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Evaluation of Derived Schiff Bases as Eco-Friendly Organic Corrosion Inhibitors for Mild Steel in Acidic Media: A Sustainable Approach to Industrial Wastewater Management

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Article

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Abstract

Industrial metal pickling, acid descaling, and oil-well acidizing operations generate massive volumes of highly corrosive wastewater that degrade industrial assets and release hazardous effluents into the surrounding biosphere. Traditional inorganic corrosion inhibitors, such as chromates and nitrites, are severely restricted globally due to high aquatic toxicity, non-biodegradability, and bioaccumulation. This study evaluates the synthesis, structural characterization, and eco-friendly corrosion mitigation performance of two organic Schiff bases: (E)-2-(((2-chlorophenyl)imino)methyl)phenol (Inhibitor A) and (E)-N-(2-chlorophenyl)-1-(2-chlorophenyl)methanimine (Inhibitor B), derived via the condensation of 2-chloroaniline with salicylaldehyde and 2-chlorobenzaldehyde, respectively. The synthesized azomethine compounds were characterized using melting profiles and Fourier-Transform Infrared (FT-IR) spectroscopy. Distinctive imine (C = N) stretching bands were confirmed at 1616 cm^{-1} and 1618 cm^{-1}, respectively, with an absolute absence of parental carbonyl signals. Corrosion mitigation efficiencies on mild steel coupons were evaluated via gravimetric (weight loss) experiments in an aggressive 0.2 M HCl electrolyte at 298 K across 6-hour and 24-hour immersion periods. The gravimetric results revealed that corrosion rates decreased sharply with an increase in inhibitor concentration from 40 g/L to 160 g/L. Inhibitor A displayed superior maximum inhibition efficiency (99.43% at 24 h) due to the synergistic adsorption effect of its molecular geometry, active heteroatoms (N, O, Cl), π-electron clouds, and the supplementary phenolic hydroxyl (-OH) group. The molecular adsorption mechanisms are proposed as a sustainable engineering solution to mitigate infrastructure destruction and suppress heavy metal pollution in industrial effluents.

1. Introduction

Corrosion of metallic infrastructure represents an immense environmental and economic challenge globally. In industrial applications such as oil and gas transport pipelines, industrial heat exchangers, boilers, and pickling plants, mild steel is widely utilized due to its outstanding mechanical properties and cost-effectiveness. However, these structural systems are routinely exposed to highly aggressive acidic media (such as hydrochloric acid solutions) during descaling and asset cleaning processes. This exposure results in rapid electrochemical oxidation, causing uniform degradation, localized pitting, and catastrophic structural failures.

From an environmental chemistry perspective, the consequences of uncontrolled industrial corrosion extend far beyond economic asset loss. Structural failures induce pipeline leakages and plant ruptures that spill hydrocarbons and hazardous materials directly into terrestrial and aquatic ecosystems, as frequently documented across the Niger Delta region of Nigeria (Dueke-Eze et al. 2022). Furthermore, unchecked metallic dissolution discharges significant concentrations of heavy metals into adjacent water systems, driving bioaccumulation up the food chain.

To mitigate these phenomena, chemical corrosion inhibitors are universally deployed (Jones 1996; Dariva and Galio 2014). However, conventional industrial practices have historically relied on inorganic

variants containing toxic heavy metals, such as chromates, zinc salts, and nitrites (Quraishi and Jamal 2000). Upon effluent discharge, these compounds severely damage localized flora and fauna, disrupt microbial water purification dynamics, and pollute localized soils. Strict environmental consumer protection directives and international regulations have heavily restricted these inorganic matrices, creating an urgent demand for non-toxic, eco-friendly organic alternatives (Bentiss et al. 1999).

Green chemistry principles favor the design of organic corrosion inhibitors containing electron-rich heteroatoms (O, N, S, P) and conjugated π-systems. These structural features supply a steady stream of unshared electron pairs to vacant d-orbitals of surface iron atoms, inducing coordinate bond formation and creating a protective, molecularly thin barrier film (Dariva and Galio 2014).

Schiff bases (imines/azomethines) featuring the central -C = N- group represent a highly promising class of sustainable inhibitors (Fasina and Idika 2011). The presence of the azomethine group deepens the molecule's ability to adsorb to metallic matrices, stabilizing the protective film over extended temporal scales (Ashraf et al. 2011).

