

Development and Application of a Schiff-Base Colorimetric Sensor for Lead (Pb^{2+}) Detection in Borehole Water from Kaduna Metropolis, Nigeria

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Abstract

Groundwater accessed through boreholes constitutes a major source of domestic water supply in many Nigerian cities, including Kaduna metropolis. However, increasing urbanization and industrial activities have heightened concerns about heavy metal contamination, particularly lead (Pb^{2+}), which poses severe health risks even at low concentrations. Conventional analytical techniques for lead determination, such as atomic absorption spectroscopy and inductively coupled plasma-based methods, although highly sensitive, are often limited in routine application by cost, infrastructural requirements, and technical expertise in resource-limited settings. This study reports the synthesis, spectroscopic characterization, and application of a Schiff-base ligand as a simple colorimetric sensor for Pb^{2+} detection in borehole water. The ligand was synthesized via condensation of salicylaldehyde and ethylenediamine, yielding a yellow crystalline solid (melting point $189\text{--}191^\circ\text{C}$, yield 78.4%). Fourier transform infrared spectroscopy confirmed azomethine formation and coordination through nitrogen and oxygen donor atoms, while UV-Visible spectroscopy revealed characteristic $\pi\rightarrow\pi^*$ and $n\rightarrow\pi^*$ transitions and the emergence of a ligand-to-metal charge transfer band at 445 nm upon Pb^{2+} binding, accompanied by a visible color change. Quantitative evaluation showed linear Beer-Lambert behavior ($R^2 = 0.995$) over the investigated concentration range. The sensor exhibited high selectivity toward Pb^{2+} over common interfering metal ions. Application to twelve borehole water samples collected across Kaduna metropolis produced recovery values of 92–98% with relative standard deviations below 3%, indicating good accuracy and precision. The results demonstrate the potential of the developed Schiff-base colorimetric sensor as a low-cost and effective tool for preliminary screening of lead contamination in groundwater.

1. Introduction

Groundwater constitutes a critical component of global freshwater resources and serves as a primary source of drinking water for a substantial proportion of the world's population. In many developing countries, particularly across sub-Saharan Africa, groundwater accessed through boreholes and wells represents the most reliable and accessible source of potable water due to inadequate municipal water infrastructure and increasing urban water demand (Adelana & MacDonald, 2008). Nigeria exemplifies this dependence, with millions of households relying on borehole water for drinking, cooking, and other domestic purposes. However, the quality of groundwater in rapidly urbanizing regions has become a growing concern due to escalating anthropogenic pressures and limited regulatory monitoring.

Among the various threats to groundwater quality, contamination by heavy metals remains one of the most persistent and challenging environmental problems. Heavy metals are characterized by high atomic weight and density and are of particular concern because they are non-biodegradable, environmentally persistent, and capable of bioaccumulating in living organisms (Tchounwou et al., 2012). Once introduced into groundwater systems, heavy metals can persist for extended periods, posing long-term risks to ecosystems and human health. Sources of heavy metal contamination include natural geogenic processes such as rock weathering and mineral dissolution, as well as anthropogenic

activities including industrial effluent discharge, improper waste disposal, agricultural runoff, vehicular emissions, and corrosion of metal-containing water distribution systems (Alloway, 2013).

Lead (Pb^{2+}) is one of the most widely studied and hazardous heavy metals in environmental systems due to its high toxicity and lack of any known biological function. Lead occurs predominantly in the divalent oxidation state (Pb^{2+}) in aqueous environments, where it exhibits strong affinity for oxygen-, nitrogen-, and sulfur-containing ligands. This chemical behavior underpins its ability to interact with critical biological molecules, disrupting enzymatic processes, impairing neurotransmission, and interfering with calcium metabolism (Flora et al., 2012). Chronic exposure to lead has been associated with irreversible neurological damage, particularly in children, where it impairs cognitive development, reduces intelligence quotient, and causes behavioral disorders. In adults, prolonged exposure has been linked to renal dysfunction, hypertension, cardiovascular diseases, and reproductive toxicity (Needleman, 2004).

Given these severe health implications, international regulatory bodies have established stringent guidelines for lead in drinking water. The World Health Organization recommends a maximum permissible limit of 0.01 mg L^{-1} for lead in potable water and emphasizes that no level of lead exposure can be considered completely safe (WHO, 2023). Despite these guidelines, numerous studies have reported lead concentrations in groundwater that approach or exceed recommended limits, particularly in urban and peri-urban areas of developing countries where environmental regulation and routine monitoring are limited.

In Nigeria, groundwater contamination by lead has been documented in several regions, reflecting both natural and anthropogenic influences. Geological formations rich in metal-bearing minerals can contribute to background lead levels through weathering and leaching processes, while human activities such as industrial operations, artisanal metal workshops, battery recycling, and indiscriminate disposal of electronic waste significantly exacerbate contamination (Akan et al., 2014; Ojekunle et al., 2016). Studies conducted in northern Nigeria have reported detectable levels of lead in borehole and well water, raising concerns about chronic exposure among populations that rely heavily on groundwater for domestic use (Yusuf et al., 2015; Abdulrahman et al., 2018).

Kaduna metropolis represents a particularly relevant case study within this context. As a major urban, industrial, and military hub in northern Nigeria, Kaduna hosts diverse anthropogenic activities, including textile manufacturing, metal fabrication, automobile repair workshops, and dense residential settlements. These activities, combined with inadequate waste management infrastructure and aging water distribution systems, increase the likelihood of heavy metal infiltration into groundwater resources (Sadiq et al., 2020). Borehole water quality assessments conducted in different parts of Kaduna State have reported variations in physicochemical parameters and trace metal concentrations linked to land use patterns, population density, and proximity to industrial zones. Although several studies have confirmed the presence of lead in groundwater within the metropolis, routine monitoring remains sporadic and largely dependent on centralized laboratory analyses.

From an analytical perspective, the determination of lead in environmental water samples is commonly performed using instrumental techniques such as atomic absorption spectroscopy (AAS), inductively coupled plasma optical emission spectroscopy (ICP-OES), and inductively coupled plasma mass spectrometry (ICP-MS). These methods offer excellent sensitivity and accuracy and are widely regarded as reference techniques for trace metal analysis (Skoog et al., 2018). However, their application in routine groundwater monitoring is often constrained by high capital and operational costs, the need for sophisticated laboratory infrastructure, and reliance on skilled personnel. These limitations are particularly pronounced in resource-limited settings, where frequent sampling and analysis of groundwater sources may not be feasible.

In response to these challenges, there has been increasing interest in the development of alternative analytical approaches that are simple, cost-effective, and suitable for rapid or preliminary screening of heavy metals in environmental samples. Among these approaches, colorimetric sensing has emerged as a promising strategy due to its operational simplicity, low cost, and potential for visual detection without the need for complex instrumentation. Colorimetric sensors typically rely on specific chemical interactions between a sensing molecule and a target analyte, leading to measurable changes in absorbance or visible color (Anand et al., 2022).

Schiff-base ligands occupy a prominent position in the design of such sensors. Schiff bases, characterized by the azomethine ($-C=N-$) functional group, are readily synthesized through condensation reactions between primary amines and carbonyl compounds. Their structural versatility, ease of functionalization, and strong metal-binding affinity make them attractive candidates for coordination chemistry and sensing applications (Callan et al., 2005). In bioinorganic and analytical chemistry, Schiff-base ligands have been extensively explored as chemosensors for metal ions due to their ability to form stable complexes and translate coordination events into optical signals.

