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Recent Advances in Fluorescent-Based Chemosensors for Lead(II) Detection: A Decade Review (2015–2025)

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Abstract: Lead contamination remains a pressing global challenge due to its severe toxicity and persistence in the environment. In recent years, fluorescent-based chemosensors have emerged as powerful tools for the rapid, selective, and sensitive detection of Pb^{2+} ions. This review provides a comprehensive analysis of the progress made between 2015 and 2025 in the development of fluorescent chemosensors for lead ion detection. The discussion focuses on six major classes of chemosensors: rhodamine-, coumarin-, thiophene-, quinoline-, thiosemicarbazone-, and triazole-based systems. For each category, design principles, sensing mechanisms, photophysical properties, and detection performance are systematically examined. The review also highlights challenges such as interference from competing metal ions, limitations in aqueous/biological environments, and the need for real-time detection platforms. The highest analytical sensitivity (lowest LODs) in this decade has been realized to have come from DNAzyme/amplification/aptamer platforms (pM to low-pM). Small-molecule chemosensors (rhodamine, naphthalene, coumarin, Schiff bases) commonly achieve nM to sub-nM LODs and report binding constants when the work focuses on coordination chemistry. Stoichiometries vary (1:1, 2:1, etc.). Selectivity remains a challenge in many studies because authors typically test against a panel of common metal ions (Na^+, K^+, Ca^{2+}, Mg^{2+}, Zn^{2+}, Cd^{2+}, Hg^{2+}, Cu^{2+}). Hg^{2+} and Cd^{2+} are recurring interfering ions for Pb^{2+} sensors; many papers explicitly benchmark against them. Finally, future perspectives are provided on integrating fluorescent chemosensors with nanomaterials, microfluidic devices, and portable sensing platforms to advance practical applications in environmental and biomedical monitoring.

Keywords: lead(II) detection; fluorescent chemosensors; rhodamine-based sensors; quinoline and triazole derivatives; environmental monitoring.

1. Introduction

Lead is a major environmental contaminant that originates from sources such as gasoline, batteries, and industrial dyes, and it poses serious health risks to humans, including muscle paralysis, memory impairment, anaemia, heart problems, and psychological issues [1]. Developing chemosensors that are both sensitive and selective for detecting and quantifying essential analytes is crucial for assessing levels of these chemical species across various environments and matrices [2]. It is crucial to explore rapid, simple, and practical methods for detecting Pb^{2+} ions. Consequently, numerous approaches have been developed to measure Pb^{2+} concentrations. Atomic absorption spectroscopy (AAS) [3], anodic stripping voltammetry

(ASV) [4], inductively coupled plasma atomic emission spectroscopy (ICP-AES) [5], and inductively coupled plasma mass spectrometry (ICP-MS) [6] are a variety of this kind of technique.

However, these techniques are often time-consuming, complex, and costly. In contrast, many fluorescent probes have been reported for the detection of lead ions due to their advantages of high specificity, sensitivity, and ease of use [6-8]. Fluorescence-based chemosensors are particularly promising because of their remarkable sensitivity, enabling detection at concentrations as low as picomolar levels [9]. The diverse range of chromophores and fluorophores allows for the fine-tuning of the optical properties exhibited by the final sensor molecule. Chemosensors are particularly appealing due to their ability to enable localized observation, detect sensitive ion-induced fluorescence changes, and provide real-time analysis of metal ion content. The binding of metal ions ultimately leads to a change in fluorescence intensity. Most sensors are designed with a fluorophore linked to a metal-chelating site [10]. This design is predicated on the changes in the optical properties of both free and metal-complexed fluorescent or chromogenic chemosensors. Detection of analytes relies on ligand exchange reactions between the complex and an analyte that exhibits a strong binding affinity for the complex [11].

Recently, there has been a surge in research on the development of bi- and multifunctional fluorescent ion probes [12,6]. The detection of metal ions in biological samples is highly influenced by pH and environmental conditions, and it can be achieved at low concentrations **(**Table 1**)**. The fluorescence responses are governed by several mechanisms. This paper reviews fluorescent-based chemosensors for the selective detection of lead Pb^{2+} ions. This is because fluorescent chemosensors for lead (Pb^{2+}) detection offer several distinct performance advantages over colorimetric and electrochemical methods, particularly in terms of sensitivity, selectivity, and real-time applicability.

Table 1. Key numerical performance indicators such as limit of detection (LOD) ranges, binding (selectivity/affinity) metrics, and, in some cases, quantum yields, for selected lead(II) chemosensors, drawn from recent literature. These are illustrative examples rather than a comprehensive survey.

Example	LOD or detection range	Binding/selectivity	Quantum yield or signal change notes
Rhodamine-based turn-on fluorescent and colorimetric chemosensor for selective Pb^{2+} detection (Schiff-base rhodamine L)	LOD ~ 3.77 nM for Pb^{2+}.	1:1 binding stoichiometry; binding constant $K_a \approx 0.954\times10^4$ M^{-1}.	Turn-on fluorescence response; quantum yield not explicitly reported.
Highly Selective Ratiometric Sensors for Pb^{2+} Based on Luminescent Zn(II)-Coordination Polymers (Zn-polymer chemosensor)	LOD ~ 1.78 µM in 20% aqueous ethanol.	Binding constant $K_a \approx 5.62\times10^4$ M^{-1}; 1:1 stoichiometry.	Quantum yield (Φ) of the sensor material ~ 0.09 in suspension.
A highly selective fluorescent chemosensor for Pb^{2+} based on quinoline–coumarin (Coumarin–quinoline sensor)	LOD ~ 0.5 µM for Pb^{2+} in CH_3CN/HEPES (9:1) at pH 7.4.	1:1 binding stoichiometry; selectivity over many other metal ions.	Fluorescence “turn-off” response (quenching) with ≈ 99% quenching efficiency.
Detection of lead (II) with a “turn-on” fluorescent biosensor based on energy transfer from CdSe/ZnS quantum dots to graphene oxide (QD–GO aptamer sensor)	LOD ~ 90 pM for Pb^{2+}.	Excellent selectivity toward Pb^{2+} vs many other metal ions.	Turn-on fluorescence via separation of QDs from GO; exact quantum yield of system not given.

Finally, Fluorescent chemosensors are favored for lead detection since they combine exceptional sensitivity, selectivity, and real-time visualization capabilities with versatility for biological and environmental applications, outperforming colorimetric (limited by visual sensitivity) and electrochemical (limited by electrode dependence) approaches.

2. Materials and Methods (Review Methodology)

2.1. Literature search strategy.

A comprehensive literature search was conducted to identify peer-reviewed studies on chemosensors developed for the detection of lead (Pb^{2+}) ions. The search covered publications from 2015 to 2025 to capture recent advances in sensor design, analytical performance, and application.

