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Pioneering perovskite quantum dot nanosensors for heavy metal ion detection: mechanisms, design, and industrial applications

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Perovskite quantum dots (PQDs) are a transformative platform for ultrasensitive heavy metal ion detection, leveraging high photoluminescence quantum yield (PLQY, 50-90%), narrow emission spectra (FWHM 12-40 nm), tunable bandgaps, and defect-tolerant optoelectronic properties. This review is the first systematic evaluation of PQD-based nanosensors for detecting Hg²⁺, Cu²⁺, Cd²⁺, Fe³⁺, Cr⁶⁺, and Pb²⁺, elucidating key mechanisms like cation exchange, electron/hole transfer, Förster resonance energy transfer, and surface trap-mediated quenching. Advanced synthesis methods, including hot-injection, ligand-assisted reprecipitation, and microwave-assisted techniques, enable precise control over size, crystallinity, and surface chemistry. Lead-based PQDs (e.g., CsPbX₃) achieve limits of detection (LODs) as low as 0.1 nM with rapid response times (<10 s), while lead-free variants (e.g., Cs₃Bi₂X₉, CsSnX₃) offer eco-friendly alternatives with enhanced aqueous stability. PQD@MOF composites and ratiometric designs enhance selectivity in complex matrices, surpassing carbon quantum dots and semiconductor QDs in sensitivity and versatility. Applications include industrial wastewater remediation, lubricant quality control, and environmental compliance, ensuring ecosystem protection and product integrity. This seminal work addresses challenges like aqueous instability, Pb toxicity, scalability, and matrix interference, benchmarking PQDs against alternative nanomaterials. Future directions include comparisons with other nanoparticles, multiplexed sensing platforms, and sustainable lead-free innovations. By integrating fundamental insights with practical applications, this review establishes PQDs as a high-impact paradigm for advancing heavy metal ion sensing in industrial and environmental contexts, guiding innovations in sensitivity, selectivity, and scalability

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1. Introduction

Heavy metal ion contamination in environmental, industrial, and biological systems poses significant risks to ecosystems, human health, and industrial processes due to their toxicity, persistence, and bioaccumulation. 1-3 Elements such as mercury (Hg²⁺), copper (Cu²⁺), cadmium (Cd²⁺), iron (Fe³⁺), chromium (Cr⁶⁺), and lead (Pb²⁺) are prevalent pollutants in industrial wastewater, lubricants, and natural water bodies, necessitating robust detection methods to ensure environmental compliance and product integrity.4-6 Traditional sensing technologies, including atomic absorption spectroscopy,7,8 inductively coupled plasma mass spectrometry,9,10 and electrochemical methods,11,12 offer high sensitivity but are often hindered by high costs, complex instrumentation, and limited portability, making them less suitable for real-time or on-site applications.13,14 In response, nanomaterial-based nanosensors have emerged as promising alternatives, offering rapid response, portability, and cost-effectiveness.¹⁵ Among these, perovskite quantum dots (PQDs) have garnered significant attention due to their exceptional optoelectronic properties, positioning them as a transformative platform for heavy metal ion detection. 16,17

PQDs, characterized by the general formula ABX₃ (where A is a monovalent cation, B is a divalent metal cation, and X is a halide anion), exhibit unique attributes that make them ideal for sensing applications. Their high photoluminescence quantum yield (PLQY, 50–90%), narrow emission spectra (full width at half maximum (FWHM) 12–40 nm), and tunable bandgaps enable ultrasensitive detection with high color purity and specificity. These properties arise from quantum confinement effects at nanoscale dimensions (2–10 nm), which result

in discrete energy levels and enhanced oscillator strengths. ^{20,21} Additionally, PQDs possess large absorption coefficients (10⁵ to 10⁶ cm⁻¹) and fast radiative recombination rates, facilitating efficient light harvesting and stable fluorescence signals critical for detecting analyte-induced changes. The structural versatility of PQDs allows compositional tuning through substitutions at the A, B, or X sites, enabling tailored optical and electronic properties for specific sensing needs. ^{19,20} Lead-based PQDs, such as CsPbX₃ and CH₃NH₃PbX₃, are renowned for their superior PLQY and tunable emission across the visible spectrum, while lead-free variants, such as Cs₃Bi₂X₉ and CsSnX₃, address toxicity concerns, offering eco-friendly alternatives with improved stability in aqueous environments. ²²

The detection of heavy metal ions using PQDs relies on their ability to undergo fluorescence quenching or enhancement triggered by interactions with analytes. Mechanisms such as cation exchange, electron transfer, and Förster Resonance Energy Transfer (FRET) underpin these responses, driven by the high surface-to-volume ratio and defect-tolerant nature of PODs. 23,24 For instance, the ionic radius similarity between Pb2+ and Hg2+ facilitates rapid cation exchange in lead-based PQDs, leading to efficient quenching, while electron transfer dominates in interactions with transition metal ions like Cu2+ or Fe3+.17,21 Surface ligands, such as oleylamine or poly(ethylenimine) (PEI), play a critical role in modulating selectivity and sensitivity by passivating defects and mediating ion-PQD interactions. Advanced synthesis methods, including hotinjection, ligand-assisted reprecipitation, and microwaveassisted techniques, enables precise control over PQD size, crystallinity, and surface chemistry, directly impacting their sensing performance.25

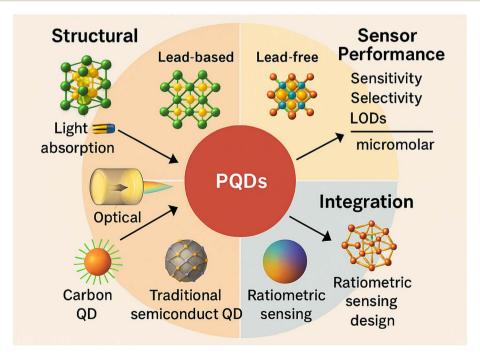


Fig. 1 Overview of PQD-based nanosensors for heavy metal ion detection, highlighting structure, performance, integration strategies, and comparison with other quantum dots.

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The industrial relevance of PQD-based nanosensors lies in their ability to address critical monitoring needs in sectors such as chemical processing, wastewater treatment, and lubricant quality control. 26,27 Their high sensitivity and rapid response times make them suitable for detecting trace contaminants in real-time, ensuring compliance with stringent environmental regulations and maintaining product quality. However, challenges such as the aqueous instability of lead-based PQDs, toxicity concerns, and scalability of synthesis methods must be addressed to facilitate widespread adoption. Emerging strategies, including the development of lead-free PQDs, advanced encapsulation techniques, and computational modeling, offer pathways to overcome these limitations, paving the way for practical implementation. 28,29

This review provides the first comprehensive analysis of PQD-based nanosensors for heavy metal ion detection, systematically exploring their structural, optical, and mechanistic foundations. It covers diverse PQD types, including leadbased (e.g., CsPbBr₃) and lead-free (e.g., Cs₃Bi₂Br₉) systems, their synthesis methods, and their advantages and limitations for sensing applications. The review evaluates sensor performance, focusing on sensitivity, selectivity, and limits of detection (LODs) ranging from sub-nanomolar (e.g., 0.1 nM for Cu²⁺ in organic solvents) to micromolar levels, depending on the ion and matrix. Integration with stable matrices like metal-organic frameworks and ratiometric sensing designs enhances performance in complex industrial and environmental matrices. By comparing PQDs with other nanomaterials, such as carbon QDs and traditional semiconductor quantum dots, and addressing both fundamental and applied aspects, this work aims to guide future research, fostering innovations to improve the sensitivity, selectivity, and scalability of PQD-based nanosensors for diverse heavy metal ion detection applications (Fig. 1).

2. Fundamentals of perovskite quantum dots

2.1. Structural and optical properties of perovskite quantum dots

PQDs are nanoscale semiconductor materials characterized by the general formula ABX₃, where A is a monovalent cation (e.g., Cs⁺, methylammonium (MA⁺), or formamidinium (FA⁺)), B is a divalent metal cation (e.g., Pb²⁺, Sn²⁺, or bismuth (Bi³⁺)), and X is a halide anion (e.g., Cl⁻, Br⁻, or I⁻). The crystal structure of PQDs typically adopts a cubic, tetragonal, or orthorhombic lattice in 3D ABX₃ forms, depending on the composition and temperature.30,31 In this 3D structure, the B cation is coordinated octahedrally by six X anions, forming interconnected [BX₆]⁴⁻ octahedra that create a three-dimensional framework, with A cations occupying cuboctahedral voids for charge neutrality. This extended connectivity enables efficient charge transport and high PLQY (50-90%). In contrast, 0D/2D derivatives like $A_3B_2X_9$ (e.g., $Cs_3Bi_2X_9$) feature isolated $[B_2X_9]^{3-}$ dimers or layered structures with reduced octahedral connectivity, resulting in stronger quantum confinement, broader emission spectra (FWHM ~40-60 nm), and typically lower PLQY (2050%), which impacts sensitivity in sensing applications due to increased defect states. ^{19,28,40} The structural versatility of perovskites enables compositional tuning at A, B, or X sites to modulate properties critical for heavy metal ion detection.