The optical response of Schiff-base sensors is often governed by changes in electronic transitions, including $\pi \rightarrow \pi^*$, $n \rightarrow \pi^*$, and ligand-to-metal charge transfer (LMCT) bands, which can be monitored using UV–Visible spectroscopy. These spectral changes provide both qualitative and quantitative information about metal–ligand interactions and can be exploited for selective detection of specific metal ions (Lever, 1984). For lead detection in particular, Schiff-base ligands containing oxygen and nitrogen donor atoms have demonstrated promising selectivity and sensitivity, owing to favorable coordination geometry and electronic compatibility with Pb^{2+} ions (Anand et al., 2022).

Despite the growing body of research on Schiff-base-based metal sensors, relatively few studies have focused on their application to real groundwater samples in Nigerian urban settings. Moreover, there remains a need for locally relevant analytical tools that can complement conventional laboratory methods and support more frequent monitoring of borehole water quality. The development of simple colorimetric sensors that are effective under local environmental conditions could significantly enhance community-level screening and early detection of lead contamination.

In this study, a Schiff-base ligand synthesized from salicylaldehyde and ethylenediamine was developed and evaluated as a colorimetric sensor for Pb^{2+} detection. The ligand was characterized using Fourier transform infrared (FTIR) and UV–Visible spectroscopy to elucidate its structural and electronic properties. Its analytical performance was assessed through calibration, selectivity studies, and application to borehole water samples collected from twelve locations across Kaduna metropolis. By integrating coordination chemistry principles with practical environmental monitoring, this work aims to contribute to the development of low-cost, accessible tools for groundwater quality assessment in resource-limited urban environments.

2. Materials and Methods

2.1 Study Area Description

The study was conducted within Kaduna metropolis, Kaduna State, Nigeria. Kaduna metropolis is located in north-central Nigeria and serves as a major administrative, industrial, and military center. The city experiences rapid urban expansion, high population density, and diverse anthropogenic activities, including textile manufacturing, metal fabrication, automobile repair workshops, small-scale industries, and extensive residential development. These activities, combined with inadequate waste management systems, present potential risks for groundwater contamination.

The geology of Kaduna State is dominated by Precambrian Basement Complex rocks, including granites, gneisses, and schists, which can influence groundwater chemistry through weathering and leaching processes. Borehole water remains a primary source of domestic water supply across the metropolis due to inconsistent municipal water provision. The selection of Kaduna metropolis for this study was informed by its heavy reliance on groundwater resources and previous reports indicating variable physicochemical quality and trace metal presence in borehole water (Adelana & MacDonald, 2008; Sadiq et al., 2020).

2.2 Chemicals and Reagents

All chemicals and reagents used in this study were of analytical grade and were used without further purification to ensure reproducibility and analytical reliability. Salicylaldehyde and ethylenediamine were employed as precursor materials for Schiff-base synthesis. Lead(II) nitrate was used as the source of Pb^{2+} ions for calibration, selectivity, and recovery studies. Copper(II) nitrate, zinc(II) nitrate, iron(III) chloride, nickel(II) nitrate, and cadmium(II) nitrate were used to assess selectivity against competing metal ions.

Absolute ethanol and methanol were used as solvents for synthesis and spectroscopic analysis due to their good solvating ability and compatibility with UV–Visible measurements. Distilled and deionized water was used throughout for solution preparation to minimize background contamination. The use of high-purity reagents and solvents is consistent with standard analytical chemistry protocols for trace metal sensing studies (Skoog et al., 2018).

2.3 Instrumentation and Analytical Equipment

Fourier transform infrared (FTIR) spectra were recorded using a standard FTIR spectrometer equipped with a mid-infrared source, operating in the range 400–4000 cm^{-1} . Samples were prepared using the KBr pellet technique to ensure uniform spectral quality. UV–Visible absorption spectra were recorded using a UV–Visible spectrophotometer over the wavelength range of 200–600 nm, with ethanol serving as the blank solvent.

A digital melting point apparatus was used to determine the melting point of the synthesized Schiff-base ligand as an indicator of purity. An analytical balance with ± 0.1 mg sensitivity was used for all mass measurements. Reflux reactions were conducted using a hot plate equipped with a magnetic stirrer and a reflux condenser. A calibrated pH meter was used where necessary to monitor solution conditions. All glassware was thoroughly cleaned and rinsed with distilled water prior to use to avoid contamination.

2.4 Synthesis of the Schiff-Base Ligand

The Schiff-base ligand was synthesized via a condensation reaction between salicylaldehyde and ethylenediamine, following established procedures for azomethine formation (Shriver & Atkins, 2010). An equimolar quantity (0.01 mol) of salicylaldehyde was dissolved in ethanol and added dropwise to an ethanolic solution containing 0.01 mol of ethylenediamine under continuous magnetic stirring. The dropwise addition was employed to promote controlled reaction kinetics and uniform product formation.

The reaction mixture was refluxed for 2 h to facilitate completion of the condensation reaction. Formation of the Schiff-base ligand was indicated by the gradual appearance of a yellow precipitate. After completion of the reaction, the mixture was allowed to cool to room temperature, and the solid product was filtered under vacuum. The crude product was washed several times with cold ethanol to remove unreacted starting materials and impurities and then dried under ambient laboratory conditions. The percentage yield of the ligand was calculated based on the theoretical yield, and the melting point was determined as a preliminary indicator of compound purity. Schiff-base formation via this route is well documented and reliably produces azomethine-containing ligands suitable for metal coordination studies (Callan et al., 2005).

2.5 Preparation of Lead(II) and Metal Ion Solutions

A stock solution of Pb^{2+} with a concentration of 1×10^{-2} M was prepared by dissolving an accurately weighed quantity of lead(II) nitrate in distilled water in a volumetric flask. Working Pb^{2+} solutions of lower concentrations were prepared by serial dilution of the stock solution using distilled water. All solutions were freshly prepared prior to analysis to minimize potential changes due to precipitation or adsorption.

Solutions of competing metal ions (Cu^{2+} , Zn^{2+} , Fe^{3+} , Ni^{2+} , and Cd^{2+}) were similarly prepared at comparable concentrations for selectivity studies. The preparation of stock and working solutions

followed standard solution chemistry principles to ensure accuracy and reproducibility (Miller & Miller, 2018).

2.6 Spectroscopic Characterization

FTIR spectroscopy was employed to confirm the formation of the Schiff-base ligand and to investigate coordination behavior upon interaction with Pb^{2+} ions. The characteristic azomethine $\text{C}=\text{N}$ stretching vibration and phenolic $\text{O}-\text{H}$ bands were monitored, and shifts in these bands upon metal binding were used as indicators of coordination through nitrogen and oxygen donor atoms (Lever, 1984).

UV–Visible spectroscopy was used to investigate the electronic properties of the free ligand and its interaction with Pb^{2+} ions. Absorption bands corresponding to $\pi \rightarrow \pi^*$ and $n \rightarrow \pi^*$ transitions were identified, and spectral changes upon Pb^{2+} addition were monitored. The appearance of ligand-to-metal charge transfer (LMCT) bands was used as evidence of complex formation, consistent with previously reported Schiff-base-based colorimetric sensors (Anand et al., 2022).