2.2. Databases searched.

We carefully searched the following scientific databases for relevant literature: Scopus, Web of Science (Core Collection), ScienceDirect (Elsevier), PubMed, SpringerLink, ACS Publications, and RSC Journals. Additional grey literature, such as conference proceedings and theses, was excluded to ensure quality and reproducibility.

2.3. Search keywords.

Search terms combined relevant descriptors using Boolean operators:
(“lead ion” OR “Pb^{2+}”) AND (“chemosensor” OR “fluorescent sensor” OR “colorimetric sensor” OR “optical sensor” OR “nanosensor” OR “probe”) AND (“detection” OR “sensing”). Filters were applied to restrict results to English-language articles published between 2015 and 2025.

2.4. Inclusion and exclusion criteria.

2.4.1. Inclusion criteria.

This study examined original research articles detailing the design, synthesis, or analytical application of lead chemosensors. The focus was on research that developed new sensing molecules, materials, or analytical methods specifically for detecting lead ions. The studies included were those that presented quantitative performance metrics like detection limit, selectivity, response time, and linear range. These are important for figuring out how well the chemosensors work and how useful they are in real life. Furthermore, both experimental and computational studies were examined, especially those utilizing optical sensing methods such as fluorescent and colorimetric detection, electrochemical sensing techniques, or hybrid sensing mechanisms that integrate various detection methods.

2.4.2. Exclusion criteria.

The following categories of literature were excluded from consideration in this study: reviews, book chapters, patents, and conference abstracts. Furthermore, studies concentrating on non-selective metal sensors or analytes other than lead were excluded. Moreover, reports that lacked experimental validation or failed to furnish comprehensive details on sensor performance were excluded.

2.5. Data extraction and analysis.

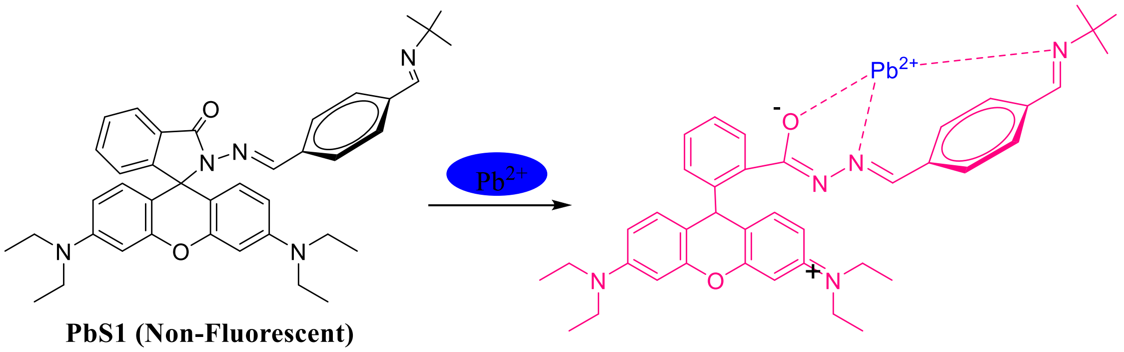
From each eligible publication, the following data were extracted: sensing mechanism, receptor type, signaling unit, detection limit, linear range, solvent or medium, selectivity, and real-sample application. Extracted data were synthesized qualitatively to highlight trends in design strategies, detection performance, and emerging materials and technologies.

3. Types of Fluorescent Chemosensors for Lead(II) Ion Detection (PbS)

Mechanisms that recur for Pb^{2+} chemosensors are CHEF (chelation-enhanced fluorescence), PET (photoinduced electron transfer) suppression, ICT changes (intramolecular charge transfer), and DNA structural switches (G-quadruplex/DNAzymes). LODs for Pb^{2+} ions vary widely (sub-nM to 10^{-7}–10^{-6} M) depending on probe design and readout method. For example, DNA-based and macrocycle designs often reach the lowest LODs (sub-nM). For real-sample analysis (tap/river water, serum), some probes are optimized only for buffered lab conditions, and others are validated on spiked real samples.

3.1. Rhodamine-based chemosensors for lead(II) ion detection.

Rhodamine-based Schiff bases have attracted attention as fluorescent and colorimetric chemosensors due to their outstanding photophysical properties [13]: exceptional photostability, high quantum yields [14], good solubility, high molar absorption coefficients, and emission properties [15]. Additionally, since the rhodamine fluorophore emits light at wavelengths of 550 nm or above, the impact of background fluorescence (below 500 nm) can be minimized, allowing for highly sensitive detection. Various rhodamine derivatives can serve as starting materials for these chemosensors and exhibit different properties based on their functional groups [16]. The spirolactam moiety, commonly found in rhodamine derivatives, consists of a five-membered ring that exhibits non-fluorescent and colorless characteristics. However, when subjected to a ring-opening reaction in the presence of a heavy-metal atom, it undergoes a transformation that results in notable changes in absorbance and strong fluorescence [17]. Rhodamine derivatives commonly rely on a spirolactam ring-opening mechanism, where Pb^{2+} binding induces conversion from a colorless spirolactam (non-fluorescent) to an open-ring amide form (highly colored and fluorescent). These distinctive alterations in absorbance and fluorescence properties highlight its potential as an ON-OFF fluorescent chemosensor.



PbS1 (Non-Fluorescent)

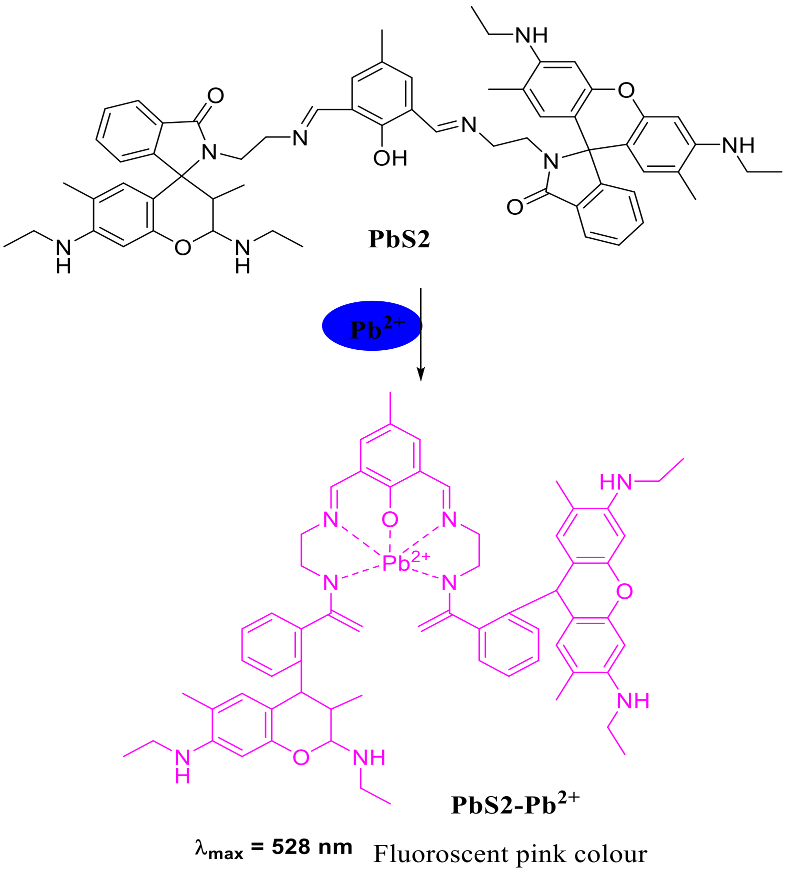
$PbS1\text{-}Pb^{2+}$ λ_{ab} = 540 nm, λ_{em} = 588 nm