The stability of the perovskite lattice is governed by the Goldschmidt tolerance factor (t), defined as:

$$t = \frac{r_{\rm A} + r_{\rm X}}{\sqrt{2}(r_{\rm B} + r_{\rm X})}\tag{1}$$

where $r_{\rm A}$, $r_{\rm B}$, and $r_{\rm X}$ are the ionic radii of A, B, and X ions, respectively. A tolerance factor between 0.8 and 1.0 ensures a stable 3D cubic structure, while lower values favor 0D/2D phases. For instance, CsPbBr₃ ($t\approx0.81$) adopts a cubic 3D structure at room temperature, offering high optical efficiency, whereas Cs₃Bi₂Br₉ (t<0.8) forms a 0D layered structure, enhancing aqueous stability but reducing radiative efficiency.^{32,33,43}

The optical properties of PQDs are dominated by quantum confinement effects due to their nanoscale dimensions (2-10 nm), resulting in discrete energy levels and size-dependent bandgaps. This confinement enhances oscillator strength, leading to high PLQY (50-90% for 3D ABX3; 20-50% for 0D/2D A₃B₂X₉) and narrow emission spectra (FWHM 12-40 nm for 3D; broader for 0D/2D). For example, 3D CsPbBr₃ emits green light at ~520 nm with FWHM ~20 nm, ideal for selective sensing, while 0D Cs₃Bi₂Br₉ shows blue emission (~450 nm) with higher stability in polar media. 15,26,43 The bandgap can be tuned by size or halide composition; smaller PQDs or Cl-rich 3D variants exhibit wider bandgaps (\sim 3.0 eV for CsPbCl₃), while I-rich 3D forms have narrower ones (~1.7 eV for CsPbI₃). 0D/2D structures often display wider effective bandgaps due to confinement. PQDs possess large absorption coefficients (10⁵ to 10⁶ cm⁻¹) and fast radiative recombination rates, with defect tolerance minimizing non-radiative losses-more pronounced in 3D forms where defects lie within bands.30,34

The surface chemistry of PQDs significantly influences their properties. PQDs are capped with ligands like oleylamine (OAm) or oleic acid (OA), which passivate defects and enhance stability. In 3D ABX3, ligands primarily provide steric protection, while in 0D/2D $A_3B_2X_9$, they also mitigate interlayer defects for better aqueous sensing. ^{18,35} Exciton dynamics in PQDs feature short radiative lifetimes (1–10 ns) and high binding energies (20–100 meV), enabling sensitive energy transfer for detection. The high surface-to-volume ratio amplifies ion interactions, with 0D/2D structures showing enhanced trap states for quenching but potentially slower kinetics compared to 3D forms. ^{14,36}

2.1.1. Crystal structure and compositional flexibility. A tolerance factor between 0.8 and 1.0 typically ensures a stable cubic perovskite structure, while deviations may lead to tetragonal or orthorhombic phases, impacting optical and sensing performance. For instance, CsPbBr₃ adopts a cubic structure at room temperature, offering high symmetry and optical efficiency, whereas CH₃NH₃PbBr₃ may transition to a tetragonal phase under certain conditions, affecting its photoluminescence stability.^{32,33} The ability to substitute halides (*e.g.*, Cl⁻ for Br⁻) or cations (*e.g.*, Sn²⁺ for Pb²⁺) allows precise

control over the lattice parameters, enabling tailored bandgap energies and emission properties.

2.1.2. Quantum confinement and optical properties. The optical properties of PQDs are dominated by quantum confinement effects due to their nanoscale dimensions (2-10 nm), which result in discrete energy levels and size-dependent bandgaps. This confinement enhances the oscillator strength, leading to high photoluminescence quantum yields (PLQY), often exceeding 50-90%, and narrow emission spectra with full width at half maximum (FWHM) values of 12-40 nm. For example, CsPbBr3 PQDs emit green light at ~520 nm with a FWHM of ~20 nm, ensuring high color purity ideal for sensing applications. 15,26 The bandgap can be tuned by adjusting the particle size or halide composition; smaller PQDs or those with higher Cl content exhibit wider bandgaps (e.g., ~3.0 eV for CsPbCl₃), while larger PQDs or I-rich compositions have narrower bandgaps (e.g., ~1.7 eV for CsPbI₃). PQDs possess large absorption coefficients (10⁵ to 10⁶ cm⁻¹), enabling efficient light harvesting, and fast radiative recombination rates due to their direct bandgap nature. Their high defect tolerance, where defect states often lie within the conduction or valence bands rather than the bandgap, minimizes non-radiative recombination, enhancing PL efficiency.30,34 This property is critical for sensing, as it ensures strong and stable fluorescence

signals responsive to analyte-induced changes, such as quenching or enhancement.

Panel (a) demonstrates the PLQY of PQDs as a function of ligand amount (10⁴ v/v%), comparing solution and film states, with PLOY values reaching up to 90%, reflecting the high oscillator strength and quantum confinement effects due to their nanoscale dimensions (2-10 nm).20 This high PLQY, often exceeding 50-90%, is attributed to the discrete energy levels and size-dependent bandgaps, enhancing color purity with narrow emission spectra (FWHM 12-40 nm). Panel (b) presents timeresolved PL decay curves for pristine PQDs and those treated with PLAP at concentrations of 5×10^3 , 1×10^3 , and 2×10^3 v/ v%, showing varied decay rates, which indicate tunable radiative recombination influenced by ligand-induced changes, aligning with the fast recombination rates and high absorption coefficients (10⁵ to 10⁶ cm⁻¹) typical of direct bandgap PQDs. Panel (c) displays PL spectra of PQDs at temperatures of 100 °C, 120 °C, 140 °C, 160 °C, and 180 °C, with emission peaks ranging from 493 to 530 nm, illustrating how temperature affects the bandgap and emission intensity due to quantum confinement and defect tolerance, where defect states within the bands minimize non-radiative recombination for stable fluorescence.21 The narrow FWHM (~20 nm for CsPbBr3 at ~520 nm) ensures high color purity, critical for sensing applications.

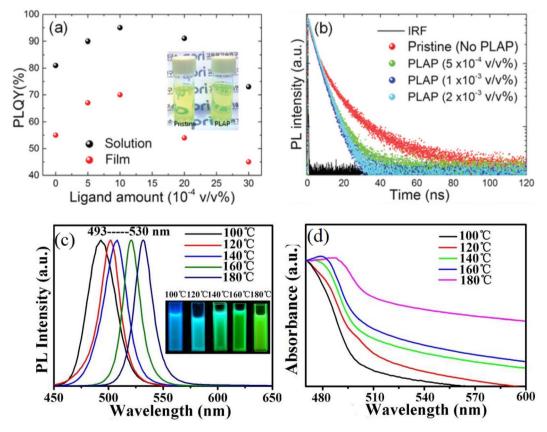


Fig. 2 (a) PLQY of PQDs as a function of ligand amount in solution and film, (b) time-resolved PL decay curves for pristine PQDs and PLAPtreated PQDs at different concentrations. Reprinted with permission from ref. 20. Copyright 2018, Royal Society of Chemistry. (c) PL spectra of PQDs at various temperatures, and (d) absorbance spectra of PQDs at different temperatures. Adapted with permission from ref. 21. Copyright 2017, Elsevier.

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Panel (d) shows absorbance spectra under the same temperature conditions, revealing shifts in the absorption edge (e.g., \sim 3.0 eV for CsPbCl₃ to \sim 1.7 eV for CsPbI₃) due to size or halide composition tuning, highlighting the large absorption coefficients and efficient light harvesting, which support responsive fluorescence signals for analyte detection (Fig. 2).

2.1.3. Surface chemistry and ligand effects. The surface chemistry of PQDs significantly influences their optical and sensing properties. PQDs are typically capped with organic ligands, such as oleylamine (OAm) or oleic acid (OA), which passivate surface defects, enhance colloidal stability, and prevent aggregation. The ligand type and density affect the PLQY and environmental stability. For instance, long-chain ligands like OAm provide steric stabilization but may hinder analyte access in sensing applications, reducing sensitivity. Conversely, shorter or zwitterionic ligands can improve ion accessibility while maintaining stability in polar media. 18,35 Surface defects, if unpassivated, can act as non-radiative recombination centers, lowering PLQY and affecting sensing selectivity.33 Ligand exchange strategies, such as replacing OAm with zwitterionic molecules, have been explored to enhance water compatibility for aqueous sensing.

2.1.4. Exciton dynamics and sensing relevance. The exciton dynamics in PQDs, characterized by short radiative lifetimes (1–10 ns) and high exciton binding energies (20–100 meV), contribute to their sensitivity in sensing applications. The strong excitonic effects enable efficient energy transfer mechanisms, such as FRET or electron transfer, when PQDs interact with metal ions. For example, the presence of heavy metal ions like Cu²⁺ or Hg²⁺ can induce fluorescence quenching through electron transfer or ion exchange, providing a measurable signal for detection. ^{14,36} The high surface-to-volume ratio of PQDs amplifies these interactions, making them highly

responsive to low analyte concentrations, often achieving LOD in the nanomolar range.

