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REVIEW ARTICLE

Advances in Coordination Chemistry–Based Sensors for Monitoring Toxic Metal Pollutants in Aquatic Environments

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Abstract: Toxic metal contamination of surface water, groundwater and wastewater threatens ecosystems and the communities that depend on them. Conventional methods such as atomic absorption spectrometry and inductively coupled plasma-based techniques are reliable but need laboratory facilities, which restricts routine monitoring in remote and resource-limited settings. Coordination chemistry links metal-ion recognition to measurable optical or electrochemical responses. This review summarises the principles, major platforms and environmental applications of coordination-based sensors for lead(II), mercury(II), cadmium(II), copper(II) and chromium species, including fluorescent and colorimetric probes, coordination polymers, metal–organic frameworks and electrochemical systems. Representative studies are compared using their reported detection limits, working ranges, selectivity and real-water evidence, and the detection limits are set against WHO drinking-water guideline values. The comparison shows that a low detection limit alone does not establish practical performance: matrix interference, chemical speciation, pH dependence, material stability and validation against reference methods remain decisive. Future development should prioritise water-compatible receptors, realistic sample validation, portable instrumentation and responsible management of sensing materials.

Key words: Chemosensors; water quality; speciation; ligand design; analytical validation

Introduction

Toxic metals are not degraded, accumulate in sediments and living organisms, and threaten ecosystems and the people who depend on rivers, lakes and groundwater for drinking water, irrigation and livelihoods (Järup, 2003). Industrial effluents, mining wastes and inadequately treated wastewater are major sources, from which metals pass into the food chain and drinking-water supplies. Lead is especially harmful to the nervous system of children, cadmium and inorganic mercury damage mainly the kidneys, copper is essential but harmful at high intakes, and the toxicity of chromium depends strongly on its oxidation state, Cr(VI) being considerably more toxic than Cr(III) (Saha et al., 2011; WHO, 2022). The WHO drinking-water guideline values are 10 µg/L for lead (provisional), 3 µg/L for cadmium, 6 µg/L for inorganic mercury and 50 µg/L (provisional) for total chromium (WHO, 2022), so monitoring methods must be reliable at trace concentrations.

Atomic absorption spectrometry (AAS), inductively coupled plasma optical emission spectrometry (ICP-OES) and inductively coupled plasma mass spectrometry (ICP-MS) are the established methods for determining metals in water. They require specialised instruments, trained personnel and laboratory facilities, which limits the frequency of measurement and rapid screening in remote or resource-limited settings (Prasad et al., 2026). Chemical sensors offer a complementary approach by converting a chemical interaction into a signal that can be read out with simple or portable instruments (Kim et al., 2012; Ding et al., 2021).

In coordination-based sensing, a target ion binds to a ligand containing suitable donor atoms, and the resulting change is read out as colour, fluorescence, current, potential or impedance (de Silva et al., 1997). Strong binding alone does not give a useful sensor: the interaction must also produce a distinguishable signal, remain selective against competing species and work under realistic conditions (Iftikhar et al., 2023; Prasad et al., 2026). Sensors are, however, often reported with a single low detection limit obtained in the laboratory, which does not show that they will perform in river water, groundwater or wastewater. This review therefore examines coordination-based sensors for Pb(II), Hg(II), Cd(II), Cu(II) and chromium species from an environmental-monitoring perspective, beginning with the coordination principles and aqueous speciation that govern sensor behaviour.