(Highly Fluorescent)

Scheme 1. Sensing mechanism of Pb^{2+} using PbS1.

Kumar and Roy [18] designed a novel approach to detecting lead ions using a hybrid organic-inorganic optical nanochemosensor. The authors developed a chemosensor that combines a rhodamine-derived compound (**PbS1**) with silica-coated upconverting nanophosphors (UCNPs), **PbS1**. This combination enables selective, ultrasensitive detection of Pb2+ ions via energy-transfer (ET) mechanisms. The detection mechanism relies on the energy transfer from UCNPs to the **PbS1**-Pb^{2+} complex when excited by near-infrared (NIR) light (980 nm). The presence of Pb^{2+} ions leads to a decrease in green emission at 542 nm and an increase in yellow emission at 588 nm, indicating successful energy transfer. The chemosensor exhibits a visible colour change from colourless to magenta upon the addition of Pb^{2+} ions, which can be observed with the naked eye (Scheme 1).

Ghosh *et al.* [9] synthesized a Rhodamine 6G-based sensing material (Scheme 2) that exhibits a strong affinity for Pb^{2+} in aqueous solutions. Upon the addition of Pb^{2+}, a prominent absorption band is observed at 528 nm, indicating an increase in the acyclic xanthene form, which causes the solution's colour to change from light yellow to pink. Additionally, fluorescent titration and other analyses revealed that PbS2 can selectively detect Pb^{2+} with a low limit of detection (LOD) of 2.7 nM in acetonitrile media, demonstrating a binding ratio of 1:1.



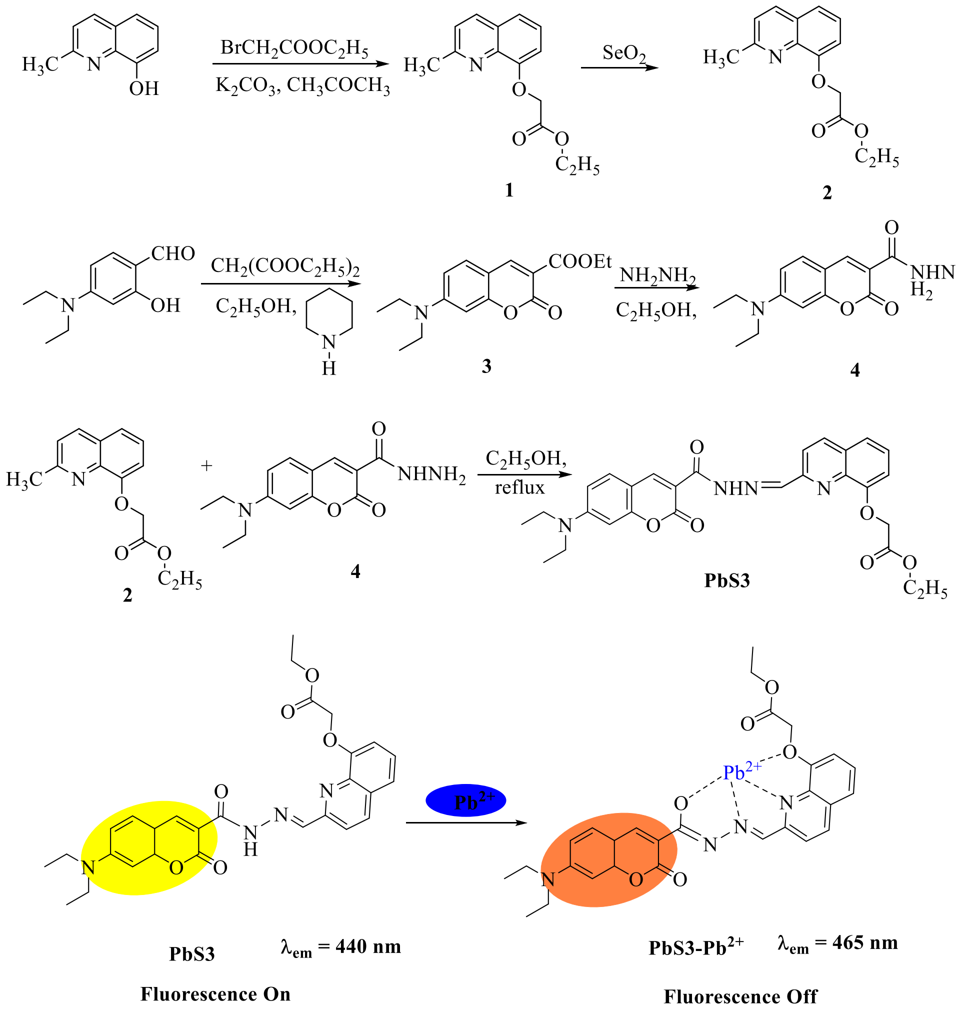
Scheme 2. Sensing mechanism of **Probe PbS2**.

3.2. Coumarine-based chemosensors for lead(II) ion detection.

Coumarin systems detect Pb^{2+} through photoinduced electron transfer (PET) or intramolecular charge transfer (ICT) modulation upon metal coordination.

In this study, Meng *et al.* [19] reported a novel, highly sensitive, and selective fluorescent chemosensor (Scheme 3). This chemosensor employs coumarin as the fluorophore, a C=N bond, and quinoline as the recognition unit for the detection of Pb^{2+}. The incorporation of hydroxyl groups into the flexible chain enhanced both the stability and selectivity for metal ions. Their findings indicated **PbS3** exhibited superior selectivity and sensitivity toward Pb^{2+} compared to various other metal ions within a CH_3CN/HEPES buffer medium (9:1 v/v, pH = 7.4). The absorption behaviour of probe **PbS3** was examined using UV-Vis spectroscopy in the presence of Pb^{2+} within a CH_3CN/ HEPES buffer medium (9:1 v/v, pH = 7.4). The absorption spectra revealed a significant change; specifically, the addition of Pb^{2+} caused a red shift from 440 nm to 465 nm, accompanied by a colour transition from bright yellow to orange.

