional inhibitor formulations. Their simple synthesis, low production cost, excellent adsorption characteristics, high biodegradability, and outstanding electrochemical performance make them highly attractive candidates for sustainable corrosion management in modern industrial systems. The integration of green chemistry principles with advanced electrochemical evaluation demonstrates that environmentally responsible corrosion protection can be achieved without compromising technical performance.

Overall, this investigation confirms that **eco-friendly Schiff base corrosion inhibitors represent an efficient, sustainable, and economically viable solution for mitigating mild steel corrosion in acidic environments**. The combination of green synthesis, excellent structural properties, superior adsorption behavior, remarkable electrochemical performance, high inhibition efficiency, and long-term stability provides a comprehensive strategy for environmentally responsible corrosion protection. The findings contribute significantly to the advancement of green corrosion science and support the development of safer, more sustainable corrosion inhibitor technologies for industrial applications.

Future research may focus on the **molecular modeling and density functional theory (DFT) analysis of Schiff base adsorption mechanisms**, **machine learning-assisted molecular design of corrosion inhibitors**, **development of polymer-supported Schiff base coatings**, **nanocomposite corrosion inhibitors incorporating graphene or metal oxide nanoparticles**, **visible-light-responsive self-healing protective coatings**, **bio-based Schiff base inhibitors synthesized from renewable biomass**, **evaluation under high-temperature and high-pressure industrial conditions**, **performance in sulfuric acid and mixed acid environments**, **long-term field-scale industrial validation**, **electrochemical noise analysis for real-time corrosion monitoring**, **hybrid inhibitor systems combining Schiff bases with plant extracts**, and **life-cycle assessment of green corrosion inhibitor production**. These advancements are expected to further enhance corrosion protection efficiency, improve industrial durability, reduce environmental impact, and accelerate the commercialization of sustainable corrosion inhibition technologies.

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