Coordination principles and aqueous speciation

Coordination compounds are formed when a Lewis-acidic metal centre accepts electron pairs from the donor atoms of a ligand; nitrogen, oxygen and sulfur donors (amines, imines, pyridyl nitrogen, carboxylates, phenolates, thiolates) are common in sensing receptors. A ligand that binds through two or more donor atoms forms a chelate, which generally increases complex stability and can change the absorption, emission or electron transfer of a sensor. The hard and soft acids and bases (HSAB) principle gives a qualitative guide to donor selection (Pearson, 1963): hard ions such as Cr(III), Ca(II) and Mg(II) favour oxygen donors, soft ions such as Hg(II) and Cd(II) favour sulfur donors, and borderline ions such as Pb(II) and Cu(II) bind nitrogen and mixed donor sets (Kim et al., 2012). Geometry adds control (Cu(II) typically forms distorted square-planar or octahedral complexes, Hg(II) often prefers low coordination numbers and Pb(II) has an often irregular coordination sphere), and kinetics matter: Pb(II), Cd(II), Hg(II) and Cu(II) exchange ligands rapidly (they are labile), whereas Cr(III) is kinetically inert, so chromium sensors often target Cr(VI) or use a conversion step (Helm & Merbach, 2005; Saha et al., 2011). HSAB is only a starting point, since hydration, competing ions, pH and alternative complexes also decide selectivity in water (Iftikhar et al., 2023; Prasad et al., 2026).

In environmental water, calcium, magnesium, sodium and potassium occur at milligram-per-litre to gram-per-litre levels, whereas the toxic metals occur at microgram-per-litre levels, so weak binding of an abundant ion can outweigh strong binding of a trace pollutant (Stumm & Morgan, 1996). Similar divalent ions, dissolved organic matter, chloride, carbonate and hydroxide compete with the receptor for the metal, and protons compete for its donor atoms, so selectivity shown in pure water remains a hypothesis until confirmed in the intended matrix (Stumm & Morgan, 1996; Prasad et al., 2026).

Speciation is equally important. A metal may be present as a hydrated ion, a hydroxo or carbonate complex, an organic-matter complex or a particle-bound form; the freely dissolved ion is generally the most biologically active, whereas bound forms are usually less available. Chromium illustrates the effect: Cr(VI) occurs as the anions $HCrO_4^-$ and CrO_4^{2-} and readily penetrates cell membranes, whereas cationic Cr(III) does so far less readily (WHO, 2022).

Speciation also determines what a sensor detects: it responds only to forms that exchange ligands with its receptor within the measurement time (the labile fraction), whereas AAS and ICP methods usually report total dissolved or total recoverable metal. Studies should therefore state which fraction they report, and the measured species must be related to the regulated quantity, for example total chromium or inorganic mercury (WHO, 2022) before results are used for decisions.

Materials and Methods

This article is a narrative review of coordination-based sensors for lead(II), mercury(II), cadmium(II), copper(II) and chromium species in water, emphasising how ligand design, coordination chemistry and aqueous speciation relate to sensor performance. Relevant literature was identified through Google Scholar, Scopus, Web of Science and ScienceDirect, supplemented by the publisher platforms of the American Chemical Society, the Royal Society of Chemistry, Elsevier and Springer, using combinations of keywords such as “coordination chemistry”, “chemosensor”, “heavy metal ions”, “water” and the names of the target metals; the guideline values were taken from the WHO drinking-water guidelines. Four representative studies (Table 1) were chosen to illustrate different recognition and signalling routes rather than to rank sensors. Their reported detection limits were compared with the WHO guideline values (WHO, 2022) given above; because the studies used different procedures and sample matrices, the comparison is indicative and not a quantitative meta-analysis.

Results

A reliable evaluation goes beyond the response to a single metal ion under controlled laboratory conditions. The limit of detection (LOD) should be reported together with its calculation method (for example, $3.3\sigma/S$, where σ is the standard deviation of the blank or of the lowest-level response and S is the calibration slope). For monitoring against a guideline value, however, the limit of quantification (LOQ), the lowest concentration that can be determined with acceptable precision and accuracy (commonly $10\sigma/S$, about three times the LOD), and the validated working range are more important. Selectivity should be tested against plausible competing ions at realistic concentration ratios. Response time and reversibility determine suitability for screening or continuous monitoring, and pH and ionic strength should match the conditions of use. Accuracy should be demonstrated by spike-recovery experiments, replicate measurements and comparison with a validated reference method, ideally at concentrations near the guideline value (Thompson et al., 2002).