To gain further insight into the sensing behaviour of sensor 3 toward Pb^{2+}, fluorescence titration experiments were conducted. These experiments involved 10 mM of sensor 3 in the presence of various metal ions. Upon the addition of 10 equivalents of Pb^{2+} ions, the solution exhibited significant fluorescence quenching. These results indicate that sensor 3 can serve as an effective chemosensor for the selective detection of Pb^{2+} across a wide array of metal ions. The fluorescence intensity decreased progressively with increasing concentrations of Pb^{2+}. Notably, a dramatic quenching was observed, with the quenching efficiency reaching a maximum of 99% $[(I_0 - I)/I_0 \times 100\%]$ upon the addition of 10 equivalents of Pb^{2+}. Additionally, there was no noticeable shift in the emission spectra with increasing Pb^{2+} concentration, consistent with the photo-induced electron transfer (PET) mechanism.

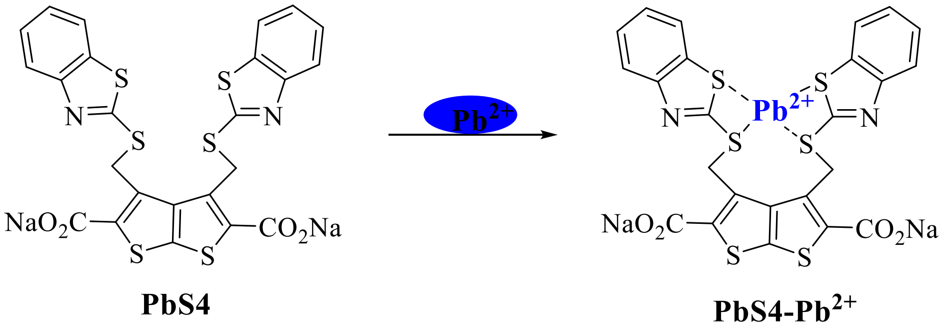


Scheme 3. Synthesis and possible sensing mechanism of probe PbS3.

3.3. Thiophene-based chemosensors for lead(II) ion detection.

One of the most widely utilized chemosensors is based on thiophene derivatives, which serve as fluorescent signalling promoters for organic acids, metal ions, and cations [20]. Thiophene is among the most extensively researched five-membered heterocyclic compounds. These compounds often exhibit strong photoluminescent properties, including long emission and absorption wavelengths, a high absorption coefficient, and an increased fluorescence quantum yield. Consequently, thiophene is frequently employed in light-emitting materials [21], making the thiophene moiety a valuable functional group in the design of chemosensors. Due to their significant potential for structural variation and the high polarizability of sulfur atoms within the ring, thiophenes enhance the stability of the conjugated chain, resulting in it phenomenal electronic and charge-transfer properties [22]. Oligo- and polythiophenes exhibit fluorescence frequencies that can be tuned across a broad visible spectrum, coupled with high absorbance and fluorescence efficiency. As a result, they are increasingly utilized as fluorometric and colorimetric chemosensors for protein detection. The interactions, both chemical and physical, between these sensors and the analytes are explored, focusing on how they influence changes in emission intensity and probe colour. Thiophene derivatives exploit π-conjugation and sulfur–metal coordination. Pb^{2+} binding perturbs conjugation, altering absorbance/emission.

Cao *et al*. [23] produced an original water-soluble thiophene-functionalized chemical sensor, **PbS4,** that has a *benzo[d]thiazole-2-thio* unit for the detection of Pb^{2+}. In HEPES buffer, the probe demonstrated remarkable fluorescence intensity and a bathochromic shift in the absorption maxima occurs solely in the presence of Pb^{2+} ions, indicating no interference from other ions. This response is likely due to the formation of a binding pocket (as illustrated in Scheme 4) within probe **PbS4**, which serves as a probable binding site for Pb^{2+} ions, exhibiting a binding stoichiometry ratio of 1:1. At the outset, probe 4 exhibits a peak in absorption at 405 nm and 530 nm in the absorption and emission spectra, respectively. However, when Pb^{2+} was added, a notable fluorescence quenching was observed. This phenomenon can be attributed to the change in the shape of probe 4 that occurs when the metal ions bond to form a complex.

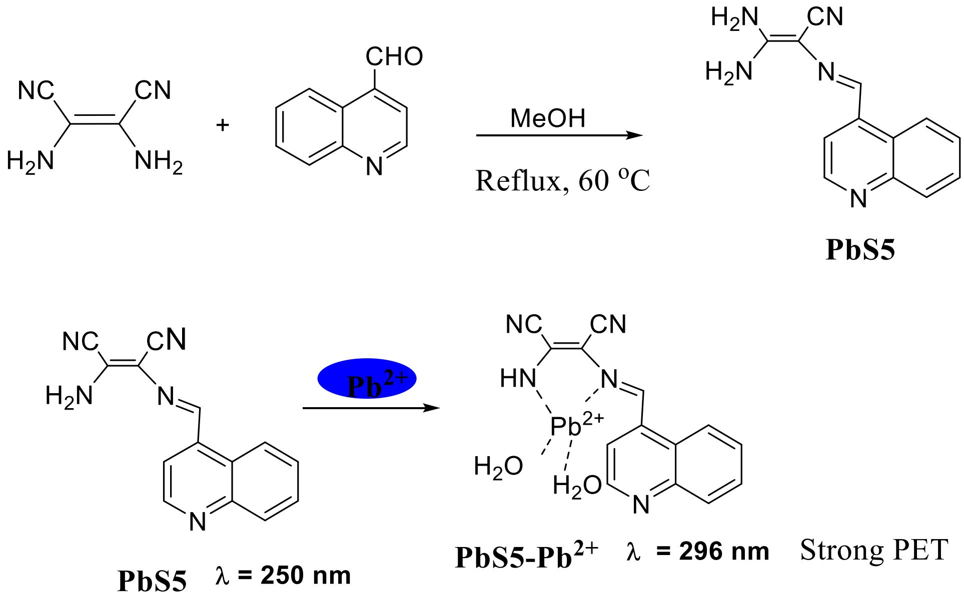


Scheme 4. Synthesis of probe PbS4 and possible sensing mechanism.

3.4. Quinoline-based chemosensors for lead(II) ion detection.

Quinoline is recognized as an effective fluorophore and chromophore due to the numerous advantages of quinoline and its derivatives. These advantages include excellent coplanarity within the conjugated system, strong intramolecular charge transfer, outstanding solubility, stability, and the potential for structural modification [24]. An additional significant feature of quinoline-based chemosensors is their use of low-energy two-photon lasers as excitation sources, which minimizes cellular damage [25]. However, their applications in fluorescent chemosensing remain relatively underexplored. The mechanism of sensing involves Pb^{2+} interacting with the nitrogen donor of the quinoline ring, modulating ICT and PET processes, often yielding strong fluorescence quenching or enhancement.