2.7 Calibration and Quantitative Analysis

Quantitative evaluation of Pb^{2+} detection was carried out by monitoring absorbance changes at 445 nm, the wavelength corresponding to the LMCT band observed upon Pb^{2+} binding. Calibration curves were constructed by plotting absorbance against Pb^{2+} concentration over the investigated range. Linearity was assessed using regression analysis, and the correlation coefficient (R^2) was used to evaluate adherence to Beer–Lambert law.

All measurements were performed in triplicate, and mean absorbance values were used for calibration to improve analytical reliability. The use of Beer–Lambert principles for quantitative spectrophotometric analysis is well established in analytical chemistry and provides a robust basis for concentration determination (Miller & Miller, 2018).

2.8 Selectivity Studies

Selectivity of the Schiff-base ligand toward Pb^{2+} ions was evaluated in the presence of potentially interfering metal ions commonly found in groundwater. Equal concentrations of Cu^{2+} , Zn^{2+} , Fe^{3+} , Ni^{2+} , and Cd^{2+} were added separately to ligand solutions under identical experimental conditions. Absorbance responses and visible color changes were recorded and compared with those observed for Pb^{2+} .

The selectivity assessment aimed to establish preferential binding of the ligand toward Pb^{2+} relative to other metal ions, an essential criterion for practical sensing applications. Comparative selectivity studies are standard practice in sensor development and provide insight into coordination preferences and interference tolerance (Callan et al., 2005).

2.9 Borehole Water Sample Collection and Preparation

Twelve borehole water samples were collected from different locations across Kaduna metropolis to ensure spatial representation. Samples were collected in clean polyethylene bottles that had been pre-

rinsed with distilled water and then with the sample water to minimize contamination. The samples were transported to the laboratory and filtered to remove suspended particulates.

Recovery studies were conducted by spiking known concentrations of Pb^{2+} into the borehole water samples. The spiked samples were analyzed using the developed colorimetric method, and percentage recovery and relative standard deviation (RSD) values were calculated to assess method accuracy and precision. This approach is widely employed for validation of analytical methods applied to real environmental samples (Skoog et al., 2018).

2.10 Quality Assurance and Data Analysis

All experiments were performed in triplicate, and results are reported as mean $\pm$ standard deviation. Analytical precision was evaluated using relative standard deviation values, while accuracy was assessed through recovery studies. Graphical and statistical analyses were performed using standard data analysis tools. The methodological framework adopted in this study conforms to accepted practices for environmental analytical chemistry and method validation (Miller & Miller, 2018).

3. Results and Discussion

3.1 Physicochemical Properties of the Synthesized Schiff-Base Ligand

The Schiff-base ligand synthesized via condensation of salicylaldehyde and ethylenediamine was obtained as a yellow crystalline solid with a melting point of 189–191°C and a percentage yield of 78.4%. The sharp melting range indicates good purity and minimal presence of unreacted starting materials or side products. In Schiff-base chemistry, melting point determination is commonly used as a preliminary purity check, particularly where chromatographic purification is not employed (Shriver & Atkins, 2010). The observed yield is consistent with reported yields for salicylaldehyde-based azomethine ligands synthesized under similar reflux conditions (Callan et al., 2005).

The yellow coloration of the ligand is indicative of extended conjugation involving the azomethine ($-\text{C}=\text{N}-$) moiety and the aromatic ring system. Such coloration is typical of Schiff-base compounds and arises from π -electron delocalization, which also underpins their suitability for optical sensing applications (Anand et al., 2022). These physicochemical properties confirm successful ligand formation and provide a suitable basis for subsequent spectroscopic and sensing investigations as shown in Table 1.

Table 1
Physical and Physicochemical Properties of the Synthesized Schiff-Base Ligand

Parameter	Observation / Value
Physical appearance	Yellow crystalline solid
Odour	Odourless
Melting point (°C)	189–191
Percentage yield (%)	78.4
Solubility	Soluble in ethanol and methanol; sparingly soluble in water
Stability	Stable at room temperature for > 3 months

3.2 FTIR Spectral Characterization of the Schiff-Base Ligand and Pb²⁺ Complex

The FTIR spectrum of the free Schiff-base ligand (Fig. 1 and Table 2) provides clear evidence of successful azomethine formation. The disappearance of the aldehydic C = O stretching vibration of salicylaldehyde (typically observed near 1700 cm⁻¹) and the appearance of a strong band at 1624 cm⁻¹ are characteristic of the azomethine C = N stretching vibration. This observation confirms the condensation reaction between the aldehyde and primary amine groups and is consistent with reported FTIR features of Schiff-base ligands derived from salicylaldehyde (Lever, 1984; Callan et al., 2005).

Additional bands observed in the FTIR spectrum include broad absorptions in the region of 3200–3400 cm⁻¹ attributable to phenolic O–H stretching vibrations and aromatic C–H stretching bands near 3050 cm⁻¹. The presence of these bands further supports the structural integrity of the ligand and indicates the availability of donor sites for metal coordination.

Table 2
FTIR Spectral Assignments of the Schiff-Base Ligand and Pb²⁺ Complex

Functional Group / Vibration	Ligand (cm ⁻¹)	Pb ²⁺ Complex (cm ⁻¹)	Assignment
C = N (azomethine)	1624	1598	Coordination through azomethine N
O–H (phenolic)	3428	3412	Hydrogen bonding / metal interaction
C–O (phenolic)	1258	1234	Coordination via oxygen
Pb–N	—	530	Metal–ligand vibration
Pb–O	—	485	Metal–ligand vibration

Upon interaction with Pb^{2+} ions, significant changes were observed in the FTIR spectrum of the ligand (Fig. 2). The azomethine $\text{C}=\text{N}$ stretching band shifted from 1624 cm^{-1} to 1598 cm^{-1} , indicating coordination of the azomethine nitrogen atom to the Pb^{2+} ion. Such downward shifts in $\text{C}=\text{N}$ stretching frequencies are well documented in Schiff-base metal complexes and are attributed to a reduction in bond order upon coordination (Lever, 1984). In addition, the phenolic $\text{O}-\text{H}$ band intensity decreased, suggesting involvement of the phenolic oxygen in metal binding, likely through deprotonation and coordination.

New bands appearing in the low-frequency region around 530 cm^{-1} and 485 cm^{-1} were assigned to $\text{Pb}-\text{N}$ and $\text{Pb}-\text{O}$ stretching vibrations, respectively. The emergence of these bands provides further confirmation of metal–ligand coordination and supports a bidentate binding mode involving both nitrogen and oxygen donor atoms. Similar coordination behavior has been reported for Pb^{2+} complexes of salicylaldehyde-based Schiff bases in previous studies (Anand et al., 2022).

Overall, the FTIR results confirm successful ligand synthesis and demonstrate effective coordination of Pb^{2+} ions through azomethine nitrogen and phenolic oxygen atoms as shown in Fig. 2. These findings establish the structural basis for the observed colorimetric response and sensing behavior.