Fluorescent chemosensors

Fluorescent sensors report binding through changes in emission intensity, wavelength or intensity ratio. Most combine a fluorophore with a donor-atom receptor, and signalling typically proceeds by photoinduced electron transfer (PET), intramolecular charge transfer (ICT), chelation-enhanced fluorescence or quenching (CHEF/CHEQ), excited-state intramolecular proton transfer (ESIPT), aggregation-induced emission (AIE) or Förster resonance energy transfer (FRET) (de Silva et al., 1997; Iftikhar et al., 2023; Ciupa, 2025). The direction of the response cannot be predicted from the metal alone: an aminothiourea-derived Schiff-base probe showed increased fluorescence with one equivalent of Hg(II) and decreased fluorescence on further addition (Quang et al., 2013). Recognition may be reversible coordination, which allows reuse, or an irreversible metal-triggered reaction, as in chemodosimeters and many rhodamine probes, which can be strongly selective but consume the probe (AbhijnaKrishna & Velmathi, 2022). For environmental use, a sensor should work in water with little or no organic cosolvent, cover the pH range of natural waters and discriminate the target from competing ions (Prasad et al., 2026). Ratiometric and turn-on responses are easier to interpret than quenching, which many species can cause.

Colorimetric sensors

Colorimetric sensors give a colour change that can be judged by eye, measured with a spectrophotometer or read with a portable device, including optodes in which the reagent is held in a polymer membrane (Darwish et al., 2024). Visual detection limits are usually higher than instrumental ones: a nanoparticle sensor reached 22.9 µg/L with a spectrometer but 50 µg/L by eye (Karn-Orachai et al., 2024), and smartphone readout can reduce observer dependence (Wei et al., 2014). Sensors based

on precipitation, redox reaction or nanoparticle aggregation should be distinguished from molecular coordination sensors, since their mechanisms and limitations differ.

Coordination polymers and metal–organic frameworks

Coordination polymers and metal–organic frameworks (MOFs), built from metal nodes and organic linkers, have designable structures, large surface areas and tunable pores (Furukawa et al., 2013), and detect heavy metal ions through fluorescence change, electrochemical response or colour change (Liu et al., 2025). Their water stability varies widely (Burtch et al., 2014), and a framework that degrades at the pH or ionic strength of the sample, or releases its own metal ions or linkers, can give false signals or add a contaminant. Stability should therefore be demonstrated under relevant conditions.

Electrochemical sensors

Electrochemical sensors detect changes in current, potential, charge transfer or impedance, and coordination chemistry contributes selective ligands, functionalised surfaces and recognition layers (Sulthana et al., 2024). In the EDTA-functionalised graphene oxide electrode of Sridharan and Mandal (2022), the chelating EDTA groups bind Pb(II) and Cd(II) at the electrode surface, and the metals are quantified by differential pulse voltammetry. Miniaturised instrumentation makes these systems promising for portable monitoring, including turbid or coloured samples where optical methods struggle (Ding et al., 2021; Sulthana et al., 2024), but fouling, dissolved oxygen, competing electroactive species and pH can affect the response, and many studies use buffer rather than the original water, so validation against an established method is essential.

Target metals: environmental context and sensor design

Lead(II). Lead enters water from mining, industry and the corrosion of plumbing; the WHO guideline value is 10 µg/L (provisional) (WHO, 2022). As a borderline ion, Pb(II) can be bound by receptors with mixed nitrogen, oxygen and sulfur donors, but because lead is strongly particle-associated, the labile fraction seen by a sensor may be much smaller than the total. A coumarin-based fluorescent probe (Muthusamy et al., 2021; about 2.2 µg/L) and an EDTA-functionalised graphene oxide electrode (Sridharan & Mandal, 2022; about 1.0 µg/L) detect Pb(II) by optical and electrochemical routes (Table 1).