Sharma *et al*. [26] synthesized the organic ligand, 2-amino-3-((E)-quinolin-4-ylmethyleneamino)maleonitrile, through the condensation reaction of 1:1 Schiff base between 2,3-diaminomaleonitrile and 4-quinoline carboxaldehyde, employing a 1:1 mole ratio in anhydrous methanol solvent Scheme 5. When 1.2 equivalents of Pb^{2+} ions are introduced, the absorption peak of the free chemosensor L, originally at 250 nm, increases to 296 nm, with a blue shift. This shift occurs because Pb^{2+} coordinates with the free amine group and the azomethine nitrogen (–C=N–) of probe **PbS5** (Scheme 5). Notably, **PbS5** does not display any significant spectral changes in alcoholic medium when additional metal ions are added, including Hg^{2+}, Zn^{2+}, Ni^{2+}, Fe^{2+}, Cd^{2+}, Cu^{2+}, Fe^{3+}, Co^{2+}, Mn^{2+}, Ag^{+}, Sr^{2+}, Ca^{2+}, Ba^{2+}, Mg^{2+}, Sm^{3+}, Gd^{3+}, Cr^{3+}, and Al^{3+}. The observed blue shifts in the absorption spectra of Pb^{2+} interacting with the sensor suggest the possibility of ligand-to-metal charge transfer (LMCT) and the formation of a complex between the sensor and Pb^{2+}. This interaction results in a change of the sensor's colour from yellow to colourless.



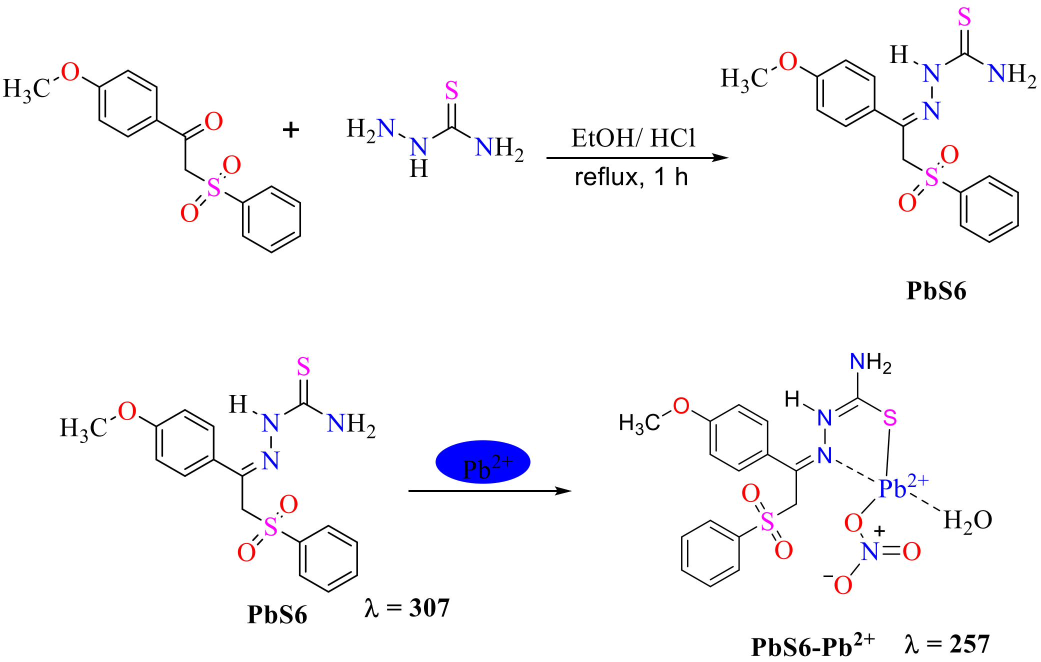
Scheme 5. Synthesis and possible sensing mechanism of probe PbS5.

3.5. Thiosemicarbazone-based chemosensors for lead(II) ion detection.

Thiosemicarbazone-Based Chemosensors rely on thiocarbonyl (C=S) and azomethine (C=N) donor sites, which chelate Pb^{2+} strongly, altering the electron density distribution and absorption/emission spectra.

Recent studies have highlighted the impressive ability of thiosemicarbazone derivatives to coordinate with various metal ions [19,20]. This is attributed to the presence of electron-donating atoms such as nitrogen and sulfur within their structure. The complexes formed from thiosemicarbazone derivatives have demonstrated numerous applications across industrial, agricultural, and medical fields [21-23]. Consequently, thiosemicarbazones are instrumental in the detection of various metal ions in aqueous solutions through coordination [24].

Building on these findings, Mohammed *et al*. [32] aimed to detect and quantify lead(II) ions in solution using a rapid, straightforward, and cost-effective colorimetric method that involves the formation of a complex with the thiosemicarbazone 2-benzenesulfonyl-1-(4-methoxyphenyl) *ethanone*. The absorption spectra of the Pb (II) complex and the ligand were analyzed. In the ligand spectrum, the most significant absorption peak was observed at 307 nm. Upon the introduction of the Pb (II) solution, the ligand's pale yellow colour became colourless, resulting in an absorption maximum recorded at 257 nm (Scheme 6). These results prompted the selection of 257 nm as the analytical wavelength for detecting Pb^{2+} ions.