2.2. Types of perovskite quantum dots

PQDs can be broadly classified into lead-based and lead-free variants, each with distinct structural, optical, and practical characteristics. Lead-based PQDs, such as CsPbX₃ and CH₃-NH₃PbX₃, are the most studied due to their superior optical properties, while lead-free PQDs, such as Cs₃Bi₂X₉ and CsSnX₃, are gaining attention for their reduced toxicity and environmental compatibility.^{31,37}

2.2.1. Lead-based perovskite quantum dots. Lead-based PQDs, including inorganic $CsPbX_3$ (X = Cl, Br, I) and organicinorganic hybrids like CH3NH3PbX3 or FAPbX3, are renowned for their high PLQY (up to 90%), narrow emission spectra, and tunable bandgaps (1.7-3.0 eV). The lead cation (Pb²⁺) in the Bsite contributes to strong spin-orbit coupling, resulting in a direct bandgap and efficient radiative recombination. CsPbX₃ PQDs are fully inorganic, offering enhanced thermal and chemical stability compared to hybrids. For example, CsPbBr₃ exhibits robust green emission (~520 nm) and is widely used for detecting ions like Cu²⁺ and Cd²⁺ due to its high sensitivity to quenching mechanisms.38 Organic-inorganic hybrids, such as CH₃NH₃PbBr₃, incorporate organic cations like methylammonium, which increase lattice flexibility but reduce stability under moisture or heat due to the volatility of the organic component. The halide composition in lead-based PQDs enables precise optical tuning, with CsPbCl₃ emitting blue (410 nm), CsPbBr₃ green, and CsPbI₃ red (680 nm). Mixedhalide systems like CsPb(Br/Cl)₃ allow continuous spectral adjustment, vital for ratiometric sensing.37,39 However, Pb2+ toxicity poses challenges, necessitating stringent handling and

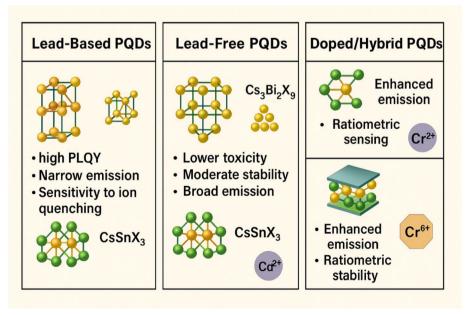


Fig. 3 Classification of PQDs into lead-based, lead-free, and doped/hybrid types, highlighting their structural features, optical properties, and sensing capabilities for heavy metal ion detection.

disposal protocols for environmental and biological sensing applications.

- **2.2.2.** Lead-free perovskite quantum dots. Lead-free PQDs, such as $Cs_3Bi_2X_9$, $CsSnX_3$, or MASn X_3 , are developed to address the toxicity concerns of lead-based counterparts. These materials replace Pb^{2+} with less toxic metals like Bi^{3+} or Sn^{2+} . $Cs_3Bi_2X_9$ PQDs adopt a layered or dimer structure rather than the standard ABX $_3$ perovskite lattice, resulting in lower PLQY (typically 20–50%) and broader emission spectra (FWHM \sim 40–60 nm). Despite these limitations, they offer improved environmental stability and are suitable for detecting ions like Cu^{2+} or Cr^{6+} in aqueous media. $CsSnX_3$ PQDs, while promising, suffer from rapid oxidation of Sn^{2+} to Sn^{4+} , leading to reduced stability and PL efficiency. Doping strategies, such as incorporating Eu^{3+} or Mn^{2+} , enhance the optical properties and stability of lead-free PQDs, making them viable for eco-friendly sensing applications.
- **2.2.3. Doped and hybrid perovskite quantum dots.** Doping PQDs with transition metal ions (*e.g.*, Mn²⁺, Eu³⁺) or forming hybrid structures (*e.g.*, CsPbBr₃–MXene) introduces additional functionalities. Mn²⁺-doped CsPbCl₃ PQDs exhibit dual emission (excitonic and dopant-induced), enabling ratiometric sensing for improved accuracy. Hybrid structures, such as CsPbBr₃ encapsulated in metal–organic frameworks (MOFs) or combined with MXene, enhance stability and sensitivity by providing a protective matrix or facilitating charge transfer.⁴¹ These advanced PQDs are particularly effective for detecting multiple analytes, including heavy metal ions, in complex matrices (Fig. 3).
- 2.2.4. Comparison of PQD types. The diverse classes of PQDs exhibit distinct optical, structural, and stability characteristics, making them suitable for various sensing applications. Lead-based PQDs offer superior PLQY and tunable emission but are hindered by toxicity and environmental concerns. In contrast, lead-free PQDs prioritize eco-friendliness and stability, albeit with compromised optical performance. Doped and hybrid PQDs combine enhanced stability and multifunctionality, enabling advanced sensing capabilities in complex environments. The below table summarizes their key properties to facilitate a comparative understanding (Table 1).

2.3. Synthesis methods and their impact on sensing performance

The synthesis strategy employed for PQDs plays a critical role in determining their particle size, crystallinity, surface chemistry, and ultimately their performance in sensing applications. Controlled synthesis influences the PLQY, surface defect density, ion accessibility, and stability in aqueous media—key parameters governing their suitability for detecting heavy metal ions. This section systematically discusses five major synthesis methods, highlighting their operational principles, advantages, and limitations, as well as their implications for sensor performance.

2.3.1. Hot-injection method. The hot-injection method is one of the most widely used and precise techniques for synthesizing high-quality PQDs. Typically, cesium oleate is

| Table 1 Comparative overview of perovskite quantum dot types | view of perovskite quantur | m dot types and their properties | operties | | | | |
|--|---|----------------------------------|----------|----------------------------------|-------------------------------------|---|-----------|
| РQD type | Composition example | Lead-based/lead-free PLQY (%) | PLQY (%) | Emission range (nm) Stability | Stability | Sensing applications | Ref. |
| Inorganic lead-based | $CsPbX_3$ (X = Cl, Br, I) | Lead-based | 20–90 | 410–680 | Moderate (sensitive to moisture/UV) | Cu^{2+} , Hg^{2+} , Cd^{2+} detection | 37 and 39 |
| Organic-inorganic hybrid | $CH_3NH_3PbX_3$, $FAPbX_3$ | Lead-based | 40-80 | 450-700 | Low (volatile organic cations) | Cu^{2+} , Fe ³⁺ detection | 42 |
| Lead-free bismuth-based | $\mathrm{Cs_3Bi_2X_9}$ | Lead-free | 20-50 | 400-600 | | Cu ²⁺ , Cr ⁶⁺ detection | 43 |
| Lead-free tin-based | CsSnX ₃ , MASnX ₃ | Lead-free | 10-40 | 008-009 | Low (Sn ²⁺ oxidation) | Pb ²⁺ detection | 44 and 45 |
| Doped/hybrid | $CsPbCl_3$:Mn, | Lead-based/lead-free | 30-80 | 400-700 | High (matrix-protected) | Ratiometric sensing, | 41 |
| | $CsPbBr_3@MOF$ | | | | | multi-ion detection | |

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rapidly injected into a hot solution (140-200 °C) containing a lead halide precursor (e.g., PbBr₂) dissolved in a noncoordinating solvent (e.g., octadecene) along with ligands such as oleic acid (OA) and oleylamine (OAm), under an inert atmosphere (e.g., N₂ or Ar). The sudden introduction of the cesium source induces burst nucleation followed by controlled growth, yielding monodisperse nanocrystals with tunable sizes (2-8 nm) and high crystallinity. This technique allows precise control over the halide composition (Cl-, Br-, I-) and particle size, enabling direct tuning of bandgap and emission wavelength. PQDs synthesized by hot-injection typically exhibit PLQYs above 80% and low surface defect densities. 46,47 These features contribute to enhanced sensing performance through

efficient fluorescence quenching mechanisms such as cation exchange or electron transfer, with LODs reaching subnanomolar levels for ions like Cu2+ and Hg2+. However, the method requires rigorous control of reaction parameters and inert conditions, limiting scalability and water stability unless surface modification or encapsulation is performed.

2.3.2. Hydrothermal and solvothermal synthesis. Hydrothermal (aqueous-based) and solvothermal (organic solventbased) methods involve sealing precursors in an autoclave and heating to elevated temperatures (100-200 °C) and pressures for several hours. These methods are particularly wellsuited for the synthesis of lead-free PQDs, such as Cs₃Bi₂X₉ or CsSnX₃, offering improved environmental compatibility. The

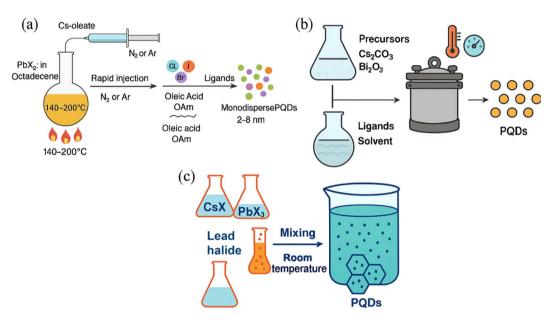
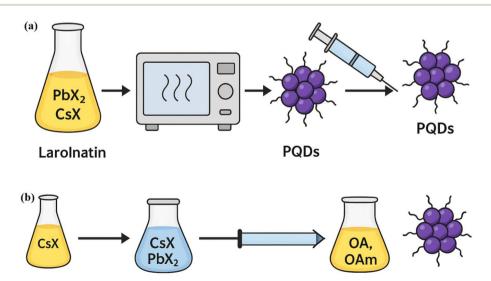


Fig. 4 Diverse synthetic routes for perovskite quantum dots: (a) hot-injection method; (b) hydrothermal and solvothermal synthesis procedures; (c) room-temperature precipitation technique.



Synthesis approaches for PQDs: (a) microwave-assisted synthesis technique; (b) ligand-assisted reprecipitation method.

high-pressure environment promotes better ligand coordination, resulting in nanocrystals with moderate crystallinity and PLQYs in the range of 50-70%. Moreover, these methods yield PQDs with enhanced water stability, essential for applications in aqueous sensing. 48,49 Nevertheless, they often require longer reaction times and complex equipment setups, which can impede throughput and reproducibility.