Mercury(II). The WHO guideline value of 6 µg/L applies to inorganic mercury (WHO, 2022); mercury can also be converted to methylmercury in aquatic systems (Hsu-Kim et al., 2013). Hg(II) is a soft ion, so sulfur-containing receptors are widely used (Kim et al., 2012). In the Schiff-base probe of Quang et al. (2013), Hg(II) is proposed to be coordinated by two imine nitrogen and two sulfur atoms, but the measurements were made in ethanol–water (1:9, v/v), so some organic cosolvent was still needed. The coumarin-based probe of Muthusamy et al. (2021) detects Hg(II) at about 1.7 µg/L through ESIPT/PET processes. A sensor for inorganic Hg(II) should not be assumed to measure methylmercury or total mercury without validation.

Cadmium(II). The WHO guideline value is 3 µg/L (WHO, 2022). Cd(II) is chemically similar to zinc and other divalent ions, so interference studies at realistic concentration ratios are needed. On the EDTA-modified electrode of Sridharan and Mandal (2022), Cd(II) was determined together with Pb(II) with a detection limit of about 2.5 µg/L and a quantification limit of 8.4 µg/L; because the guideline value is so low, the quantification limit, not only the detection limit, determines suitability for compliance screening.

Copper(II). The WHO guideline value of 2 mg/L is two to three orders of magnitude higher than those of the other metals (WHO, 2022), so selectivity and speciation, rather than sensitivity, are the main challenges; copper is largely complexed by dissolved organic matter, so a sensor may detect only the labile fraction. Paramagnetic Cu(II) often quenches fluorescence, so turn-off responses are common and turn-on designs are of particular interest (Ciupa, 2025). None of the studies in Table 1 targets copper, a gap for future work.

Chromium species. Chromium sensing requires explicit attention to oxidation state: Cr(VI) is considerably more toxic than Cr(III), but the WHO guideline value of 50 µg/L is expressed as total chromium (WHO, 2022). Cr(VI) is present as oxyanions and generally requires anion-suited strategies, such as anion exchange in a membrane optode (Darwish et al., 2024), nanoparticle-based approaches (Karn-Orachai et al., 2024) or a validated conversion step. In the optode of Darwish et al. (2024), total chromium is obtained after oxidation of Cr(III) to Cr(VI) and Cr(III) is calculated by difference, so a Cr(VI) result cannot be compared directly with a guideline for total chromium.

Representative studies and detection limits relative to guideline values

Table 1 summarises the four representative studies. Detection limits are given as reported, with nanomolar values converted to µg/L, and no Cu(II) study is included.

Table 1. Representative sensors for selected toxic metal species in water.

Target	Sensor and recognition / signal mechanism	Reported LOD (µg/L)	Real-sample evidence and critical assessment
Hg(II), Pb(II)	Coumarin-based fluorescent probe; ESIPT/PET response (Muthusamy et al., 2021)	Hg(II): 8.3 nM (≈1.7); Pb(II): 10.5 nM (≈2.2)	Applied to various water samples (sources not specified in the abstract). One probe responds to two ions, so cross-selectivity and matrix effects are key.
Pb(II), Cd(II)	EDTA-functionalised reduced graphene oxide on a glassy carbon electrode; differential pulse voltammetry (Sridharan & Mandal, 2022)	Pb(II): 1.02; Cd(II): 2.52[a]; LOQ: Pb 3.41, Cd 8.40	Range 0.01–100 ppm in 0.1 M acetate buffer (pH 5). River water by standard addition: Pb(II) 200.2 ± 0.38 µg/L vs ICP-OES 199.90 ± 0.49 µg/L, but at twenty times the WHO value; Cd(II) not distinctly detected in the unspiked sample.
Cr(VI)	Cellulose triacetate membrane optode with a chromophore and Aliquat 336; yellow-to-violet change (Darwish et al., 2024)	2.85	10–220 ng/mL; response ≈5 min; pH 4.25. Spiked tap, river and sea water, food, soil and biological samples; comparison with graphite-furnace AAS for food and soil. Total chromium follows Cr(III) oxidation, so Cr(VI) and total results must be distinguished.
Cr(VI)	Gold/silver nanoparticle colorimetric system; Ag dissolution and Au aggregation (Karn-Orachai et al., 2024)	22.9 (spectrometer); 50 (visual)	Tap water, natural water and artificial urine. Suited to visual screening, but the signal arises from nanoparticle changes rather than a molecular receptor.