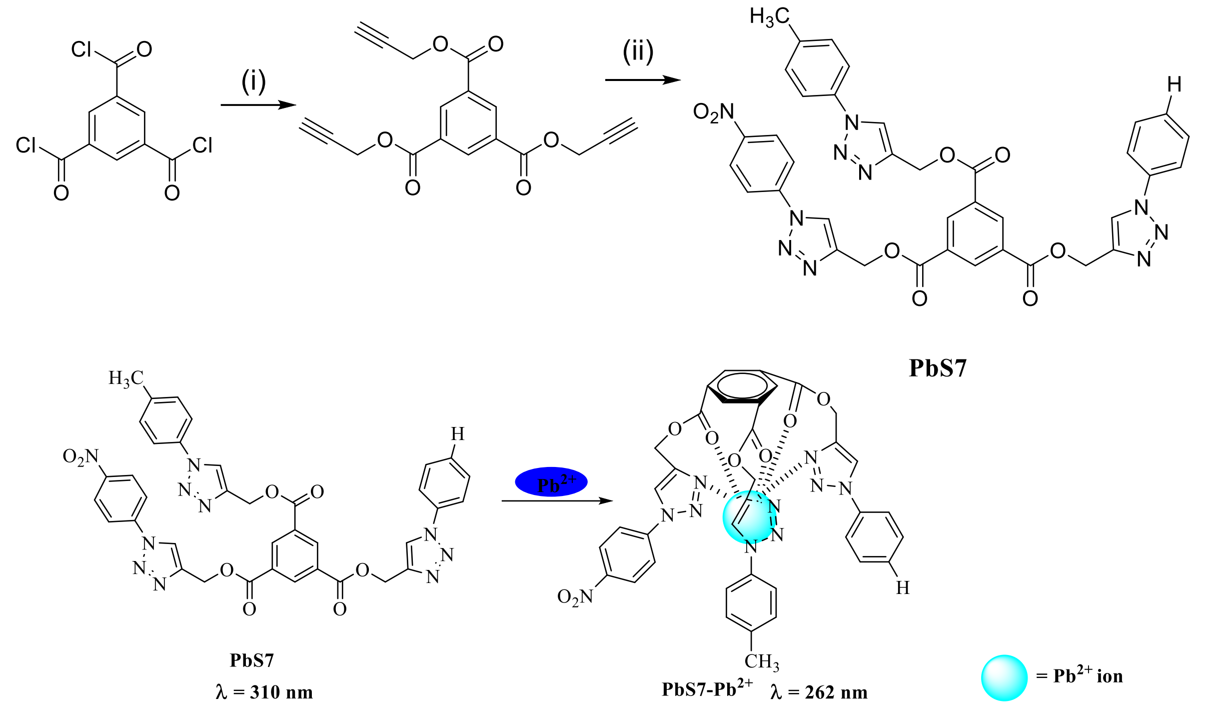


Scheme 6. Synthesis of probe 6 and possible sensing mechanism.

3.6. Triazole-based chemosensors for lead(II) ion detection.

The triazole structure is an attractive framework for the creation and development of chemosensor molecules due to its ability to engage in hydrogen bonding and dipole-dipole interactions, which can be applied to metal ion detection [33]. A 1,2,3-triazole compound has been used to stabilize silver nanoparticles or to serve as a capping agent for them. The resulting stabilized or capped silver nanoparticles are used to detect and quantify mercury ions, either through the aggregation of silver nanoparticles induced by mercury or through the formation of an Ag-Hg amalgam [34]. A review of the literature indicates that the application of 1,2,3-triazole derivatives in the design of sensor materials for detecting toxic metal ions other than mercury remains limited, despite their distinctive structural characteristics [27-29]. The triazole (N_3-ring) serves as a strong donor, forming a stable coordination bond with Pb^{2+}. Detection occurs through modulation of PET or ICT in triazole-linked fluorophores.

In the efforts to discover the recognition of different metal ions, Rani *et al.* [38] successfully synthesized 1,2,3-tris-triazoles (**PbS7**) according to the synthetic protocol illustrated in Scheme 7. The ion recognition properties of the synthesized receptor were examined through UV-visible studies in a DMSO/CH_3CN (1:9 v/v) solvent system. The binding interactions of **PbS7** were analyzed by introducing perchlorates of various ions, such as Cu^{2+}, Zn^{2+}, Ca^{2+}, Co^{2+}, Cd^{2+}, Hg^{2+}, Pb^{2+}, and Ni^{2+}, into a standard solution of the sensor. Notably, a significant shift in the absorption spectrum of the sensor was observed upon the addition of lead perchlorate. The absorption spectrum of **PbS7** in the presence of Pb^{2+} ions remained largely unchanged despite the presence of other competing metal ions. The introduction of Pb^{2+} ions to a solution of sensor 7 resulted in a gradual decrease in intensity at 310 nm and the appearance of a new absorption band at 262 nm. This observed blue shift suggests that the Pb^{2+} ion interacts with the carbonyl oxygen and nitrogen atoms of the triazole moiety in probe **PbS7**.



Scheme 7. Synthesis and possible sensing mechanism of probe PbS7.

Table 2. Comparative summary table of the lead(II) chemosensors.

Chemosensor type	Detection mechanism	Typical detection limit	Optical signal	Selectivity	Major advantages	Major limitations
Rhodamine	Spirolactam ring opening	10^{-8}–10^{-7} M	Color + Fluorescence	High	Dual-mode response	Cu^{2+} interference
Coumarin	PET/ICT modulation	10^{-9}–10^{-7} M	Fluorescence shift	Moderate–High	Ratiometric detection	Solvent dependence
Thiophene	π–Metal coordination	10^{-8}–10^{-7} M	Colorimetric + weak fluorescence	Moderate	Strong absorption	Weak fluorescence
Quinoline	N–Pb^{2+} coordination	10^{-9}–10^{-7} M	Fluorescence “on/off”	High	Photostable	pH sensitivity
Thiosemicarbazone	C=N/S coordination	10^{-8}–10^{-6} M	Color change	Moderate	High binding affinity	Poor fluorescence
Triazole	N_3 coordination/PET	10^{-10}–10^{-8} M	Fluorescence shift	Very High	Click-chemistry tunability	Solubility constraints

4. Conclusions

Fluorescent-based chemosensors have shown remarkable progress in detecting lead(II) ions over the last decade. Diverse molecular scaffolds, including rhodamine, coumarin, thiophene, quinoline, thiosemicarbazone, and triazole derivatives, have been engineered to achieve enhanced selectivity, sensitivity, and tunable photophysical responses. Despite significant advancements, challenges such as interference from competing ions, solubility in aqueous media, and applicability in complex biological and environmental samples remain. Looking ahead, the integration of chemosensors with nanomaterials, device miniaturization, and real-time sensing platforms will be pivotal in transforming laboratory-based systems into practical tools for environmental safety and biomedical monitoring.

Author Contributions

Conceptualization, I.Y.; software, I.Y. and P.A.P.; validation, I.Y.; formal analysis, I.Y. and P.A.P.; investigation, I.Y. and P.A.P.; data curation, I.Y. and P.A.P.; writing—original draft

preparation, I.Y. and P.A.P.; writing—review and editing, I.Y.; visualization, I.Y. and P.A.P.; supervision, I.Y.; project administration, I.Y.; funding acquisition, I.Y. Both authors have read and agreed to the published version of the manuscript.

Institutional Review Board Statement

Not applicable.

Data Availability Statement

No new data were created or analyzed in this study. Data sharing is not applicable.

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Conflicts of Interest

The authors declare no conflict of interest.