3.3 UV–Visible Spectral Properties and Electronic Transitions

The UV–Visible absorption spectrum of the free Schiff-base ligand (Fig. 3) exhibits two prominent absorption bands at 243 nm and 328 nm. The band observed at 243 nm is attributed to $\pi\rightarrow\pi^*$ transitions within the aromatic ring system, while the band at 328 nm corresponds to $n\rightarrow\pi^*$ transitions associated with the lone pair electrons on the azomethine nitrogen atom. These assignments are consistent with established interpretations of electronic transitions in azomethine-containing ligands (Lever, 1984).

Upon addition of Pb^{2+} ions to the ligand solution, pronounced changes were observed in the UV–Visible spectrum (Fig. 4 and Table 3). The $n\rightarrow\pi^*$ band exhibited a bathochromic shift, and a new absorption band emerged at 445 nm. This new band is assigned to ligand-to-metal charge transfer (LMCT) transitions, arising from electron donation from ligand donor atoms to the vacant orbitals of the Pb^{2+} ion. The appearance of the LMCT band was accompanied by a visible color change from pale yellow to orange, which forms the basis of the colorimetric sensing mechanism.

The emergence of LMCT bands in the visible region is a defining feature of Schiff-base-based colorimetric sensors and has been widely exploited for metal ion detection (Anand et al., 2022). The distinct spectral changes observed upon Pb^{2+} binding indicate strong electronic interaction between the ligand and the metal ion and confirm the suitability of the ligand for optical sensing applications.

Table 3
UV–Visible Absorption Bands and Electronic Transitions

Species	λ_{max} (nm)	Electronic Transition	Assignment
Free ligand	243	$\pi \rightarrow \pi^*$	Aromatic conjugation
Free ligand	328	$n \rightarrow \pi^*$	Azomethine nitrogen
Pb ²⁺ complex	368	$n \rightarrow \pi^*$ (shifted)	Coordination-induced shift
Pb ²⁺ complex	445	LMCT	Ligand-to-metal charge transfer
Visible colour	—	—	Yellow $\rightarrow$ Orange

3.4 Calibration Curve and Quantitative Performance

Quantitative evaluation of Pb²⁺ detection was carried out by monitoring absorbance changes at 445 nm, corresponding to the LMCT band (Fig. 5). The calibration curve constructed by plotting absorbance against Pb²⁺ concentration exhibited excellent linearity over the investigated concentration range, with a correlation coefficient (R^2) of 0.995. This high degree of linearity confirms adherence to the Beer–Lambert law and indicates reliable quantitative performance (Miller & Miller, 2018).

The linear response demonstrates that the colorimetric sensor can be effectively used for quantitative estimation of Pb²⁺ within the tested range. Although more sophisticated techniques such as ICP-MS offer lower detection limits, the performance observed here is adequate for preliminary screening and monitoring applications, particularly in settings where access to advanced instrumentation is limited. Similar linear calibration behavior has been reported for other Schiff-base-based Pb²⁺ sensors, reinforcing the validity of the approach (Anand et al., 2022).

3.5 Benesi–Hildebrand Analysis and Binding Stoichiometry

To further elucidate the binding interaction between the Schiff-base ligand and Pb²⁺ ions, Benesi–Hildebrand analysis was employed (Fig. 6). The linearity of the Benesi–Hildebrand plot indicates a 1:1 binding stoichiometry between the ligand and Pb²⁺ ions. This stoichiometric relationship is consistent with the bidentate coordination mode inferred from FTIR analysis and is commonly observed in Schiff-base–metal complexes (Lever, 1984).

The confirmation of 1:1 binding provides insight into the sensing mechanism and supports the use of simple equilibrium models for quantitative interpretation. The application of Benesi–Hildebrand analysis is well established in spectrophotometric studies of metal–ligand interactions and lends additional credibility to the analytical framework adopted in this study (Miller & Miller, 2018).

3.6 Selectivity toward Pb²⁺ in the Presence of Competing Metal Ions

Selectivity is a critical parameter for practical sensing applications, particularly in complex environmental matrices where multiple metal ions may coexist. The selectivity of the Schiff-base ligand toward Pb^{2+} was evaluated in the presence of Cu^{2+} , Zn^{2+} , Fe^{3+} , Ni^{2+} , and Cd^{2+} ions under identical experimental conditions (Table 4).

Table 4
Selectivity Study of the Schiff-Base Ligand

Metal Ion	λ_{max} (nm)	Absorbance	Visible Change	Inference
Pb^{2+}	445	0.865	Yellow $\rightarrow$ Orange	Strong response
Cu^{2+}	410	0.238	Faint yellow	Weak interference
Zn^{2+}	386	0.210	None	No response
Fe^{3+}	396	0.192	Pale brown	Minimal response
Ni^{2+}	402	0.205	None	No response
Cd^{2+}	388	0.176	None	No response

The results demonstrate a markedly higher absorbance response and more pronounced color change for Pb^{2+} compared to other tested metal ions. While minor spectral changes were observed in the presence of some competing ions, these responses were significantly lower than those induced by Pb^{2+} . This preferential response suggests favorable coordination geometry and electronic compatibility between the ligand and Pb^{2+} ions.

The observed selectivity can be rationalized based on the soft acid–base interactions between Pb^{2+} and the donor atoms present in the ligand. Pb^{2+} , being a borderline soft metal ion, exhibits strong affinity for nitrogen and oxygen donors, particularly in flexible ligand environments that can accommodate its relatively large ionic radius. Similar selectivity trends have been reported in previous studies of Schiff-base-based Pb^{2+} sensors (Anand et al., 2022).

3.7 Application to Borehole Water Samples from Kaduna Metropolis

The practical applicability of the developed colorimetric sensor was evaluated using twelve borehole water samples collected from different locations across Kaduna metropolis (Table 5). Recovery studies were performed by spiking known concentrations of Pb^{2+} into the samples, followed by analysis using the developed method.

The recovery values obtained ranged from 92% to 98%, with relative standard deviation (RSD) values below 3%. These results indicate good analytical accuracy and precision and demonstrate that the sensor performs reliably in real water matrices. The low RSD values reflect good repeatability and minimal matrix interference, which is essential for practical environmental monitoring.

Comparable recovery ranges have been reported for colorimetric Pb²⁺ sensors applied to environmental water samples, further supporting the robustness of the method (Anand et al., 2022). Although centralized instrumental methods such as AAS and ICP-MS remain indispensable for confirmatory analysis, the present method offers a valuable complementary approach for rapid screening and preliminary assessment.