The aim of this study is to investigate the synthesis, spectroscopic validation, and corrosion inhibition performance of two heterogeneous Schiff bases—(E)-2-(((2-chlorophenyl)imino)methyl)phenol and (E)-N-(2-chlorophenyl)-1-(2-chlorophenyl)methanimine—derived from 2-chloroaniline (Esan 2023). By adjusting concentration levels across different temporal intervals, this research establishes an eco-efficient framework to reduce infrastructure degradation and provide a green solution for industrial wastewater management.

2. Materials and Methods

2.1 Reagents and Instrumentation

All chemical reagents, including 2-chloroaniline, 2-chlorobenzaldehyde, salicylaldehyde, absolute ethanol, acetone, and hydrochloric acid (HCl), were procured from the Chemistry Departmental Store at the University of Lagos. All reagents were of analytical grade and used as received without further purification. Melting points were recorded via open capillary tubes. Structural characterization was completed using a Bruker Fourier-Transform Infrared (FT-IR) Spectrometer recording transmittance profiles over the wavenumber spectral window of 4000–500 cm^{-1}.

2.2 Synthesis of Schiff Base Inhibitors

2.2.1 Synthesis of Inhibitor A: (E)-2-(((2-chlorophenyl)imino)methyl)phenol

A mass of 0.637 g (5 mmol) of 2-chloroaniline was fully dissolved in 10 mL of hot absolute ethanol within a reaction vessel. Concurrently, an equimolar quantity of salicylaldehyde (0.610 g, 5 mmol) was dissolved in 10 mL of hot ethanol. Both components were transferred into a round-bottom flask. The

resulting matrix was subjected to continuous electromagnetic stirring and refluxed at 70°C for a duration of 6 hours, utilizing generalized azomethine condensation pathways (Chakraborti et al. 2004). Upon cooling to ambient room temperature, high-purity yellow crystals precipitated out. The crystals were collected via vacuum filtration, recrystallized twice using absolute ethanol to remove unreacted precursors, and dried to a constant weight in an oven to achieve a yield of 72.6%.

- Melting Point: 187–190°C
- Key FT-IR Bands (cm^{-1}): 3054 (O-H stretch), 1616 (C = N imine stretch), 1287 (C-O stretch), 753 (C-Cl stretch).

2.2.2 Synthesis of Inhibitor B: (E)-N-(2-chlorophenyl)-1-(2-chlorophenyl)methanimine

A measured mass of 1.27 g (10 mmol) of 2-chloroaniline was combined with 10 mL of hot ethanol to achieve complete dissolution. Separately, an equimolar mass of 2-chlorobenzaldehyde (1.40 g, 10 mmol) was prepared in 10 mL of hot ethanol. The precursors were mixed in a round-bottom flask and refluxed at 70°C under constant magnetic agitation for 6 hours (Chakraborti et al. 2004). A golden-yellow precipitate formed uniformly during the reaction progress. The raw product was isolated via filtration, subjected to recrystallization inside ethanol, and oven-dried to achieve a final yield of 86.28%.

- Melting Point: 168–170°C
- Key FT-IR Bands (cm^{-1}): 3057 (C-H aromatic), 1618 (C = N imine stretch), 744 (C-Cl stretch).

2.3 Preparation of Mild Steel Coupons and Electrolyte

Mild steel specimen stocks were sourced from the Mechanical Engineering Workshop at the University of Lagos. Element compositions by weight percent were determined as: 0.16% C, 0.60% Si, 0.04% P, 1.59% Mn, and a balance of 97.61% Fe. The stock was machined into uniform coupons measuring 2.0 cm × 2.0 cm × 0.15 cm. Prior to testing, coupon surfaces underwent strict mechanical preparation. The coupons were polished sequentially using varied grades of silicon carbide emery papers, washed thoroughly with distilled water, degreased in an acetone bath, air-dried, and stored inside a desiccator according to standard protocol. The aggressive corrosive solution (0.2 M HCl) was prepared via volumetric dilution of analytical grade concentrated hydrochloric acid with deionized water. Stock solutions of Inhibitors A and B were prepared across concentrations of 40 g/L, 80 g/L, 120 g/L, and 160 g/L.