References

1. Godwin, H.A. The biological chemistry of lead. *Curr. Opin. Chem. Biol.* **2001**, *5*, 223–227, https://doi.org/10.1016/S1367-5931(00)00194-0.
2. Wu, D.; Sedgwick, A.C.; Gunnlaugsson, T.; Akkaya, E.U.; Yoon, J.; James, T.D. Fluorescent chemosensors: the past, present and future. *Chem. Soc. Rev.* **2017**, *46*, 7105-7123, https://doi.org/10.1039/C7CS00240H.
3. Zhao, S.L.; Chen, F.S.; Zhang, J.; Ren, S.B.; Liang, H.D.; Li, S.S. On-line flame AAS determination of traces Cd(II) and Pb(II) in water samples using thiol-functionalized SBA-15 as solid phase extractant. *J. Ind. Eng. Chem.* **2015**, *27*, 362-367, https://doi.org/10.1016/j.jiec.2015.01.015.
4. Prabhu, J.; Velmurugan, K.; Nandhakumar, R. Development of fluorescent lead II sensor based on an anthracene derived chalcone. *Spectrochim. Acta A Mol. Biomol. Spectrosc.* **2015**, *144*, 23-28, https://doi.org/10.1016/j.saa.2015.02.028.
5. Zhang, D.; Yin, L.; Meng, Z.; Yu, A.; Guo, L.; Wang, H. A sensitive fluorescence anisotropy method for detection of lead (II) ion by a G-quadruplex-inducible DNA aptamer. *Anal. Chim. Acta* **2014**, *812*, 161-167, https://doi.org/10.1016/j.aca.2013.12.029.
6. Wan, J.; Zhang, K.; Li, C.; Li, Y.; Niu, S. A novel fluorescent chemosensor based on a rhodamine 6G derivative for the detection of Pb^{2+} ion. *Sens. Actuators B Chem.* **2017**, *246*, 696-702, https://doi.org/10.1016/j.snb.2017.02.126.
7. Chen, S.-Y.; Li, Z.; Li, K.; Yu, X.-Q. Small molecular fluorescent probes for the detection of lead, cadmium and mercury ions. *Coord. Chem. Rev.* **2021**, *429*, 213691, https://doi.org/10.1016/j.ccr.2020.213691.
8. Xu, D.; Jia, H.; Niu, Y.; Yin, S. Fluorine-boron compound-based fluorescent chemosensors for heavy metal ion detection. *Dyes Pigments* **2022**, *200*, 110185, https://doi.org/10.1016/j.dyepig.2022.110185.
9. Ghosh, P.; Kumar, N.; Mukhopadhyay, S.K.; Banerjee, P. Sensitive and fluorescent Schiff base chemosensor for pico molar level fluoride detection: In vitro study and mimic of logic gate function. *Sens. Actuators B Chem.* **2016**, *224*, 899-906, https://doi.org/10.1016/j.snb.2015.11.022.
10. Tamil Selvan, G.; Varadaraju, C.; Tamil Selvan, R.; Enoch, I.V.M.V.; Mosae Selvakumar, P. On/Off Fluorescent Chemosensor for Selective Detection of Divalent Iron and Copper Ions: Molecular Logic

Operation and Protein Binding. *ACS Omega* **2018**, *3*, 7985-7992, https://doi.org/10.1021/acsomega.8b00748.

11. Mohanasundaram, D.; Bhaskar, R.; Sankarganesh, M.; Nehru, K.; Gangatharan Vinoth Kumar, G.; Rajesh, J. A simple pyridine based fluorescent chemosensor for selective detection of copper ion. *Spectrochim. Acta A Mol. Biomol. Spectrosc.* **2022**, *265*, 120395, https://doi.org/10.1016/j.saa.2021.120395.
12. Kumar, M.; Kumar, A.; Faizi, M.S.H.; Kumar, S.; Singh, M.K.; Sahu, S.K.; Kishor, S.; John, R.P. A selective 'turn-on' fluorescent chemosensor for detection of Al^{3+} in aqueous medium: Experimental and theoretical studies. *Sens. Actuators, B Chem.* **2018**, *260*, 888-899, https://doi.org/10.1016/j.snb.2018.01.098.
13. Park, S.; Lee, H.; Yi, Y.; Lim, M.H.; Kim, C. A rhodanine-based fluorescent chemosensor for sensing Zn^{2+} and Cd^{2+}: Applications to water sample and cell imaging. *Inorg. Chim. Acta* **2020**, *513*, 119936, https://doi.org/10.1016/j.ica.2020.119936.
14. Narmatha, G.; Antony, E.; Prabakaran, G.; Sundaram, K.; Ravi, S.; Abisha Nancy, S.; Abiram, A.; Parvatham, K.; Rajesh Kannan, V.; Almansour, A.I.; Suresh Kumar, R.; Nandhakumar, R. Silver induced self-assembly of a rhodanine derived reversible fluorescent chemosensor: Applications in smart-phone color assist app, logic gate, real sample analysis and bio-imaging. *J. Photochem. Photobiol. A: Chem.* **2025**, *459*, 116029, https://doi.org/10.1016/j.jphotochem.2024.116029.
15. Bayindir, S. A simple rhodanine-based fluorescent sensor for mercury and copper: The recognition of Hg^{2+} in aqueous solution, and Hg^{2+}/Cu^{2+} in organic solvent. *J. Photochem. Photobiol. A: Chem.* **2019**, *372*, 235–244, https://doi.org/10.1016/j.jphotochem.2018.12.021.
16. Akram, D.; Elhaty, I.A.; AlNeyadi, S.S. Synthesis and spectroscopic characterization of rhodanine azo dyes as selective chemosensors for detection of iron(III). *Chem. Data Collect.* **2020**, *28*, 100456, https://doi.org/10.1016/j.cdc.2020.100456.
17. Christopher Leslee, D.B.; Karuppannan, S.; Karmegam, M.V.; Gandhi, S.; Subramanian, S. A Fluorescent Turn-On Carbazole-Rhodanine Based Sensor for Detection of Ag^{+} Ions and Application in Ag+ Ions Imaging in Cancer Cells. *J. Fluoresc.* **2019**, *29*, 75-89, https://doi.org/10.1007/s10895-018-2312-6.
18. Kumar, J.; Roy, I. Rhodamine Derivative-Linked Silica-Coated Upconverting Nanophosphor ($NaYF_4$: $Yb^{3+}/Er^{3+}@SiO_2$-RBDA) for Ratiometric, Ultrasensitive Chemosensing of Pb^{2+} Ions. *Chemosensors* **2023**, *11*, 305, https://doi.org/10.3390/chemosensors11050305.
19. Meng, X.; Cao, D.; Hu, Z.; Han, X.; Li, Z.; Ma, W. A highly sensitive and selective chemosensor for Pb^{2+} based on quinoline–coumarin. *RSC Adv.* **2018**, *8*, 33947-33951, https://doi.org/10.1039/C8RA04935A.
20. Jeong, H.Y.; Lee, S.Y.; Han, J.; Lim, M.H.; Kim, C. Thiophene and diethylaminophenol-based "turn-on" fluorescence chemosensor for detection of Al^{3+} and F^{-} in a near-perfect aqueous solution. *Tetrahedron* **2017**, *73*, 2690-2697, https://doi.org/10.1016/j.tet.2017.03.069.
21. Rasmussen, S.C.; Evenson, S.J.; McCausland, C.B. Fluorescent thiophene-based materials and their outlook for emissive applications. *Chem. Commun.* **2015**, *51*, 4528-4543, https://doi.org/10.1039/C4CC09206F.
22. Musib, D.; Devi, L.R.; Raza, M.K.; Chanu, S.B.; Roy, M. A New Thiophene-based Aggregation-induced Emission Chemosensor for Selective Detection of Zn^{2+} Ions and Its Turn Off. *Chem. Lett.* **2020**, *49*, 473-476, https://doi.org/10.1246/cl.200001.
23. Cao, J.; Deng, H.Y.; Wang, C.H.; Xiao, Y.; Ren, M.; Zhang, Y.W. A highly selective fluorescence chemosensor for Pb(II) in neutral buffer aqueous solution. *Supramol. Chem.* **2011**, *23*, 777-781, https://doi.org/10.1080/10610278.2011.628390.
24. Senpradit, Y.; Wacharasindhu, S.; Sukwattanasinitt, M. Novel highly selective quinoline-based fluorescent chemosensors for quantitative analysis of Cu(II) ion in water and food. *Spectrochim. Acta A Mol. Biomol. Spectrosc.* **2025**, *326*, 125128, https://doi.org/10.1016/j.saa.2024.125128.
25. Saleem, T.; Khan, S.; Yaqub, M.; Khalid, M.; Islam, M.; Yousaf ur Rehman, M.; Rashid, M.; Shafiq, I.; Braga, A.A.C.; Syed, A.; Bahkali, A.H.; Trant, J.F.; Shafiq, Z. Novel quinoline-derived chemosensors: synthesis, anion recognition, spectroscopic, and computational study. *New J. Chem.* **2022**, *46*, 18233-18243, https://doi.org/10.1039/D2NJ02666J.
26. Sharma, V.; Dutta, S.; Sahu, D.; Pandey, A.; Kumar, D.; Das, S.; Patra, G.K. A new quinoline-based fluorescent-colorimetric chemosensor for sensitive and selective "on–off" detection of Pb^{2+} ions. *RSC Adv.* **2025**, *15*, 4236-4249, https://doi.org/10.1039/D4RA08193E.