Abbreviations used in Table 1: LOD, limit of detection; LOQ, limit of quantification; ESIPT, excited-state intramolecular proton transfer; PET, photoinduced electron transfer; ICP-OES, inductively coupled plasma optical emission spectrometry; AAS, atomic absorption spectrometry.

[a]In the source article (Sridharan & Mandal, 2022), the abstract and its Table 2 assign the LODs of 1.02 and 2.52 ppb to Cd and Pb, respectively, whereas the results section assigns them to Pb and Cd, respectively. The stated LOQs (Pb 3.41, Cd 8.40 µg/L) are about 3.3 times the results-section values, which supports that assignment, used here for both metals. LODs were obtained by different methods and conditions and should not be used alone to rank overall sensor quality.

Figure 1 places the detection limits of Table 1 beside the WHO guideline values (WHO, 2022).

All reported detection limits are at or below the guideline values, but the margins differ greatly. The coumarin-based fluorescent probe (Muthusamy et al., 2021) lies about 3.6-fold below the guideline value for Hg(II) and 4.6-fold below that for Pb(II), the EDTA-functionalised graphene oxide electrode (Sridharan & Mandal, 2022) about tenfold below the Pb(II) value, and the Cr(VI) membrane optode (Darwish et al., 2024) about 18-fold below the chromium value. The spectrometric limit of the gold/silver nanoparticle

system (Karn-Orachai et al., 2024; 22.9 µg/L) is about twofold below the chromium value, whereas its visual limit (50 µg/L) coincides with it, so visual readout suits screening rather than compliance assessment. For Cd(II) the margin is very small: the detection limit of the electrode (2.52 µg/L) is only about 1.2-fold below the guideline value (3 µg/L) and the quantification limit (8.40 µg/L) is above it, so the sensor could flag higher cadmium concentrations but could not reliably quantify cadmium at the guideline