2.4 Gravimetric (Weight Loss) Testing Protocol

Pre-weighed mild steel pieces were completely submerged in glass reactors containing 100 mL of the aggressive 0.2 M HCl electrolyte, both in the absence (blank control) and presence of varying concentrations of Inhibitor A and Inhibitor B. Experiments were maintained at an ambient temperature of 298 K inside an open-air testing environment across two exposure durations: 6 hours and 24 hours.

Following the immersion periods, coupons were carefully removed, scrubbed gently with a bristle brush under running water to dislodge corrosion products, rinsed with acetone, thoroughly dried inside a desiccator, and re-weighed using an analytical balance. The corrosion rate (ρ, expressed in g·cm^{-2}·h^{-2}) was determined using Eq. 1:

$\rho = \Delta W / (A \cdot t) = (W_1 - W_2) / (A \cdot t)$ (Eq. 1)

Where W_1 and W_2 represent the initial and post-exposure weights (g), respectively; A is the total exposed coupon surface area (8.0 cm² accounting for both faces of a 2.0 cm × 2.0 cm sheet); and t is the precise immersion duration (h). Inhibition efficiency (η%) was computed to assess performance using Eq. 2:

$\eta\% = [1 - (\rho_{inh} / \rho_{blank})] \times 100$ (Eq. 2)

Where ρ_blank and ρ_inh signify the corrosion velocities in the uninhibited control and inhibited configurations, respectively.

3. Results and Discussion

3.1 Spectroscopic Characterization

The successful condensation of 2-chloroaniline with the targeted aromatic aldehydes was confirmed via physical parameters and FT-IR profiles. Both Schiff bases exhibited sharp, defined melting points (Inhibitor A: 187–190°C; Inhibitor B: 168–170°C) that differed substantially from their respective starting precursors, confirming structural transitions and product purity. The infrared spectra show the absolute absence of parental carbonyl stretching bands (C = O) near 1720–1740 cm^{-2}, confirming complete chemical transformation. This was accompanied by the appearance of intense stretching bands at 1616 cm^{-2} for Inhibitor A (as shown below in Fig. 8) and 1618 cm^{-2} for Inhibitor B (as shown below in Fig. 9).

These bands are assigned to the coordinated azomethine (C = N) imine linkage, which serves as the primary electron-donor center. Furthermore, Inhibitor A displayed a broad profile stretching band at 3054 cm^{-2} and an absorption band at 1287 cm^{-2}, corresponding to the structural vibrations of phenolic -OH and C-O arrays, respectively. This confirms that Inhibitor A possesses an additional oxygen-based adsorption center capable of participating in advanced surface interactions.

3.2 Evaluation of Corrosion Mitigation Performance

3.2.1 Gravimetric Profiles for Inhibitor A

The primary data parameters extracted for mild steel coupons exposed to Inhibitor A solutions over 6-hour and 24-hour frames are summarized in Table 1 and Table 2.

Table 1
Corrosion dynamics for Inhibitor A in 0.2 M HCl (t = 6 h, T = 298 K).

Inhibitor Concentration (C, g/L)	Weight Loss (ΔW, g)	Corrosion Rate (ρ, g·cm⁻²·h⁻¹)	Inhibition Efficiency (η%)
Blank Control	0.3990	8.31×10^{-3}	—
40	0.0700	1.46×10^{-3}	82.46
80	0.0600	1.25×10^{-3}	84.96
120	0.0400	8.33×10^{-4}	89.98
160	0.0300	6.25×10^{-4}	92.48

Table 2
Corrosion dynamics for Inhibitor A in 0.2 M HCl (t = 24 h, T = 298 K).

Inhibitor Concentration (C, g/L)	Weight Loss (ΔW, g)	Corrosion Rate (ρ, g·cm⁻²·h⁻¹)	Inhibition Efficiency (η%)
Blank Control	1.5864	8.26×10^{-3}	—
40	0.1800	9.38×10^{-4}	88.64
80	0.1600	8.33×10^{-4}	89.91
120	0.1100	5.73×10^{-4}	93.06
160	0.0090	4.69×10^{-5}	99.43

3.2.2 Gravimetric Profiles for Inhibitor B

The primary parameter data for mild steel coupons treated with Inhibitor B are summarized in Table 3 and Table 4.