27. Jain, J.; Sanwaria, A.R.; Gopal, R.; Nagar, M.; Chaudhary, A. Synthesis and characterisation of zinc and cadmium thiosemicarbazones: potential precursors for nano sized metal oxides/sulphides. *Mater. Res. Innov.* **2022**, *26*, 36-43, https://doi.org/10.1080/14328917.2021.1880736.
28. Bawazeer, T.M.; El-Ghamry, H.A.; Farghaly, T.A.; Fawzy, A. Novel 1,3,4-Thiadiazolethiosemicarbazones Derivatives and Their Divalent Cobalt-Complexes: Synthesis, Characterization and Their Efficiencies for Acidic Corrosion Inhibition of Carbon Steel. *J. Inorg. Organomet. Polym. Mater.* **2020**, *30*, 1609-1620, https://doi.org/10.1007/s10904-019-01308-8.
29. Darwish, S.A.; Aish, E.H.; Elkhabiry, S.A.; Abbas, S.Y. Synthesis and polyester printing applications of transition metal complexes of tridentate 5-(*m*-tolyldiazenyl)salicylaldehyde thiosemicarbazone derivatives. *Phosphorus Sulfur Silicon Relat. Elem.* **2024**, *199*, 420-428, https://doi.org/10.1080/10426507.2024.2357365.
30. Yepseu, A.P.; Ngoudjou, L.E.T.; Tigwere, G.A.; Nyamen, L.D.; Revaprasadu, N.; Masikane, S.; Boulet, P.; Cleymand, F.; Ndifon, P.T. Hot injection synthesis of CuS decorated CdS and ZnS nanomaterials from metal thiosemicarbazone complexes as single source precursors: Application in the photocatalytic degradation of methylene blue. *Inorg. Chem. Commun.* **2024**, *166*, 112650, https://doi.org/10.1016/j.inoche.2024.112650.
31. Prajapati, N.P.; Patel, H.D. Novel thiosemicarbazone derivatives and their metal complexes: Recent development. *Synth. Commun.* **2019**, *49*, 2767-2804, https://doi.org/10.1080/00397911.2019.1649432.
32. Mohammed, G.I.; Nassar, S.; Farghaly, T.A. Spectrophotometric method for detecting lead (II) ions using a chemosensor of the thiosemicarbazone-linked phenyl sulphone moiety. *Results Chem.* **2025**, *15*, 102174, https://doi.org/10.1016/j.rechem.2025.102174.
33. Ahmed, F.; Xiong, H. Recent developments in 1,2,3-triazole-based chemosensors. *Dyes Pigments* **2021**, *185*, 108905, https://doi.org/10.1016/j.dyepig.2020.108905.
34. Salma, U.; Alam, M.Z.; Ahmad, S.; Mohasin, M.; Khan, S.A. Recent Progress in Triazole Based Chromogenic and Fluorogenic Chemosensor for the Detection of Hg^{2+} Metal ion: A Review. *J. Fluoresc.* **2025**, *35*, 10201-10231, https://doi.org/10.1007/s10895-025-04269-z.
35. George, N.; Singh, G.; Singh, R.; Singh, G.; Priyanka; Singh, H.; Kaur, G.; Singh, J. Click modified bis-appended Schiff base 1,2,3-triazole chemosensor for detection of Pb(II)ion and computational studies. *J. Mol. Struct.* **2023**, *1288*, 135666, https://doi.org/10.1016/j.molstruc.2023.135666.
36. Sharma, V.; Savita, S.; Patra, G.K. A highly sensitive triazole-based perfectly water soluble novel bis-Schiff base reversible fluorescent-colorimetric chemosensor for fast detection of Pb^{2+} ions. *RSC Adv.* **2024**, *14*, 3289–3303, https://doi.org/10.1039/D3RA06185J.
37. Serbest, K.; Özen, A.; Ünver, Y.; Er, M.; Değirmencioğlu, İ.; Sancak, K. Spectroscopic and theoretical study of 1,2,4-triazole-3-one based salicylaldimine complexes and evaluation of superoxide-scavenging properties. *J. Mol. Struct.* **2009**, *922*, 1-10, https://doi.org/10.1016/j.molstruc.2009.02.001.
38. Rani, P.; Lal, K.; Shrivastava, R. Tris-Triazole Based Chemosensors for Selective Sensing of Pb2+ Ions. *Asian J. Chem.* **2019**, *31*, 2443–2447, https://doi.org/10.14233/ajchem.2019.22076.

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