2.3.3. Room-temperature precipitation. This method represents the most accessible and energy-efficient approach to PQD synthesis. It typically involves mixing cesium and lead halide salts in low-boiling point solvents such as ethanol or water under ambient conditions. While advantageous for rapid and low-cost production, this approach generally yields PQDs with larger sizes (8-15 nm), poor crystallinity, and high surface defect densities. These features reduce the PLOY (30-50%) and make the resulting nanocrystals less suitable for high-sensitivity detection. Nonetheless, this method finds utility in preliminary screening studies or applications where ultra-trace detection is not required. 50,51 It is particularly appealing in resource-limited settings where access to sophisticated equipment is restricted (Fig. 4).

2.3.4. Microwave-assisted synthesis. Microwave-assisted synthesis employs dielectric heating to rapidly and uniformly heat reaction mixtures, enabling accelerated nucleation and growth of PQDs. Typically, lead halide and cesium precursors are combined with coordinating ligands and subjected to microwave irradiation for short durations (minutes), resulting in highly crystalline PQDs with size ranges of 3-10 nm and PLQYs between 60-85%. The homogeneous temperature profile minimizes thermal gradients and suppresses defect formation, contributing to enhanced stability and sensitivity. Microwave synthesis is particularly effective for generating PQDs used in ratiometric sensing, such as dual-emission systems for Fe³⁺ and Cr⁶⁺ detection.^{52,53} However, the method requires specialized microwave reactors and may present challenges in scaling for industrial use.

2.3.5. Ligand-assisted reprecipitation. LARP is a roomtemperature, scalable approach ideal for cost-effective PQD production. In this method, precursors (e.g., CsX and PbX₂) are dissolved in a polar solvent such as N,N-dimethylformamide (DMF) and rapidly injected into a non-polar solvent like toluene or hexane containing capping ligands (e.g., OA, OAm). The difference in solubility induces supersaturation and instantaneous nucleation of PQDs. Although LARP-synthesized PQDs typically have broader size distributions (5-12 nm) and moderate PLQY (50-70%), the process is simpler and better suited for large-scale production. The nature and concentration of ligands significantly affect the colloidal stability, ion accessibility, and defect passivation. 54,55 By incorporating hydrophilic or zwitterionic ligands, water compatibility is improved, enabling application in aqueous sensing environments. However, LARP products often require post-synthetic treatments (e.g., ligand exchange, encapsulation) to enhance longterm stability and minimize surface defects (Fig. 5).

Table 2 provides a comparative overview of commonly used PQD synthesis techniques, highlighting key physicochemical

| Table 2 Comparisor | Table 2 Comparison of synthesis methods for PQDs and their impact on heavy metal ion sensing performance | and the | eir impact | on heavy me | etal ion sensing pe | rformance | | | |
|-------------------------------------|--|--------------------|------------|-------------------|-------------------------|---|-------------|---|-----------|
| Synthesis method | Precursor type | Size PLQY (nm) (%) | ₹ _ | Defect density | Ion accessibility | Water compatibility | Scalability | Sensing Scalability performance | Ref. |
| Hot-injection | Cs-oleate + Pb X_2 in OA/OAm 2-8 | | 08< | Very low | Moderate-low | Moderate-low Low (requires treatment) Low | Low | High sensitivity (<1 nM); | 46 and 47 |
| Hydro/ solvothermal | BiX ₃ or SnX ₂ + CsX in sealed autoclave | 5-12 | 50-70 | Moderate | Moderate | High | Medium | Moderate sensitivity | 48 and 49 |
| Room-temp | PbX ₂ + CsX in ethanol/water | 8-15 | 30-20 | High | High | High | Very high | Low sensitivity | 50 and 51 |
| Piecipitation Microwave-assisted | Same as hot-injection | 3-10 | 60-85 | Low | Moderate | Moderate | Medium | High sensitivity (<5 nM); | 52 and 53 |
| LARP | $CsX + PbX_2$ in DMF/toluene | 5-12 | 50-70 | Moderate | High (short ligands) | High Moderate Short ligands) (hydrophilic ligands) | High | Moderate sensitivity; water-compatible | 54 and 55 |

properties and their implications for heavy metal ion detection sensitivity and stability.

3. Mechanisms of heavy metal ion detection

The detection of heavy metal ions using PQDs leverages their unique optoelectronic properties, including high PLOY, narrow emission spectra, and tunable bandgaps, to achieve sensitive and selective responses to analyte interactions. These responses primarily manifest as changes in PL intensity, such as quenching or, less commonly, enhancement, driven by specific physical and chemical interactions between PQDs and metal ions.56-58 This section explores the fundamental mechanisms underlying these interactions, including cation exchange, electron transfer, FRET, surface trap-mediated quenching, and charge transfer complex formation. The critical role of surface ligands in modulating selectivity and sensitivity is also discussed, alongside theoretical insights from computational methods, such as density functional theory (DFT) and molecular dynamics (MD) simulations, to elucidate the electronic and structural factors governing these mechanisms. The focus is on the fundamental processes, avoiding overlap with sensor performance or applications, which are reserved for subsequent

3.1. Fluorescence quenching and enhancement mechanisms

The interaction of heavy metal ions with PQDs typically results in fluorescence quenching, where PL intensity decreases due to the creation of non-radiative recombination pathways, or, in rare cases, enhancement, where PL intensity increases due to passivation of surface defects. These changes stem from alterations in the electronic structure, surface chemistry, or energy transfer dynamics of PQDs, driven by distinct mechanisms.^{11,59}

3.1.1. Cation exchange. Cation exchange is a dominant mechanism in lead-based PQDs, such as CsPbX₃ (X = Cl, Br, I) or CH₃NH₃PbX₃, where heavy metal ions replace the B-site cation (typically Pb²⁺) at the PQD surface. This substitution disrupts the perovskite lattice, introducing defects or mid-gap states that facilitate non-radiative recombination, leading to fluorescence quenching. For example, Hg2+ ions, with an ionic radius (110 pm) close to Pb²⁺ (119 pm), readily replace Pb²⁺ in CH₃NH₃PbBr₃, causing lattice strain and quenching PL within seconds due to rapid ion exchange kinetics.⁵⁹ The selectivity of this mechanism depends on the ionic radius, charge, and coordination chemistry of the analyte, making it highly effective for Hg²⁺ detection over other ions like Zn²⁺ or Na⁺. In lead-free PQDs, such as Cs₃Bi₂X₉, cation exchange is less prevalent due to the higher stability of Bi3+, limiting this mechanism's applicability.60 The efficiency of cation exchange is also influenced by surface ligand density, which can either facilitate or hinder ion access to the lattice.61

Panel (a) in Fig. 6 presents a TEM image of CH₃NH₃PbBr₃ QDs, revealing their nanoscale dimensions and uniform distribution, with a scale bar of 50 nm, consistent with the 2-

10 nm range where quantum confinement effects dominate.⁵⁹ Panel (b) shows the size distribution analysis, indicating an average diameter of 5.3 \pm 0.5 nm, which influences the discrete energy levels and size-dependent bandgap, enhancing photoluminescence properties critical for sensing applications. These structural characteristics support the cation exchange mechanism, where the surface accessibility of Pb2+ (ionic radius 119 pm) facilitates rapid ion substitution by analytes like Hg²⁺ (110 pm), disrupting the lattice and introducing defects. Panel (c) displays UV-vis absorption and photoluminescence emission spectra of CH₃NH₃PbBr₃ QDs, with an absorption edge around 520 nm and a sharp emission peak at 510 nm, reflecting the high oscillator strength and narrow FWHM (12-40 nm) due to quantum confinement. The inset photograph confirms the green emission, which is guenched upon Hg²⁺ exchange due to non-radiative recombination induced by lattice strain. Panel (d) presents XRD patterns of CH₃NH₃PbBr₃ QDs in the absence and presence of Hg²⁺, showing peak shifts that indicate lattice disruption and mid-gap states formation, highlighting the selectivity and rapid kinetics of cation exchange for Hg²⁺ detection over other ions. Panel (e) illustrates the evolution of fluorescence spectra of CH₃NH₃PbBr₃ QDs with increasing Hg²⁺ concentrations (0 to 1000 nM), showing a progressive quenching of the 510 nm emission peak, consistent with cation exchange disrupting the perovskite lattice and enhancing nonradiative recombination. Panel (f) provides a linear fitting curve of I₀/I versus Hg²⁺ concentration (0-100 nM), with a correlation coefficient ($R^2 = 0.994$), demonstrating the sensitivity and selectivity of this mechanism for Hg2+ detection, influenced by ionic radius compatibility and surface ligand density that modulates ion access.