Table 5
Determination and Recovery of Pb²⁺ in Borehole Water Samples (n = 12)

Sample Code	Location	Pb ²⁺ Found (mg L ⁻¹ ± SD)	Pb ²⁺ Spiked (mg L ⁻¹)	Recovery (%)	RSD (%)
BH1	Barnawa	0.47 ± 0.011	0.50	94.0	2.3
BH2	Kakuri	0.49 ± 0.008	0.50	98.0	1.6
BH3	Kawo	0.46 ± 0.012	0.50	92.0	2.6
BH4	Tudun Wada	0.48 ± 0.009	0.50	96.0	1.9
BH5	Ungwan Rimi	0.48 ± 0.010	0.50	96.0	2.1
BH6	Malali	0.47 ± 0.009	0.50	94.0	1.9
BH7	Narayi	0.49 ± 0.007	0.50	98.0	1.4
BH8	Rigasa	0.46 ± 0.011	0.50	92.0	2.4
BH9	Sabon Tasha	0.48 ± 0.010	0.50	96.0	2.1
BH10	Kabala	0.47 ± 0.009	0.50	94.0	1.9
BH11	Gonin Gora	0.49 ± 0.008	0.50	98.0	1.6
BH12	Mando	0.48 ± 0.010	0.50	96.0	2.1

3.8 Comparison with Existing Nigerian and Global Studies

The findings of this study align well with existing literature on lead detection using Schiff-base ligands and colorimetric sensors. Nigerian groundwater studies have consistently highlighted the presence and potential risks of lead contamination, emphasizing the need for accessible monitoring tools (Akan et al., 2014; Yusuf et al., 2015; Sadiq et al., 2020). However, most of these studies rely on centralized laboratory techniques, which limit monitoring frequency and spatial coverage.

Globally, Schiff-base-based colorimetric sensors have been widely investigated for metal ion detection, with reported advantages including simplicity, low cost, and visual detection capability (Callan et al., 2005; Anand et al., 2022). The present study contributes to this body of work by demonstrating

successful application in a Nigerian urban context, thereby addressing a key gap in localized environmental sensing research.

3.9 Implications for Groundwater Monitoring in Resource-Limited Settings

The results of this study have important implications for groundwater monitoring in resource-limited environments. The developed colorimetric sensor provides a simple and cost-effective means of preliminary Pb^{2+} screening that can complement conventional analytical methods. Its application to borehole water samples from Kaduna metropolis demonstrates its potential utility for community-level monitoring and early detection of contamination.

While the method does not replace advanced instrumental techniques, it offers a practical screening tool that can support more frequent monitoring and inform decision-making regarding water quality management. Such approaches are increasingly recognized as valuable components of integrated environmental monitoring strategies, particularly in developing regions (WHO, 2023).

4. Implications, Limitations, and Conclusions

4.1 Environmental and Public Health Implications

The findings of this study have important implications for environmental monitoring and public health protection, particularly in urban and peri-urban regions of developing countries where reliance on groundwater is high. Borehole water constitutes a major source of domestic water supply for millions of people in Nigeria and across sub-Saharan Africa. In such contexts, undetected lead contamination poses a serious risk, given the cumulative and irreversible health effects associated with chronic exposure to Pb^{2+} , especially among vulnerable populations such as children and pregnant women (Flora et al., 2012; WHO, 2023).

The successful application of the developed Schiff-base colorimetric sensor to borehole water samples from Kaduna metropolis demonstrates the potential of simple chemical sensing tools to complement existing groundwater quality assessment frameworks. By enabling rapid, low-cost, and visually interpretable detection of Pb^{2+} , the sensor provides an accessible means for preliminary screening of water sources that may otherwise go unmonitored due to logistical or financial constraints. This is particularly relevant in settings where centralized laboratory facilities are limited or where routine sampling and analysis are not feasible.

From a broader environmental management perspective, the use of such screening tools can support early detection of contamination hotspots and inform targeted interventions. Preliminary identification of elevated lead levels in groundwater can prompt further confirmatory analysis using advanced instrumental techniques and facilitate timely public health responses. In this way, colorimetric sensors may play a supportive role within tiered monitoring strategies that integrate field-level screening with

laboratory-based confirmation, an approach increasingly advocated in global water quality management frameworks (WHO, 2023).

4.2 Relevance to Groundwater Monitoring in Developing Countries

The relevance of this work extends beyond Kaduna metropolis to other urban centers in Nigeria and similar settings across Africa and other developing regions. Many cities face comparable challenges, including rapid urbanization, aging infrastructure, informal industrial activities, and limited regulatory oversight of groundwater quality. Studies conducted in different parts of Nigeria and Africa have consistently reported variable physicochemical parameters and trace metal contamination in groundwater, underscoring the need for more frequent and decentralized monitoring approaches (Adelana & MacDonald, 2008; Akan et al., 2014).

The Schiff-base colorimetric sensor developed in this study aligns with the growing emphasis on context-appropriate analytical solutions. Its synthesis relies on readily available reagents, and its operation does not require complex instrumentation, making it suitable for adaptation in academic laboratories, environmental agencies, and potentially community-based monitoring initiatives. While the present study was conducted under controlled laboratory conditions, the demonstrated performance in real borehole water samples suggests that such sensors could be further optimized for semi-field or field-deployable applications.

4.3 Limitations of study

Despite the encouraging results obtained, certain limitations of the present study should be acknowledged. First, the colorimetric sensor developed here is intended as a screening tool rather than a replacement for highly sensitive instrumental techniques such as AAS or ICP-MS. While the method exhibits good linearity, selectivity, and recovery within the investigated concentration range, its detection capability may not match the ultra-trace sensitivity achievable with advanced spectrometric methods (Skoog et al., 2018).

Second, the selectivity studies were conducted against a limited number of competing metal ions commonly encountered in groundwater. Although the ligand demonstrated preferential response toward Pb^{2+} under the tested conditions, the presence of complex matrices or higher concentrations of interfering species could potentially influence sensor performance. Further studies involving a broader range of ions and varying water chemistries would provide additional insight into interference effects.

Third, the study was limited to twelve borehole water samples collected within Kaduna metropolis. While this number provides meaningful spatial representation and validates real-sample applicability, larger-scale sampling across different seasons and hydrogeological settings would strengthen the generalizability of the findings. Seasonal variations in groundwater chemistry, influenced by rainfall and anthropogenic activity, may also affect metal speciation and sensor response.

4.4 Future Perspectives and Research Directions

Future research could build on the findings of this study in several ways. Structural modification of the Schiff-base ligand through functional group substitution may enhance selectivity or sensitivity toward Pb^{2+} and potentially allow discrimination among different heavy metal ions. Incorporation of the ligand into solid-state platforms, test strips, or polymer matrices could facilitate development of portable sensing devices suitable for on-site analysis.

Additionally, coupling colorimetric sensing with digital image analysis using smartphone-based platforms represents a promising avenue for semi-quantitative field measurements. Such approaches could improve data recording, facilitate community engagement, and support real-time reporting of water quality information. Integration of simple sensors into broader monitoring networks aligns with global efforts to improve access to safe drinking water and strengthen environmental surveillance systems (WHO, 2023).

4.5 Conclusions

In this study, a Schiff-base ligand synthesized from salicylaldehyde and ethylenediamine was developed and evaluated as a colorimetric sensor for Pb^{2+} detection in groundwater. Spectroscopic characterization using FTIR and UV–Visible techniques confirmed azomethine formation and coordination of Pb^{2+} ions through nitrogen and oxygen donor atoms. The interaction between the ligand and Pb^{2+} produced distinct spectral changes, including the emergence of a ligand-to-metal charge transfer band accompanied by a visible color change that enabled straightforward detection.

The sensor demonstrated reliable quantitative performance within the investigated concentration range, exhibiting linear Beer–Lambert behavior ($R^2 = 0.995$), preferential response toward Pb^{2+} in the presence of selected competing metal ions, and satisfactory accuracy and precision when applied to borehole water samples from Kaduna metropolis. Recovery values ranging from 92% to 98% with low relative standard deviations indicate consistent performance of the method under the tested experimental and sample conditions.