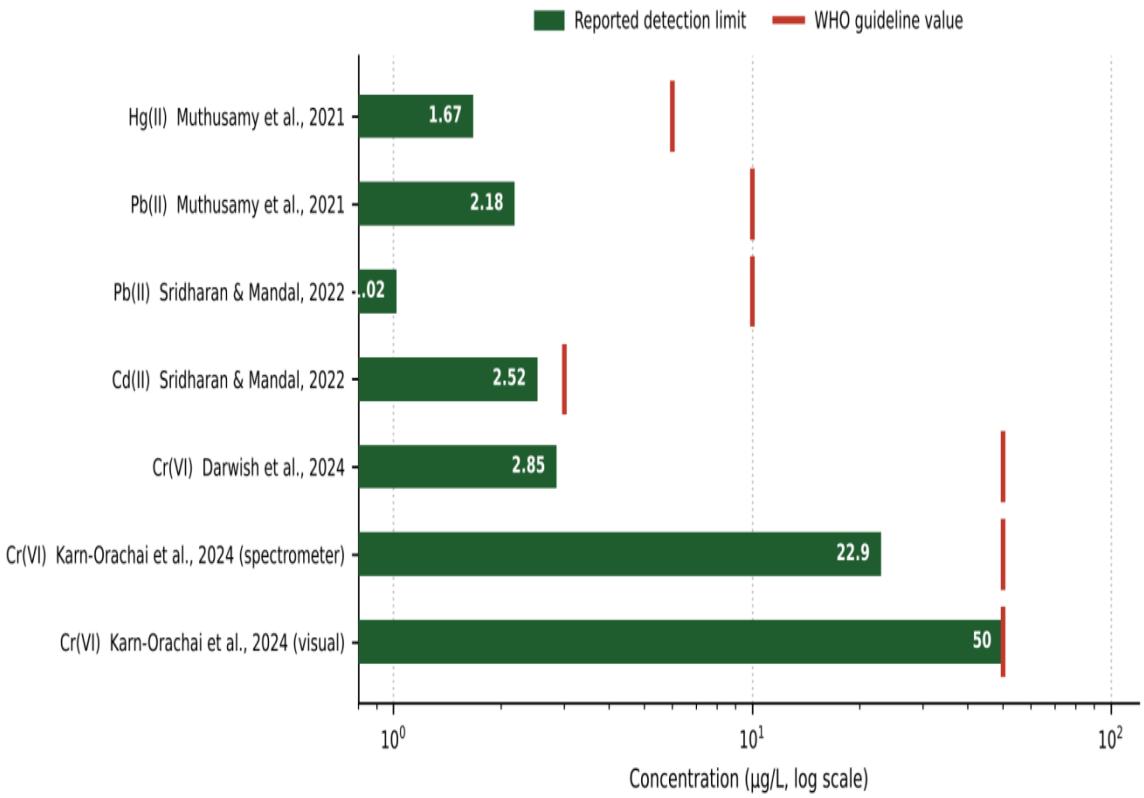


Figure 1. Reported detection limits of the sensors in Table 1 compared with WHO drinking-water guideline values (Pb 10, Cd 3, inorganic Hg 6, total Cr 50 µg/L; WHO, 2022). Nanomolar values were converted to µg/L. The Pb(II) and Cd(II) values from Sridharan and Mandal (2022) follow the assignment explained in the note to Table 1.

Discussion

Three cautions apply. First, the limits were obtained by different procedures, so the margins are indicative only. Second, the WHO chromium value refers to total chromium, whereas the Cr(VI) sensors measure one oxidation state. Third, none of the four studies demonstrates recovery and reference-method agreement at the guideline concentration in a natural-water matrix: the clearest validation, for lead in river water, was made at about 200 µg/L. A single detection-limit value is therefore insufficient for selecting an environmental sensor. Several challenges still limit the translation of coordination-based sensors from laboratory demonstrations to environmental monitoring. Selectivity in complex matrices remains the foremost difficulty: a receptor that discriminates effectively in simple aqueous solution may lose this discrimination in natural waters, where dissolved organic matter and a large excess of competing ions alter metal speciation and compete for the binding sites (Iftikhar et al., 2023). Many fluorescent probes need organic co-solvents or specific pH conditions that limit direct analysis of environmental samples (Prasad et al., 2026). Reproducibility, stability and validation in untreated water are often less well established than laboratory sensitivity, sensors containing toxic metals, persistent ligands or

nanomaterials must not create new contamination, and field devices need simple sample handling and a strategy for confirming results near regulatory thresholds. Future advances will depend on closer integration of coordination, analytical and materials chemistry. Ligand design should aim at selective binding that yields a measurable, reproducible signal under realistic conditions, with adequate water solubility, rather than at maximal binding strength. Ratiometric optical sensors, hybrid materials, smartphone-assisted colour analysis and miniaturised electrochemical systems may facilitate low-cost screening (Wei et al., 2014; Ding et al., 2021), provided they are supported by calibration, quality control and reference-method comparison, and sensors should be designed around the chemical form of concern rather than the element alone, particularly for chromium and mercury.

Conclusion

Coordination chemistry provides a versatile molecular foundation for sensors of toxic metals in water: through the choice of donor atoms, ligand architecture and coordination environment, metal recognition can be coupled to optical or electrochemical signals. Performance must, however, be judged in an environmental context, since high sensitivity in simple solution is insufficient unless a sensor also shows selectivity, stability, reproducibility and acceptable performance in real water, with a working range that covers guideline concentrations. The most useful future sensors will combine appropriate coordination chemistry with reliable measurement, practical operation and responsible material use.

Declarations

Competing interests: The author has no conflicts of interest to declare.

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Authors' contributions: Inderjeet Kour conceived the review, analysed the literature, and wrote and approved the final manuscript.

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