3.1.2. Electron transfer. Electron transfer occurs when heavy metal ions interact with the PQD surface, enabling the transfer of electrons from the conduction band of the PQD to the ion's unoccupied orbitals or vice versa, creating nonradiative recombination pathways that quench fluorescence. For instance, Cu²⁺ ions, with their partially filled d-orbitals, act as electron acceptors in CsPbBr₃ PQDs, reducing PL intensity by accepting electrons from the conduction band.62 This mechanism is particularly effective for transition metal ions like Cu²⁺, Fe³⁺, or Cr⁶⁺, whose redox potentials align with the PQD's band structure, facilitating efficient electron transfer. 62,63 The quenching efficiency depends on the energy level alignment between the PQD's conduction band and the ion's orbitals, as well as the accessibility of the PQD surface, which is modulated by ligands. Electron transfer is more pronounced in organic solvents, where ligands like OAm allow ion access, but may be limited in aqueous media due to ligand barriers.⁶¹

3.1.3. Förster resonance energy transfer. FRET involves non-radiative energy transfer from the excited state of a PQD (donor) to a heavy metal ion or a nearby acceptor molecule, resulting in fluorescence quenching. FRET requires spectral overlap between the PQD's emission and the acceptor's absorption spectrum, as well as proximity within 10 nm. For example, in a ratiometric sensor, CsPbBr₃ PQDs transfer energy to gold nanoclusters in the presence of Cu²⁺, quenching the PQD's green emission (~520 nm) while enhancing the

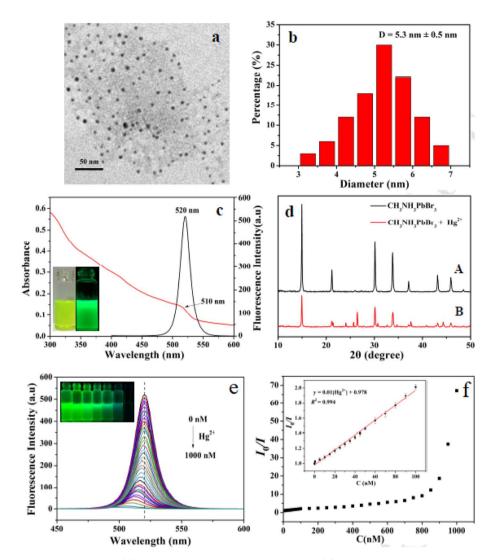


Fig. 6 (a) TEM image of $CH_3NH_3PbBr_3$ QDs, (b) size distribution of $CH_3NH_3PbBr_3$ QDs, (c) UV-vis and PL spectra of $CH_3NH_3PbBr_3$ QDs, (d) XRD patterns with/without Hg^{2+} , (e) fluorescence changes with varying Hg^{2+} , (f) I_0/I vs. Hg^{2+} (0–100 nM) linear fit. Reprinted with permission from ref. 59. Copyright 2017, Elsevier.

nanocluster's emission due to spectral overlap.⁶⁴ FRET is highly sensitive but less selective, as multiple analytes may induce similar energy transfer effects, necessitating careful sensor design to ensure specificity.⁶⁵ The efficiency of FRET depends on the dipole–dipole coupling strength, which is influenced by the PQD's emission properties and the ligand-mediated distance between the PQD and the acceptor.⁶⁶

3.1.4. Surface trap-mediated quenching. Surface trap-mediated quenching occurs when heavy metal ions interact with surface defects or trap states on PQDs, such as uncoordinated halide ions or underpassivated cation sites, creating non-radiative recombination centers that quench fluorescence. For instance, Fe³⁺ ions bind to surface defects on CsPbBr₃–CsPb₂Br₅ PQDs, forming trap states that capture excitons and reduce PL intensity.⁶⁷ This mechanism is particularly relevant for PQDs with high surface-to-volume ratios, where defects are more prevalent. In lead-free PQDs like MASnBr₃, surface trapmediated quenching is enhanced by the interaction of ions

like Cr⁶⁺ with undercoordinated Sn²⁺ sites, leading to efficient quenching.⁶⁸ The extent of quenching depends on the defect density and ligand passivation, which can either suppress or amplify trap-mediated effects. Surface modification with ligands like APTES can reduce defect density, mitigating nonspecific quenching and enhancing selectivity.⁶⁷

3.1.5. Charge transfer complex formation. Charge transfer complex formation involves the creation of a transient complex between the PQD surface and a heavy metal ion, leading to fluorescence quenching through the formation of a charge transfer state. This mechanism is driven by the coordination of metal ions with surface ligands or lattice ions, forming a complex that alters the electronic structure of the PQD. For example, Cu²⁺ ions can form coordination complexes with amine groups on CsPbBr₃ PQDs, creating a charge transfer state that quenches PL by redirecting excitons to non-radiative pathways.⁶⁹ This mechanism is particularly effective for ions with strong coordination abilities, such as Cu²⁺ or Cd²⁺, and is

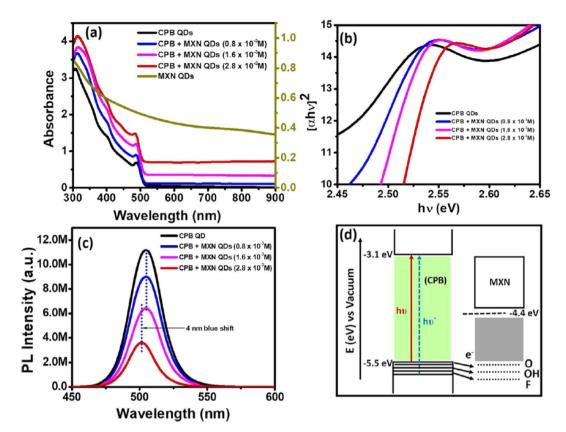


Fig. 7 (a) Absorbance spectra of CsPbBr $_3$ QDs, MXN QDs, and CPB-MXN composites, (b) Tau plots of CPB-MXN vs. pure CsPbBr $_3$, (c) PL spectra of CPB-MXN with MXN concentrations 0.8×10^{-3} , 1.6×10^{-3} , 2.8×10^{-3} M, (d) schematic of CPB-MXN band alignment. CPB QD concentration is constant (1.9 \times 10⁻⁷ M). Reprinted with permission from ref. 70. Copyright 2020, American Chemical Society.

enhanced in heterostructures like $CsPbBr_3-Ti_3C_2T_x$ MXene, where the MXene facilitates charge transfer. The stability and quenching efficiency of the complex depend on the ligand's coordination strength and the ion's electronegativity.

Panel (a) in Fig. 7 presents absorbance spectra of CsPbBr₃ QDs (black line), MXN QDs (dark yellow), and CsPbBr₃ QD-Ti₃C₂T_x QD (CPB-MXN) composites, showing distinct absorption edges influenced by the formation of charge transfer complexes, where heavy metal ions coordinate with surface ligands, altering the electronic structure [ref. 70]. Panel (b) in Fig. 7 displays tau plots of the CPB-MXN composite compared to pure CsPbBr3, indicating faster decay rates due to charge transfer states that redirect excitons to non-radiative pathways. Panel (c) shows steady-state PL spectra at 410 nm excitation for the CPB-MXN composite with varying MXN concentrations (0.8 \times 10⁻³, 1.6 \times 10⁻³, 2.8 \times 10⁻³ M), revealing a 4 nm blue shift and quenching, consistent with the transient complex formation that enhances non-radiative recombination, particularly with ions like Cu²⁺ coordinating with amine groups. Panel (d) provides a schematic diagram of the CPB-MXN band alignment, illustrating the energy levels where the charge transfer state forms, with a vacuum level at -3.1 eV and a bandgap of 2.4 eV for CPB, facilitating efficient charge transfer in heterostructures like CsPbBr₃-Ti₃C₂T_x MXene. This alignment supports the quenching mechanism driven by strong coordination abilities of ions such as Cu2+ or Cd2+, enhanced by the MXene's role in

facilitating charge transfer. The stability and efficiency of this quenching depend on the ligand's coordination strength and the ion's electronegativity, aligning with the mechanism's effectiveness in altering the PQD's electronic structure for sensing applications.

3.2. Role of surface ligands in selectivity and sensitivity

Surface ligands, such as OAm, OA, PEI, hydroxypropyl chitosan, or APTES, are critical in modulating the selectivity and sensitivity of PQD-based detection. Ligands passivate surface defects, stabilize colloidal dispersions, and mediate ion-PQD interactions, influencing the efficiency of quenching or enhancement mechanisms. Long-chain ligands like OAm and OA provide steric hindrance, reducing non-specific interactions and enhancing selectivity for ions like Hg²⁺ or Cu²⁺, which penetrate the ligand shell through coordination or ion exchange.61 For example, OAm-capped CsPbBr₃ PQDs exhibit high selectivity for Cu²⁺ due to the ion's ability to coordinate with amine groups, facilitating electron transfer or complex formation.62 However, dense ligand layers may reduce sensitivity by limiting ion access, particularly in aqueous media. Hydrophilic or zwitterionic ligands, such as hydroxypropyl chitosan, improve water compatibility and ion accessibility, enhancing sensitivity for ions like Cr6+.71 PEI-modified MASnBr3 PQDs introduce chelating groups that selectively bind Fe3+, forming stable complexes that enhance quenching specificity.68

Dynamic ligand exchange, where metal ions displace weakly bound ligands, exposes the PQD surface, amplifying quenching through cation exchange or trap-mediated mechanisms. For instance, Cd²⁺ detection with CsPbBr₃–CsPb₂Br₅ PQDs is enhanced by ammonia hydroxide, which reduces ligand density and increases surface accessibility.⁷² Conversely, strongly bound ligands like APTES improve stability and selectivity for

Fe³⁺ by minimizing non-specific interactions.⁶⁷

3.3. Theoretical insights

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Theoretical studies, particularly DFT calculations using functionals like PBE or HSE06 for accurate band structures, provide quantitative insights into the electronic, structural, and kinetic changes induced by heavy metal ions in PQDs. For cation exchange, DFT simulations of Pb2+ substitution with Hg2+ in CH₃NH₃PbBr₃ reveal the formation of mid-gap states positioned 0.5-1.0 eV below the conduction band (CB, typically at -3.5 eV vs. vacuum), which promote non-radiative recombination by increasing the rate constant from $\sim 10^7 \text{ s}^{-1}$ (pristine) to $\sim 10^9$ s⁻¹, as evidenced by shortened PL lifetimes from 10 ns to ~2 ns.59 The thermodynamic rationale is rooted in a favorable Gibbs free energy change ($\Delta G \approx -20 \text{ to } -25 \text{ kJ mol}^{-1}$), calculated from the low lattice distortion energy due to similar ionic radii (Pb2+: 119 pm; Hg2+: 110 pm) and a reduced activation barrier (\sim 0.2 eV), enabling rapid exchange kinetics on the order of seconds in organic solvents. This mechanism is particularly selective for Hg^{2+} , with ΔG more negative than for mismatched ions like Zn^{2+} ($\Delta G > -10 \text{ kJ mol}^{-1}$), aligning with experimental quenching efficiencies >90%.59