Although the method does not replace advanced instrumental techniques for trace-level quantification, it offers a practical, low-cost, and accessible approach for preliminary screening of lead contamination in groundwater. The findings highlight the potential applicability of Schiff-base-based colorimetric sensors as complementary tools for groundwater monitoring in resource-limited environments and contribute to ongoing efforts to develop context-appropriate analytical methods for environmental assessment.

Declarations

Ethical statement

Clinical trial: not applicable

Clinical trial number

Not applicable

Conflict of interest

There are no conflicts of interest to declare.

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akoredeyinka@gmail.com A.A.O. supervised the research, contributed to the study conceptualization and methodology, provided guidance on data interpretation, and critically revised the manuscript for important intellectual content. A.S. conducted the experimental work, sample collection, data analysis, and wrote the original draft of the manuscript. A. A. O Co Supervisor. Plotted the graphs and contributed to data interpretation and revision of the recommendations and contributions to knowledge. All authors reviewed and approved the final version of the manuscript.

Availability of data and materials

The data is available and will be shared with public upon reasonable request.

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Figures

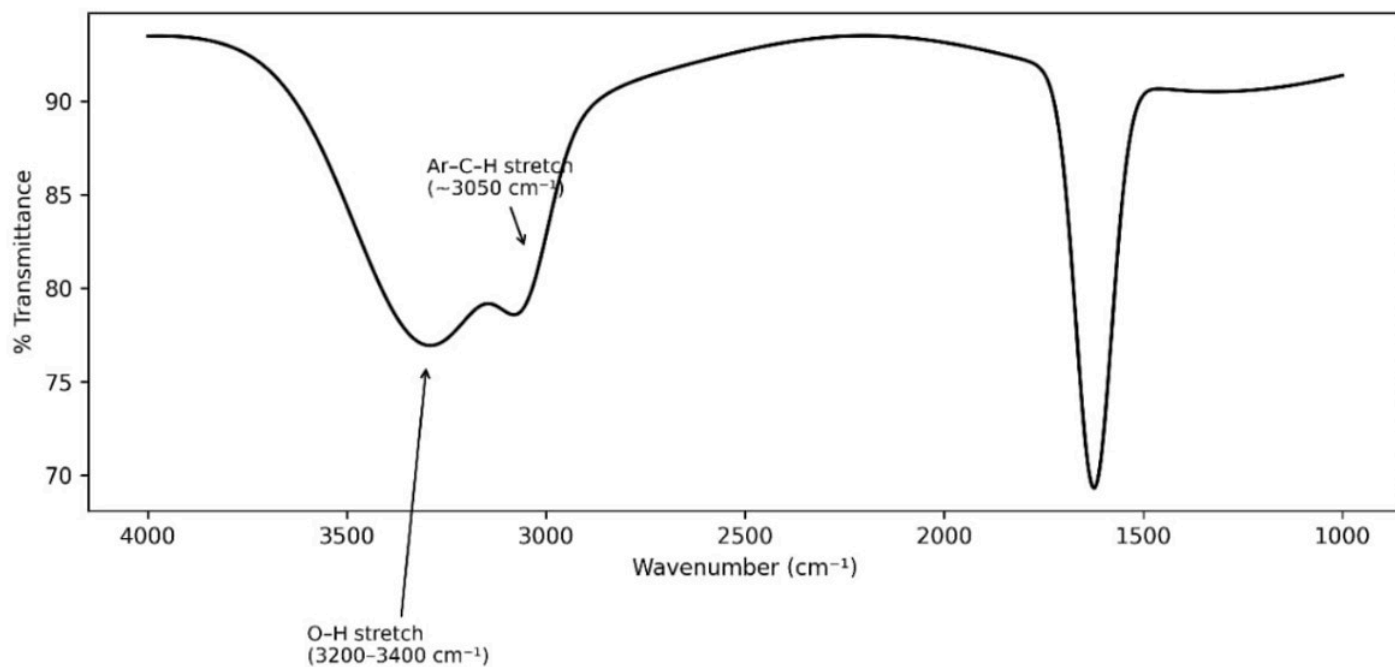


Figure 1

FT-IR spectrum of synthesized Schiff-base ligand

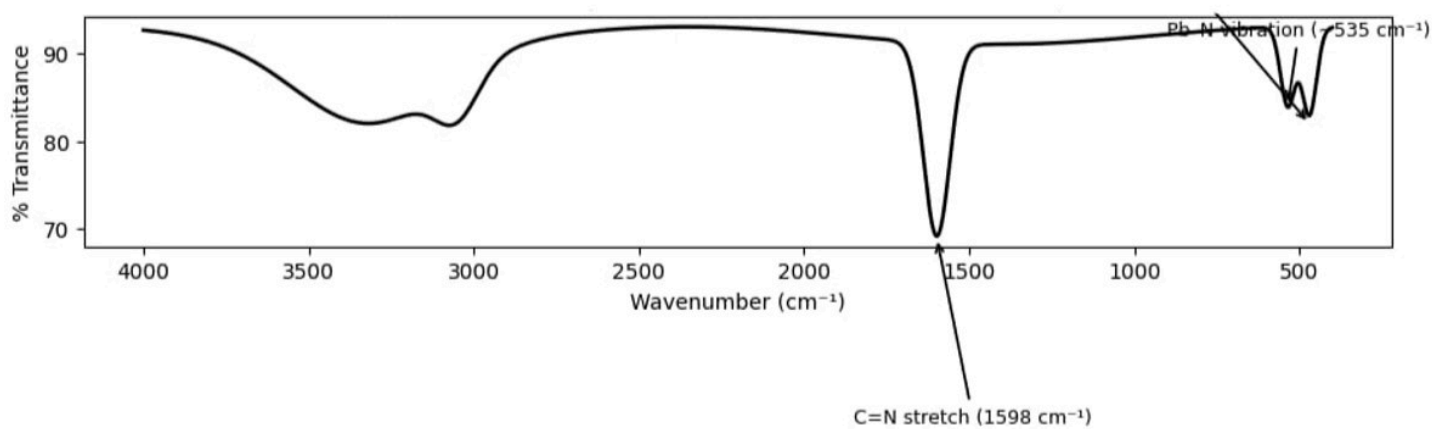


Figure 2

FT-IR spectrum of synthesized Schiff-base ligand-Pb²⁺ complex

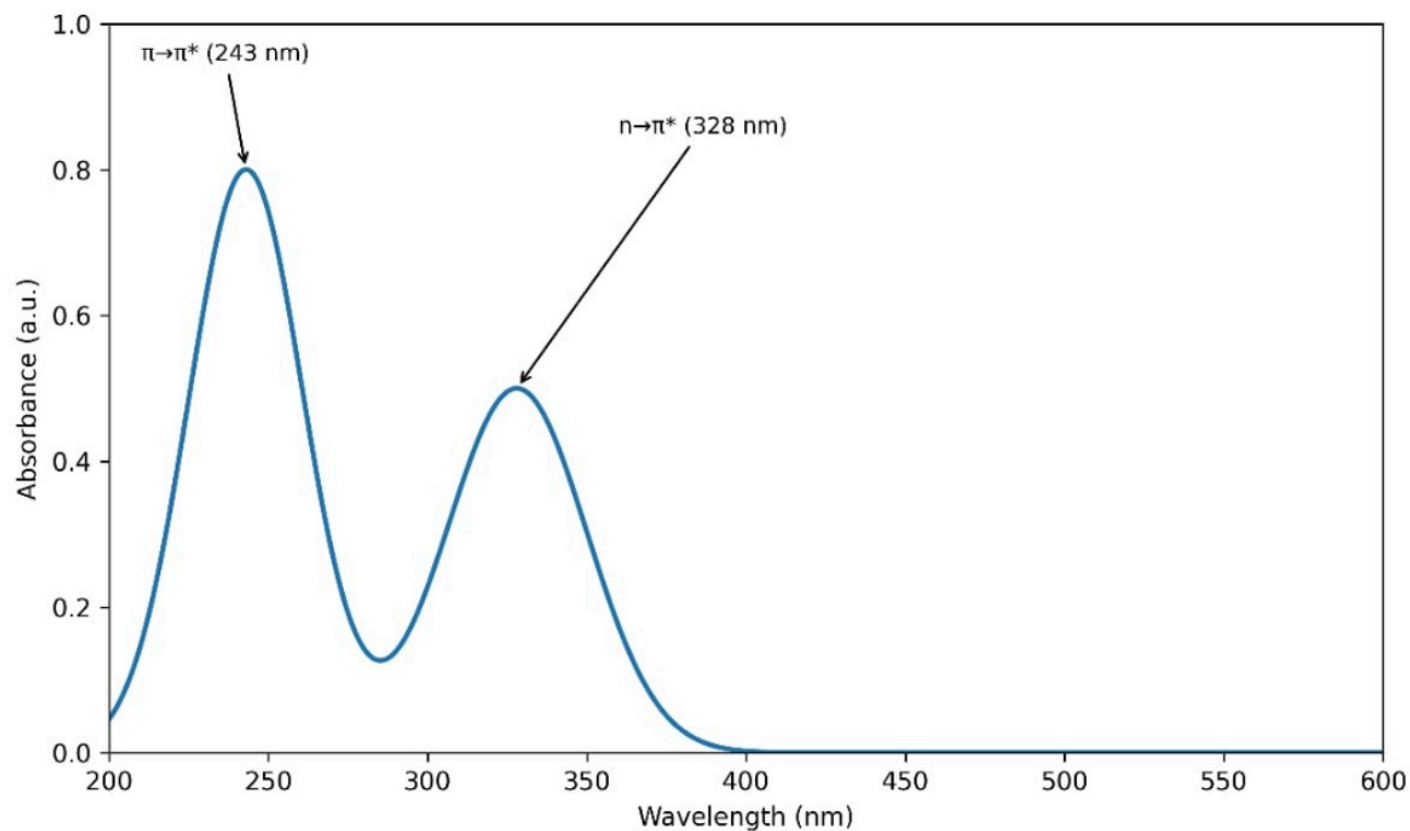


Figure 3

UV-Visible spectrum of synthesized Schiff-base ligand

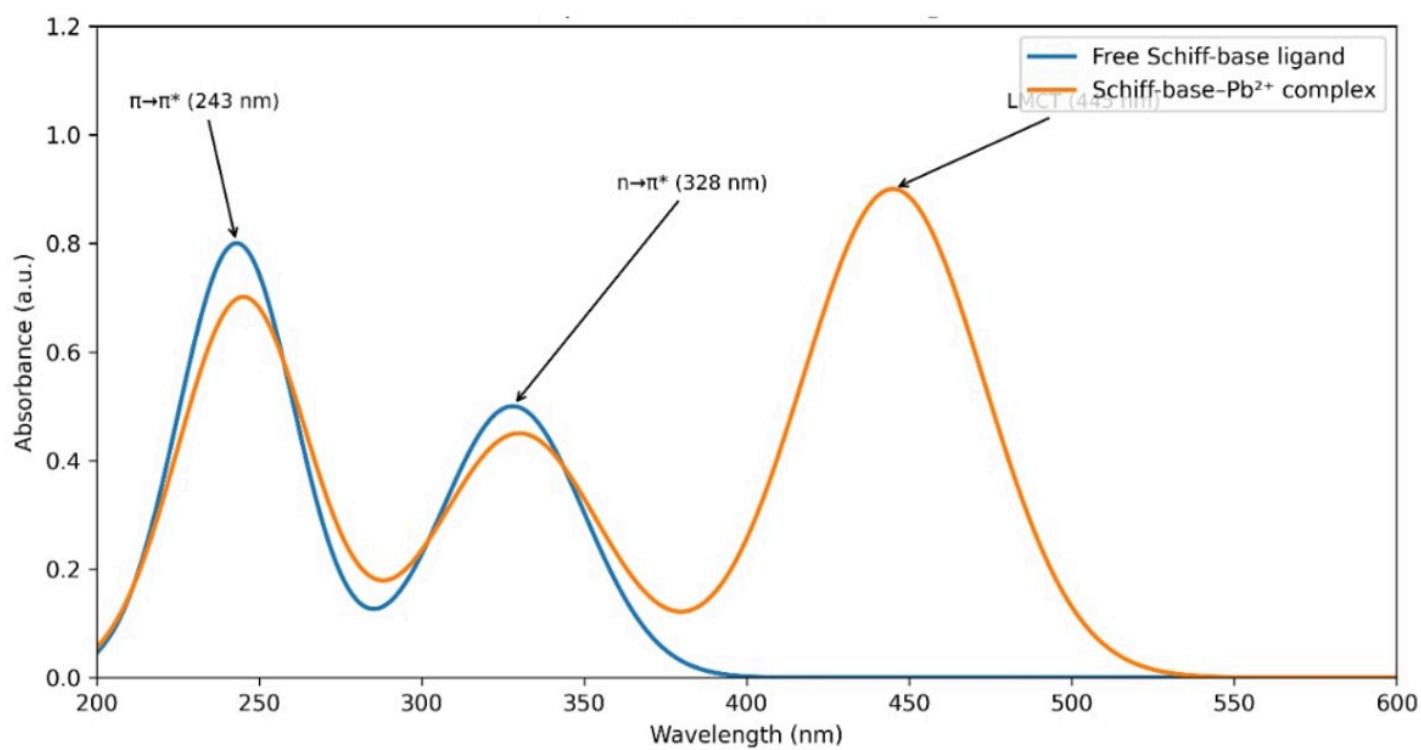


Figure 4

UV-Visible spectrum of synthesized Schiff-base-Pb²⁺ complex

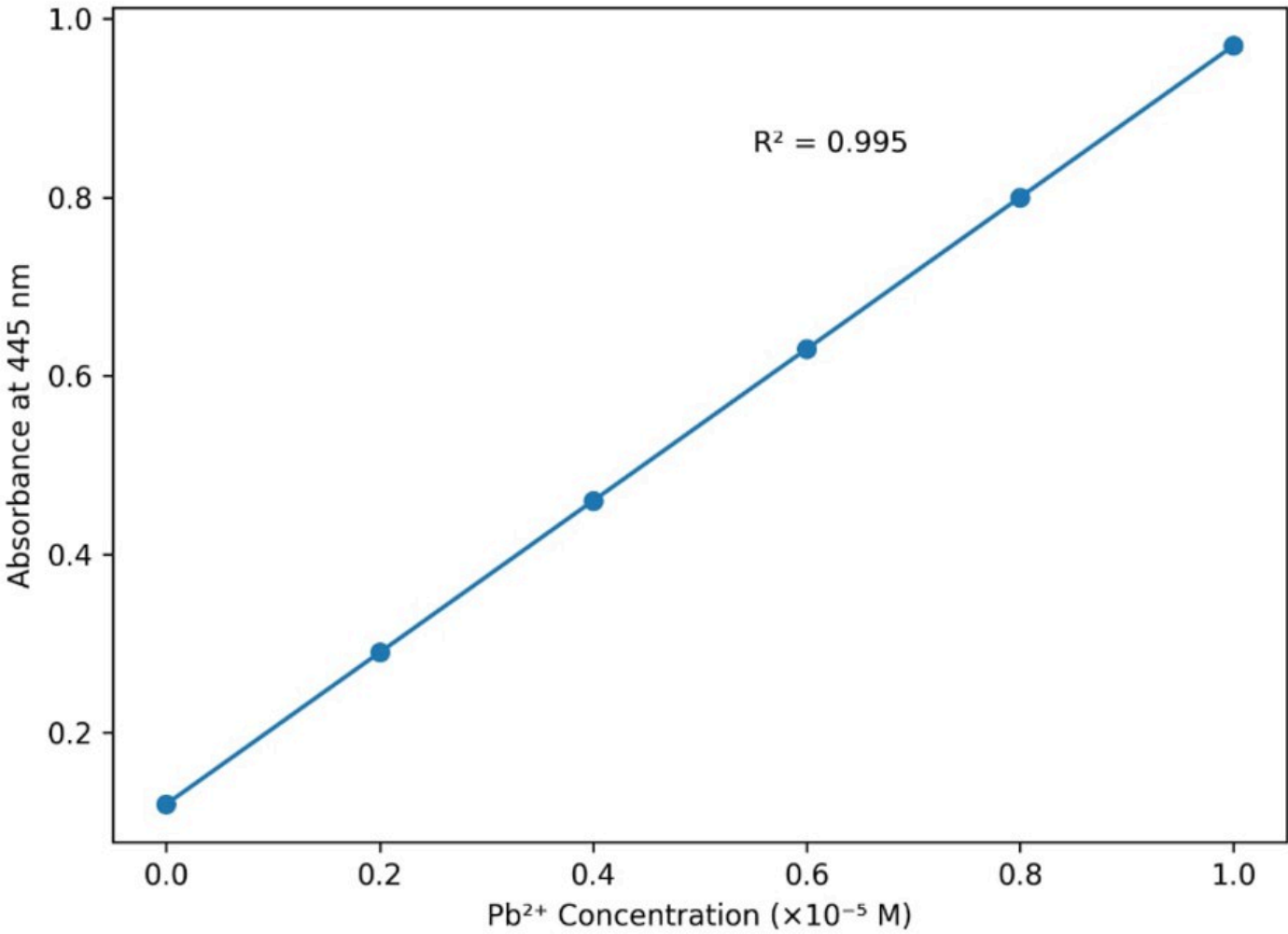


Figure 5

Calibration curve of Pb²⁺ detection

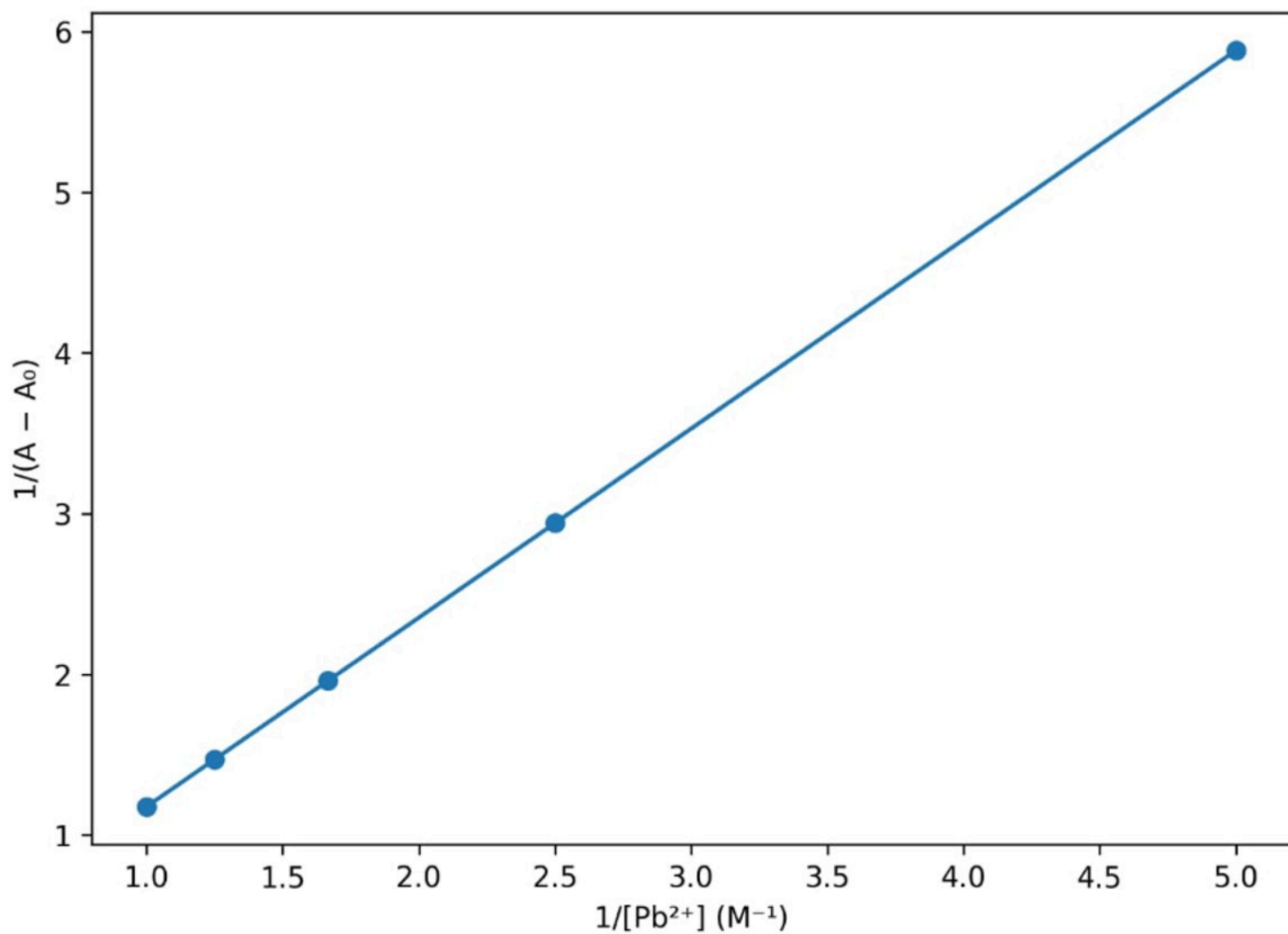


Figure 6

Benesi-Hilderbrand plot for Pb^{2+} binding