Table 3
Corrosion dynamics for Inhibitor B in 0.2 M HCl (t = 6 h, T = 298 K).

Inhibitor Concentration (C, g/L)	Weight Loss (ΔW, g)	Corrosion Rate (ρ, g·cm⁻²·h⁻¹)	Inhibition Efficiency (η%)
Blank Control	0.3864	8.05×10^{-3}	—
40	0.0600	1.25×10^{-3}	84.47
80	0.0400	8.33×10^{-4}	89.65
120	0.0300	6.25×10^{-4}	92.24
160	0.0200	4.17×10^{-4}	94.82

Table 4
Corrosion dynamics for Inhibitor B in 0.2 M HCl (t = 24 h, T = 298 K).

Inhibitor Concentration (C, g/L)	Weight Loss (ΔW, g)	Corrosion Rate (ρ, $g \cdot cm^{-2} \cdot h^{-1}$)	Inhibition Efficiency (η%)
Blank Control	1.5720	8.19×10^{-3}	—
40	0.1500	7.81×10^{-4}	90.46
80	0.1400	7.29×10^{-4}	91.10
120	0.1200	6.25×10^{-4}	92.37
160	0.1000	5.21×10^{-4}	93.64

3.3 Adsorption Mechanism and Environmental Applications

The analytical data demonstrates that both Schiff bases act as effective organic inhibitors for mild steel within a 0.2 M HCl environment. For both inhibitors, weight loss decreased and inhibition efficiency increased significantly as the chemical concentration was raised from 40 g/L to 160 g/L. This trend can be attributed to the incremental adsorption of organic molecules across active sites on the metal surface, which effectively shields the steel matrix from aggressive hydronium (H_3O^+) and chloride (Cl^-) ions.

As the inhibitor concentration increases, a compact protective film forms on the metal surface. Coordinate covalent bonds develop via a mechanism where lone electron pairs from nitrogen (within the -C = N- azomethine group) and chlorine atoms are donated into the vacant d-orbitals of surface iron (Fe^0) atoms.

Comparing the performance of the two compounds over a 24-hour period reveals that Inhibitor A reaches a peak inhibition efficiency of 99.43%, outperforming Inhibitor B (93.64%). This superior performance is driven by the structural presence of the phenolic ortho-hydroxyl (-OH) group in Inhibitor A. The oxygen atom within this group provides an additional active center with high electron density. Furthermore, the adjacent positioning of the hydroxyl and imine groups allows Inhibitor A to form stable chelate rings on the steel surface. This chelation produces a highly persistent, uniform layer that resists chemical degradation over extended exposure periods, making it an excellent candidate for eco-friendly industrial applications.

From an environmental sustainability standpoint, deploying these organic inhibitors at optimized concentrations offers dual benefits for wastewater management. First, by significantly suppressing metal dissolution rates, they prevent toxic heavy metal accumulation in industrial effluents. Second, because these organic molecules lack toxic heavy metals, they can be broken down more safely within standard wastewater treatment frameworks, minimizing long-term ecological damage to receiving aquatic and soil systems.

4. Conclusion

This study successfully evaluated the synthesis, characterization, and corrosion mitigation performance of two sustainable organic Schiff bases derived from 2-chloroaniline. FT-IR spectra confirmed the successful formation of characteristic imine (C = N) linkages at 1616–1618 cm^{-1}. Gravimetric testing over 6-hour and 24-hour intervals demonstrated that both compounds effectively inhibit mild steel corrosion in 0.2 M HCl, with efficiency scaling directly alongside inhibitor concentration. Notably, (E)-2-(((2-chlorophenyl)imino)methyl)phenol (Inhibitor A) achieved an outstanding maximum inhibition efficiency of 99.43% over 24 hours, outperforming the 2-chlorobenzaldehyde derivative due to the synergistic adsorption contributions of its phenolic hydroxyl (-OH) group. These organic inhibitors provide a sustainable, low-toxicity alternative to hazardous inorganic compounds, offering an effective chemical strategy to preserve critical infrastructure and minimize heavy metal pollution in industrial wastewater.