Similarly, for electron transfer, Cu²⁺ binding to CsPbBr₃ surfaces reduces the bandgap by shifting the CB edge downward by 0.3-0.4 eV (from -3.8 eV to -4.1 eV), facilitating efficient electron donation from the PQD CB to Cu2+ unoccupied dorbitals (LUMO at \sim -4.0 eV), with transfer rates \sim 5 \times 10¹⁰ s⁻¹—significantly faster than other mechanisms like FRET $(\sim 10^8 \text{ s}^{-1})$.⁶² Thermodynamically, this is driven by a $\Delta G \approx -15$ to -18 kJ mol⁻¹, arising from redox potential alignment (Cu²⁺/ $Cu^+E^\circ = 0.15 \text{ V} \text{ vs. NHE}$, matching PQD CB at $\sim -0.5 \text{ V}$), which lowers the energy barrier for charge separation and enhances quenching in transition metal detections. In lead-free Cs3Bi2-Br₉, DFT indicates Cu²⁺ interactions with Bi³⁺ sites create shallow trap states at 0.2-0.3 eV above the valence band (VB at -5.5 eV), increasing non-radiative rates to $\sim 8 \times 10^8$ s⁻¹ with a $\Delta G \approx -12$ to -14 kJ mol⁻¹, though kinetics are slower due to higher lattice rigidity (activation energy ~0.4 eV) compared to lead-based systems.60 This highlights a trade-off: lead-free PQDs offer eco-friendly thermodynamics but reduced kinetic efficiency for aqueous sensing.

Bandgap effects are central to all detection mechanisms, where metal ions shift band edges and alter recombination pathways. For surface trap-mediated quenching, Fe³⁺ ions induce a redshift in the bandgap of CsPbBr₃–CsPb₂Br₅ by 0.15–0.2 eV (from 2.4 eV to 2.2 eV), driven by strong electrostatic binding (energy \sim –1.5 to –2.0 eV), which creates defect states and reduces radiative lifetimes from 10–15 ns to 1–3 ns, corresponding to rate increases to 6 \times 10⁸ s⁻¹.6⁷ Thermodynamically,

 $\Delta G \approx -19~\text{kJ mol}^{-1}$ favors trap formation due to Fe $^{3+}$ coordination with underpassivated Br $^-$ sites, making this mechanism kinetically slower than electron transfer but highly selective in aqueous matrices with pH-dependent interferences. DFT also elucidates ligand roles, showing that ligand–metal coordination (e.g., OAm or PEI with Cu $^{2+}$) lowers electron transfer barriers by 0.3–0.5 eV, increasing rates by 10–100-fold and ΔG by -5 to $-10~\text{kJ mol}^{-1}$ through stabilized charge-separated states. This is particularly relevant for ratiometric designs, where FRET efficiencies reach 60–70% with dipole–dipole distances < 10 nm, but kinetics lag ($\sim 10^8~\text{s}^{-1}$) due to spectral overlap requirements (> 50% emission–absorption match) and less negative ΔG ($\sim -10~\text{kJ mol}^{-1}$) compared to direct transfer.

MD simulations further model ion kinetics, revealing that diffusion through the ligand shell (e.g., oleylamine chains ~ 1 -2 nm thick) is rate-limiting, with diffusion coefficients \sim 5 \times 10^{-10} to 10^{-9} m² s⁻¹ and residence times ~10–100 ps, affecting overall response times (seconds in experiments).74 Comparatively, electron transfer exhibits the fastest kinetics (10¹⁰ s⁻¹, low barriers) and most negative ΔG for rapid, sensitive detection of transition metals like Cu2+; cation exchange offers intermediate rates $(10^9 \,\mathrm{s}^{-1})$ with high thermodynamic stability for Hg²⁺specific sensing; while trap-mediated and FRET mechanisms provide tunable selectivity but slower dynamics (10⁸ s⁻¹) due to defect/spectral dependencies. These quantitative metrics, validated by hybrid DFT-MD approaches, guide rational PQD design-e.g., ligand engineering to optimize barriers or doping to align band edges—for enhanced sensitivity (sub-nM LODs) and selectivity in diverse matrices.

4. PQD-based nanosensors for heavy metal ion detection

PQDs have emerged as highly effective platforms for detecting heavy metal ions, leveraging their exceptional optoelectronic properties, including high PLQY, tunable emission wavelengths, and large surface-to-volume ratios. These attributes enable the development of sensors with superior sensitivity and selectivity, particularly for industrial applications where precise detection of heavy metal contaminants is critical.11,38 This section reviews the design of PQD-based nanosensors for specific heavy metal ions, evaluates their performance metrics, compares lead-based and lead-free PQDs, explores strategies for enhancing sensor performance, and details their applications in industrial settings for heavy metal detection. The focus is on practical sensor design and performance, distinct from the mechanistic insights covered previously, ensuring a comprehensive and application-oriented analysis tailored to the detection of heavy metal ions.

4.1. Design of PQD-based nanosensors for specific heavy metal ions

The design of PQD-based nanosensors is tailored to detect specific heavy metal ions, including Hg²⁺, Cu²⁺, Cd²⁺, Fe³⁺, Cr⁶⁺, and Pb²⁺, by exploiting ion-specific interactions with the PQD surface or lattice. For Hg²⁺ detection, CH₃NH₃PbBr₃ PQDs have

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been developed with a limit of detection (LOD) of 0.124 nM, capitalizing on their high PLOY (50.28%) and efficient surface interactions that lead to fluorescence quenching.⁵⁹ The sensor design leverages the chemical affinity of Hg2+ for the perovskite lattice, enabling rapid and selective detection in organic media. Cu²⁺ detection is a focal point, with CsPbBr₃ PQDs achieving an LOD of 0.1 nM in organic solvents like hexane, benefiting from fast response times (<10 s) and high selectivity over competing ions such as Na⁺ or Zn²⁺.62 The design incorporates ligands like OAm to facilitate ion access in non-polar environments. Cd²⁺ detection is achieved using CsPbBr3-CsPb2Br5 PQDs modified with ammonia hydroxide, which reduces ligand density to enhance surface accessibility, resulting in an LOD of 10⁻⁶ M.⁷² This modification improves sensitivity in aqueous media, critical for industrial wastewater analysis. Lead-free PQDs, such as MASnBr₃, are designed for Fe³⁺ and Cr⁶⁺ detection, achieving nanomolar sensitivity through tailored ligand systems like PEI, which forms selective complexes with these ions. 68 Cs3Bi2Br9 PQDs are engineered for Cu²⁺ detection in aqueous environments, achieving an LOD of 98.3 nM due to their high photostability and ligand-assisted interactions.60 For Pb2+ detection, CsSnX₃ PQDs are optimized for non-aqueous media like lubricants, achieving an LOD of 3.5 nM through synthesis methods that enhance PL stability.75 These designs highlight the

adaptability of PQDs to diverse ions and matrices, driven by tailored material compositions and surface chemistries.

Fig. 8a shows the PL intensity of Cs₃Bi₂Br₉ PQDs at varying Cu²⁺ concentrations (0 to 1200 nM), with a clear quenching trend, reflecting the high PLQY (50.28%) and efficient surface interactions that enable a low LOD of 0.1 nM in organic solvents like hexane, as designed for Cu²⁺ detection. Panel (b) presents a fitting curve for PL intensity versus Cu2+ concentration, demonstrating a linear range of 0-1200 nM with an R^2 of 0.99105, highlighting the sensor's selectivity and rapid response (<10 s) over competing ions like Na⁺ or Zn²⁺, facilitated by ligands such as OAm. Panel (c) displays time-resolved fluorescence spectra at varying Cu2+ concentrations, showing decay time reductions that underscore the fast ion-specific interactions with the POD lattice, aligning with the tailored design for heavy metal ion sensing. Panel (d) illustrates the PL responses (F_0/F) of the probe to different metal ions $(Zn^{2+}, Mg^{2+}, Sn^{2+},$ Mn²⁺, Ni²⁺, Pb²⁺, In³⁺, Cu²⁺), with Cu²⁺ exhibiting the highest quenching efficiency $(F_0/F \approx 3.5)$, confirming the sensor's selectivity and nanomolar sensitivity (LOD 0.1 nM) for Cu²⁺ in organic media. This design leverages the chemical affinity of Cu²⁺ for the perovskite surface, enhanced by ligand-assisted interactions, consistent with the adaptability of PQDs like Cs3-Bi₂Br₉ for aqueous detection (LOD 98.3 nM) or CH₃NH₃PbBr₃

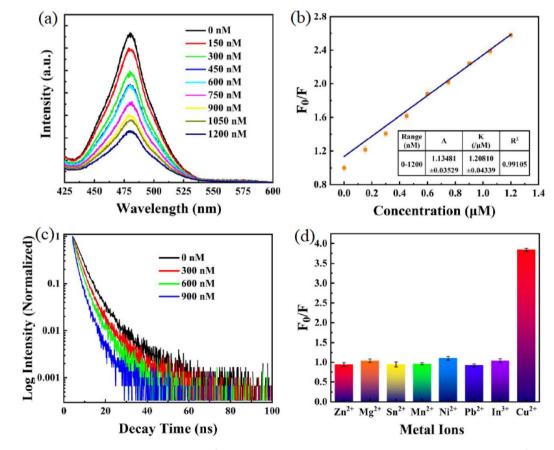


Fig. 8 (a) PL intensity of $Cs_3Bi_2Br_9$ PQDs at different Cu^{2+} concentrations, (b) calibration curve of PL intensity *versus* Cu^{2+} concentration, (c) time-resolved fluorescence profiles with varying Cu^{2+} levels, (d) PL responses of the sensor to various metal ions. Adapted with permission from ref. 60. Copyright 2023, MDPI.

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 10^{-9} to 10^{-6} M 10^{-9} to 10^{-5} M

by Cu²⁺ (ligand-modified)

for Hg²⁺ (LOD 0.124 nM), and CsSnX₃ for Pb²⁺ (LOD 3.5 nM) in non-aqueous matrices, showcasing tailored surface chemistries for diverse ion-specific applications.

4.2. Performance metrics of POD-based sensors

The performance of PQD-based nanosensors is evaluated through key metrics: sensitivity, selectivity, LOD, and linear detection range, all of which are critical for their practical application in industrial and environmental settings. These metrics are heavily influenced by the matrix in which detection occurs (e.g., organic solvents like hexane, aqueous solutions, or complex media like seawater and wastewater), necessitating standardized calibration protocols, blank measurements, and interference assessments to ensure reproducibility and comparability.

Sensitivity is defined as the change in PL intensity per unit analyte concentration ($\Delta I/\Delta C$, typically in a.u./nM). Lead-based PQDs, such as $CsPbX_3$ (X = Cl, Br, I), exhibit high sensitivity due to their strong fluorescence (PL quantum yield, PLQY, 50-90%) and large absorption coefficients (10⁵ to 10⁶ cm⁻¹). For instance, CsPbBr₃ PQDs detect Cu²⁺ in hexane with a sensitivity of $\sim 10^3$ a.u./nM across a linear range of 0-1200 nM, calibrated using Stern-Volmer plots $(I_0/I \text{ vs. } [Cu^{2+}])$ with blank hexane solutions to correct for background fluorescence. 62 In aqueous matrices, sensitivity often decreases due to matrix effects; for example, $Cs_3Bi_2Br_9$ in seawater shows a sensitivity of $\sim 10^2$ a.u./ nM for Cu²⁺, attributed to ionic strength (e.g., 0.6 M NaCl) and pH variations (pH 7.5-8.5), requiring calibration with seawater blanks.60

Selectivity is achieved through specific interactions between PQDs and target ions, such as cation exchange for Hg2+ or chelation for Fe³⁺, minimizing interference from common ions like K⁺, Na⁺, or Ca²⁺. For example, CH₃NH₃PbBr₃ PQDs selectively detect Hg^{2+} in organic solvents with >95% selectivity over Zn2+ and Mg2+, confirmed through interference tests where competing ions caused <5% PL change. 59 In complex matrices like wastewater (pH \sim 6.5, high Ca²⁺/Mg²⁺), selectivity may drop to ~80% unless ligand modifications (e.g., polyethylenimine, PEI) enhance ion-specific binding.68 Calibration protocols incorporate blank measurements in the respective matrix to establish baseline PL and interference tests to quantify selectivity (e.g., PL quenching <10% for non-target ions).

LOD varies significantly with matrix and calibration methodology. In organic solvents like hexane, where ionic interferences are minimal, LODs reach sub-nanomolar levels (e.g., 0.1 nM for Cu²⁺ with CsPbBr₃, determined via Stern-Volmer with $3\sigma/\text{slope}$, where σ is the standard deviation of blank hexane fluorescence⁶²). In contrast, aqueous matrices like seawater or wastewater yield higher LODs (e.g., 98.3 nM for Cu²⁺ with Cs₃- Bi_2Br_9 in seawater, calibrated *via* linear I_0/I fitting with seawater blanks and interference tests showing ~15% quenching from Ca²⁺/Mg²⁺ (ref. 60)). Complex matrices introduce challenges like ionic strength, pH fluctuations, and organic matter, which elevate LODs; for instance, wastewater (COD $\sim 200 \text{ mg L}^{-1}$) increases LODs to ~500 nM for Fe3+ with MASnBr3 due to competing quenching.68 Ratiometric sensors, such as CsPbBr₃

| Table 3 Summary o | of LODs and | d performance | Fable 3 Summary of LODs and performance metrics for PQD-based sensors | ed sensors | | |
|---------------------------|---------------------|---------------------|--|--|---|-------------|
| РQD tуре | Ion | TOD | Matrix | Calibration protocol | Blanks/interferences | Selectivity |
| $CsPbBr_3$ | Cu^{2+} | 0.1 nM | Hexane | Stern-Volmer (3 <i>a</i> /slope) | Hexane blanks; <5% quenching by Na $^+$. Zn $^{2+}$ | >95% |
| $\mathrm{Cs_3Bi_2Br_9}$ | Cu^{2+} | 98.3 nM | Seawater | Linear I ₀ /I fitting | Seawater blanks; \sim 15% quenching by C_2^{2+} $M\alpha^{2+}$ (livend-mitimated) | $\%08\sim$ |
| $\mathrm{CH_3NH_3PbBr_3}$ | Hg^{2+} | 0.124 nM | Organic solvent | I_0/I vs. concentration (3 σ/slope) | Solvent blanks; <5% quenching by 77,2+ Mo2+ | >95% |
| $MASnBr_3$ | Fe^{3+} | $\sim 1 \text{ nM}$ | Aqueous | Time-resolved decay $(3\sigma/\text{slope})$ | Water blanks; ~10% quenching | %06~ |
| ${ m CsPbBr_3@MOF}$ | Cu^{2+} | 1.63 nM | Hexane | Fluorescence quenching plot | by Cr. (Fb1-selective) Hexane blanks; <8% quenching | >92% |
| $CsPbBr_3-CsPb_2Br_5$ | Cd^{2^+} | 1 µM | Wastewater | Stern-Volmer $(3\sigma/\text{slope})$ | by κ , Ca Wastewater blanks; $\sim 20\%$ quenching | \sim 75% |

62 09 29

0-1000 nM 0-1200 nM

0-1000 nM

Linear range

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paired with Au nanoclusters, mitigate matrix effects by using dual-emission ratios, achieving LODs of ~1 nM for Cu²⁺ in aqueous systems with calibration against blank water and <10% interference from Na⁺/K⁺.64

Linear detection range typically spans 10^{-9} to 10^{-3} M, depending on the matrix and PQD type. In organic solvents, CsPbBr₃ detects Cu²⁺ linearly from 0-1200 nM, with high R² (>0.99) in Stern-Volmer plots.⁶² In seawater, Cs₃Bi₂Br₉ maintains linearity from 0-1000 nM but requires ligand passivation to counter matrix interferences. 60 Wastewater matrices narrow the range (e.g., 10-500 nM for Fe³⁺ with MASnBr₃) due to pH and organic matter effects, calibrated via time-resolved decay to isolate analyte-specific quenching.68

To standardize comparisons across studies, Table 3 summarizes LODs, matrices, calibration protocols, blank measurements, interference tests, selectivity metrics, and linear ranges. Organic solvents generally yield lower LODs and wider ranges due to reduced interferences, while aqueous and complex matrices require robust calibration (e.g., matrixmatched blanks) and ligand strategies to maintain performance. These insights guide sensor optimization for specific applications, such as trace metal detection in environmental monitoring.

4.3. Comparison of lead-based and lead-free PODs for heavy metal ion detection

Lead-based PQDs, such as $CsPbX_3$ (X = Cl, Br, I) and CH_3NH_3 -PbX₃, are highly effective for detecting heavy metal ions due to their superior optoelectronic properties, including high photoluminescence quantum yield and narrow emission spectra. These attributes enable ultra-low LODs, often below 10 nM, for ions like Hg2+ and Cu2+. For instance, CH3NH3PbBr3 PQDs achieve an LOD of 0.124 nM for Hg²⁺, with rapid response times (<10 s) and high sensitivity, making them suitable for environmental monitoring.⁵⁹ Similarly, CsPbBr₃ PQDs in organic solvents detect Cu2+ with an LOD of 0.1 nM, leveraging OAm ligands for enhanced specificity.62

The characterization of CsPbBr₃ PQDs, as depicted in Fig. 9, provides a comprehensive analysis of their structural and optical properties.⁶² Panels (a) and (f) present the absorption and PL spectra, respectively, showing a strong absorption peak around 510 nm and a corresponding PL emission peak, indicating the high optical quality of the PQDs dispersed in hexane under daylight and 365 nm UV lamp irradiation. The inset images in (a) visually confirm the uniform dispersion, while panel (b) offers a TEM image with a high-resolution TEM (HRTEM) inset, revealing a lattice spacing of 5.8 Å, consistent with the cubic phase of CsPbBr₃. These structural insights underscore the PQDs' crystallinity and potential for optoelectronic applications. Elemental composition and crystallographic structure are further elucidated in panels (c) and (d). Panel (c) displays the energy-dispersive X-ray spectroscopy (EDS) spectrum with an inset table detailing the atomic percentages (Cs: 20.2%, Pb: 34.83%, Br: 45.15%), confirming the stoichiometric ratio of the PQDs. Panel (d) shows the XRD pattern, matching the PDF # 54-0752 reference for the cubic

phase, which aligns with the HRTEM findings and validates the phase purity of the synthesized CsPbBr₃ PODs. These results highlight the material's compositional integrity and crystalline order, critical for its performance in heavy metal ion detection.