Declarations

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Author Contribution

This work was carried out in collaboration among the authors. Author O.I was responsible forconceptualization, methodology, supervision, and writing the original draft and Author K.A wasresponsible for investigation and writing, review and editing. Both authors read and approved the finalmanuscript

Data Availability

The data was generated from my personal research in the mild steel experiment using schiff base (weight loss model).All the process leading to the generated data was explained in the paper

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Figures

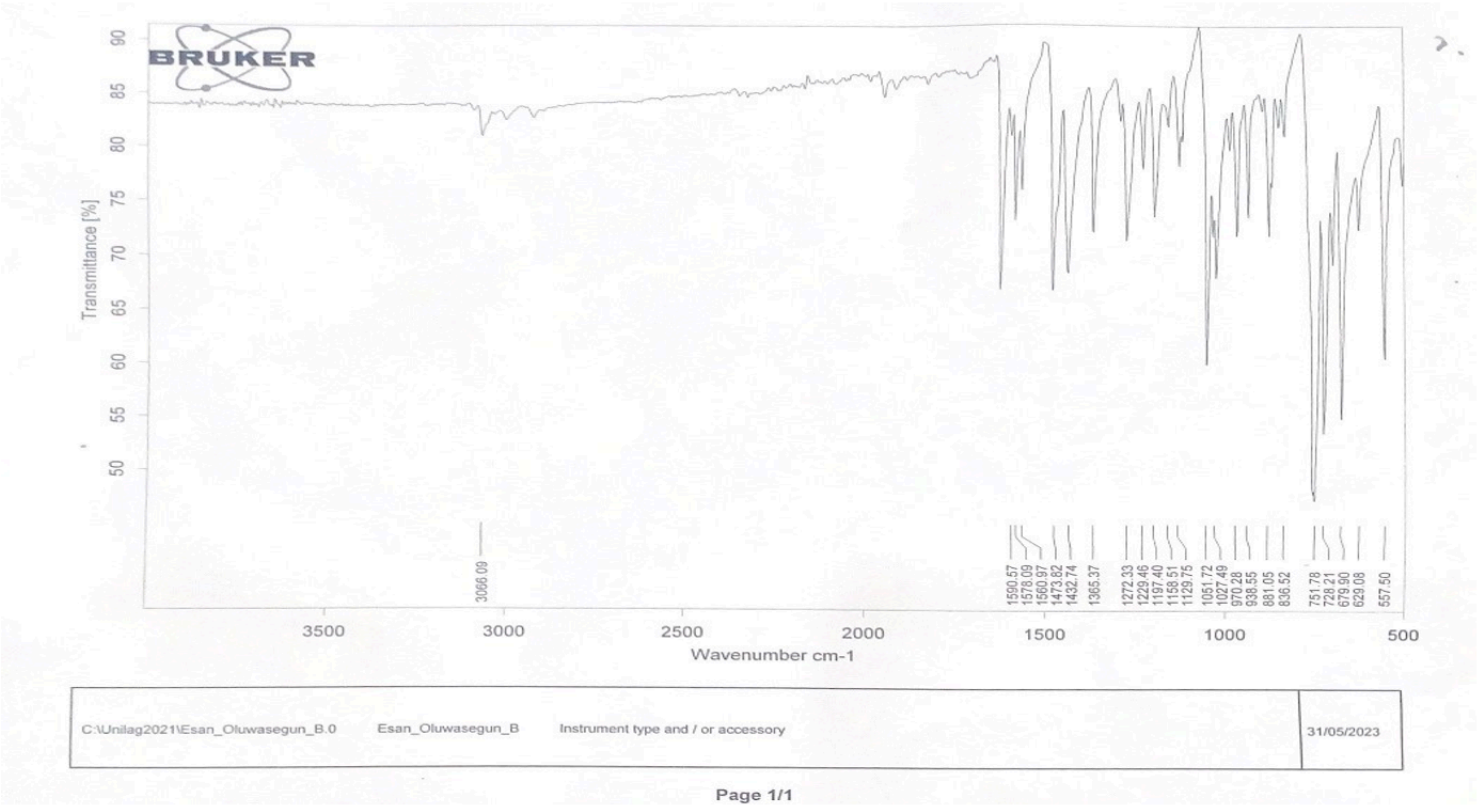


Figure 1

8: IR Spectra of 2-Chloro Aniline and Salicylaldehyde (Inhibitor A)

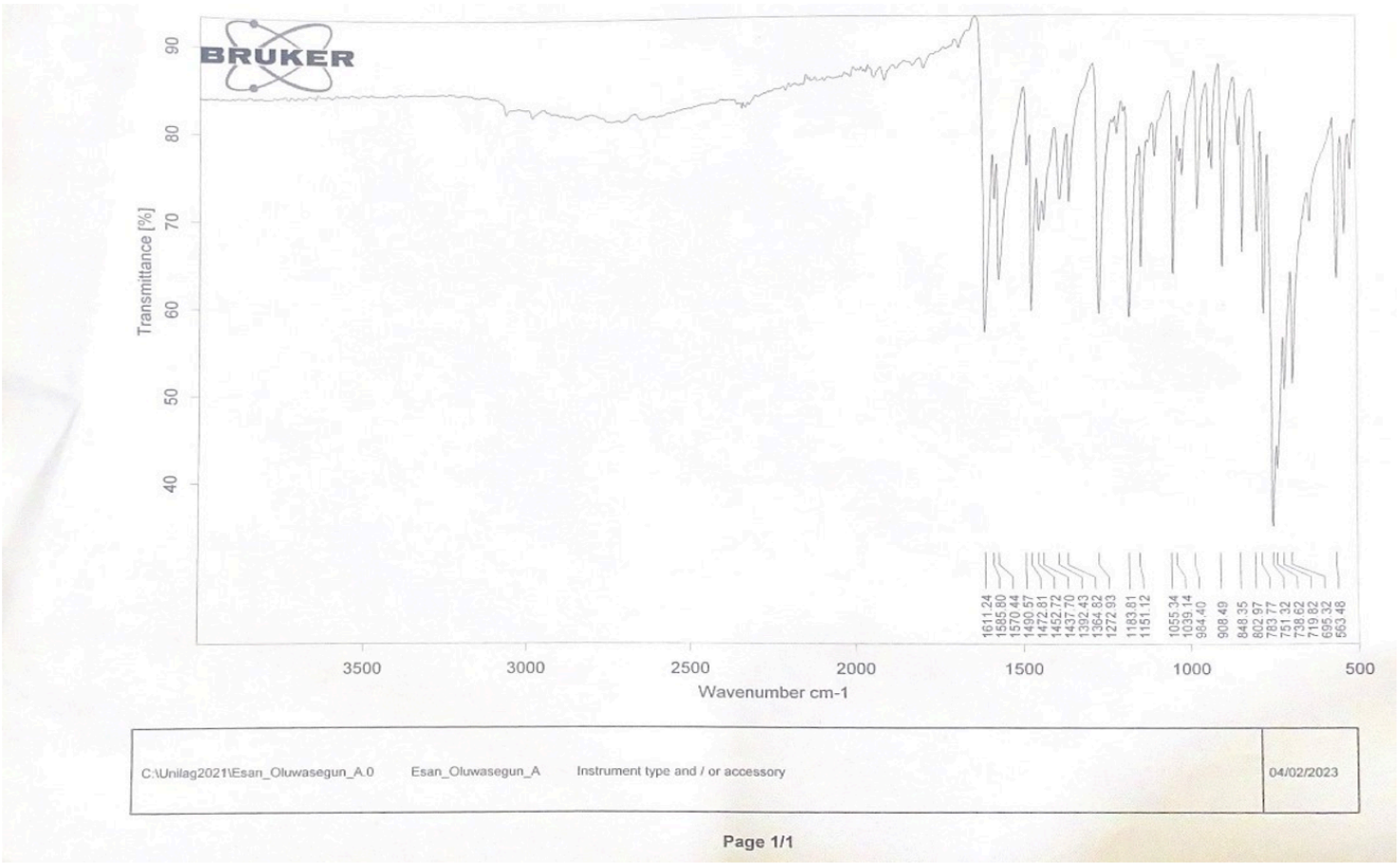


Figure 2

9: IR Spectra of 2-Chloro Aniline and 2-Chloro Benzaldehyde (Inhibitor B)