The comparison of CsPbBr₃ PQDs with and without Cu²⁺ ions is illustrated in panels (e) and (f). Panel (e) exhibits absorption spectra of CsPbBr3 PQDs at different Cu2+ concentrations (0, 50, 100 nM), showing a gradual decrease in absorption intensity with increasing Cu2+, indicative of ioninduced quenching. Panel (f) compares the PL spectra of pristine CsPbBr₃ PQDs and those with Cu-oleate, revealing a significant PL intensity drop upon Cu²⁺ addition, with an inset showing elemental ratios post-incubation. This quenching behavior is key to achieving ultra-low LODs, such as 0.1 nM for Cu²⁺, as noted in the context of environmental monitoring applications. Panels (g) and (h) provide additional spectroscopic and kinetic data. Panel (g) presents the EDS spectrum of CsPbBr₃ aggregates with an inset table (Br. 48.35%, Cs. 18.64%, Pb: 31.81%), confirming the elemental composition after Cu²⁺ interaction. Panel (h) displays time-resolved PL decay curves at different Cu2+ concentrations (0, 50, 100 nM), with average lifetimes decreasing from 80.84 ns to 60.92 ns, reflecting enhanced non-radiative recombination due to Cu2+. These kinetic changes correlate with the rapid response times (<10 s) and high sensitivity observed in lead-based PQDs for detecting heavy metal ions like Cu²⁺, reinforcing their efficacy in practical sensing applications.

These systems excel in applications requiring high sensitivity, such as industrial solvent analysis. However, lead-based PQDs face significant challenges due to the toxicity of Pb²⁺, which limits their use in environmentally sensitive applications. Their stability in aqueous media is often poor, necessitating advanced stabilization techniques. For example, CsPbBr₃ PQDs encapsulated in PCN-333(Fe) MOFs achieve an LOD of 1.63 nM for Cu²⁺ with improved stability and a 6.5-fold PL enhancement, suitable for water quality monitoring.78 Encapsulation in ZIF-8 MOFs further extends stability to 15 days in aqueous solutions, with an LOD of 2.64 nM for Cu²⁺.79 Phase transfer methods using OAm also enable aqueous detection of Cu²⁺, though complex synthesis and lead toxicity remain barriers to scalability.61

Lead-free PQDs, such as Cs3Bi2X9 and MASnBr3, offer environmentally friendly alternatives with enhanced stability in aqueous environments, critical for applications like wastewater and seawater analysis. Eu³⁺-doped Cs₃Bi₂Br₉ PQDs detect Cu²⁺ with an LOD of 98.3 nM in seawater, benefiting from high photostability and moisture resistance. 60 Cs3Bi2Cl9 PQDs, passivated with hydroxypropyl chitosan, achieve an LOD of 0.27 μM for Cr⁶⁺ in wastewater, supported by ligand-enhanced sensitivity.71 These lead-free systems are ideal for eco-friendly industrial applications, particularly in marine and environmental monitoring. Despite their environmental advantages, lead-free PQDs typically exhibit lower PLQY (20-50%) and broader emission spectra, leading to higher LODs compared to lead-based systems. For example, MASnBr₃ PQDs with PEI ligands detect Fe³⁺ and Cr⁶⁺ in the nanomolar range but face stability challenges in harsh conditions. 68 CsSnX3 PQDs achieve

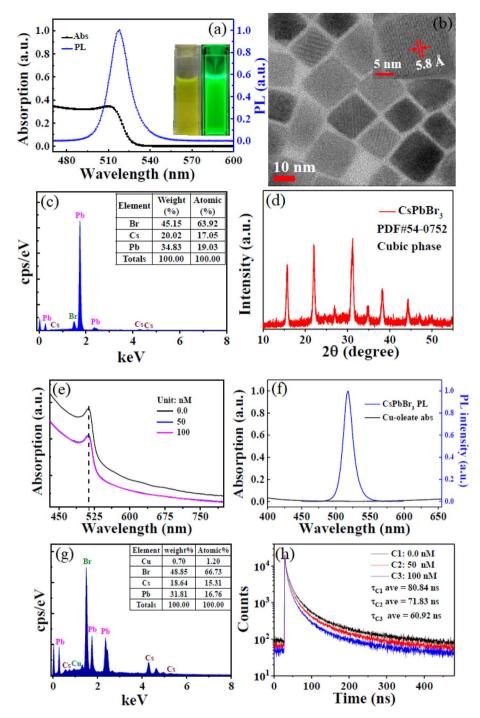


Fig. 9 Characterizations of CsPbBr₃ PQDs: (a) absorption and PL spectra, inset: images under daylight and 365 nm; (b) TEM and HRTEM inset; (c) EDS spectrum, inset: elemental ratios; (d) XRD pattern; (e) absorption spectra with Cu²⁺; (f) PL spectrum with Cu-oleate; (g) EDS of aggregates, inset: ratios; (h) time-resolved PL decay, inset: lifetimes. Adapted with permission from ref. 62. Copyright 2018, Royal Society of Chemistry.

a low LOD of 3.5 nM for Pb2+ in organic solvents, yet Sn2+ oxidation limits their long-term stability.75 These trade-offs make lead-free PQDs less competitive for ultra-sensitive applications but valuable for sustainable contexts.

Single-ion detection systems, such as CH₃NH₃PbBr₃ for Hg²⁺ (ref. 59) and CsSnX₃ for Pb²⁺,⁷⁵ provide high selectivity for specific heavy metal ions, making them suitable for targeted

applications like lubricant quality control. In contrast, multiion sensors, such as Eu3+-doped Cs3Bi2Cl6/Cs3Bi2Cl9 for Cu2+ and Fe³⁺ (LODs of 6.23 µM and 3.6 µM)⁸⁰ or MASnBr₃ for Fe³⁺ and Cr⁶⁺, 68 offer broader applicability but often at the expense of higher LODs. Ratiometric designs, like Mn²⁺-doped CsPbCl₃ for Cu²⁺ (LOD 22.12 nM),⁶⁹ improve specificity in complex matrices through dual-emission signals. Lead-based PQDs are preferred

Table 4 Comparative analysis of lead-based and lead-free PQD sensors for heavy metal ion detection

| РОД куре | Composition | Target ion | TOD | Selectivity | Stability | Application environment | Industrial applications | Advantages | Disadvantages | Ref. |
|------------|--|---|--|---|--|------------------------------------|-----------------------------|--|--|------|
| Lead-based | $\mathrm{CH}_3\mathrm{NH}_3\mathrm{PbBr}_3$ | Hg ²⁺ | 0.124 nM | High (ionic radius similarity with Pb^{2+}) | Moderate (moisture-sensitive) | Organic solvents (toluene) | Environmental monitoring | High PLQY (50.28%), rapid response (<10.8) | Lead toxicity, limited aqueous stability | 29 |
| Lead-based | CsPbX_3 | Cu^{2+} | 2 nM to 2 μM | Moderate (sensitive to transition metals) | Moderate (ligand-dependent) | Organic solvents (hexane) | Lubricants | Tunable bandgap, high sensitivity | Lead toxicity, poor aqueous | 92 |
| Lead-based | CsPbBr_3 | Cu^{2+} | 0.1 nM | High (oleylamine enhances | Moderate (stable in hexane) | Organic solvents (hexane) | Industrial solvents | Ultra-low LOD, fast response (<10 s) | Limited to non- aqueous media | 62 |
| Lead-based | $CsPbBr_3$ | Cu^{2+} | Not specified | High (oleylamine enables | Improved in aqueous media | Aqueous solutions | Water quality monitoring | Aqueous compatibility | Lead toxicity, complex synthesis | 61 |
| Lead-based | CsPbBr ₃ with Au nanoclusters | Cu^{2+} | Not specified | High (ratiometric design) | ${ m High}~({ m SiO_2}$ encapsulation) | Aqueous solutions | Environmental samples | Visual color change, high stability | Complex nanocomposite fabrication | 64 |
| Lead-based | CsPbX ₃ in Zn-MOF | Cu^{2+} | Not specified | High (MOF enhances selectivity) | High (MOF encapsulation) | Aqueous solutions | Industrial wastewater | Enhanced stability, high PLQY | Scalability challenges for MOFs | 81 |
| Lead-based | CsPbBr ₃ in PCN-333(Fe) MOF | Cu^{2+} | 1.63 nM | High (MOF- mediated coordination) | High (6.5-fold PL enhancement) | Aqueous solutions | Environmental monitoring | Ultra-low LOD, enhanced PL | Lead toxicity, MOF synthesis | 78 |
| Lead-based | ${ m CsPbBr}_3$ @BBA | Cu^{2+} | 0.8 µM | Moderate (ligand-mediated) | High (water- dispersible) | Aqueous | Food safety | Water compatibility, high stability | Moderate LOD, | 77 |
| Lead-based | CsPbBr ₃ in ZIF-8 MOF | Cu^{2+} | 2.64 nM | High (MOF enhances | High (15 day stability in water) | Aqueous solutions | Water quality monitoring | Ultra-low LOD, long-term stability | Lead toxicity, complex MOF | 79 |
| Lead-based | CsPbBr ₃ –CsPb ₂ Br ₅ with APTES | Fe^{3+} | 10 µМ | High (APTES reduces non-specific interactions) | High (APTES passivation) | Aqueous solutions | Industrial effluents | Fast response (8 s), high stability | Moderate LOD, lead toxicity | 29 |
| Lead-based | CsPbBr ₃ –CsPb ₂ Br ₅ with ammonia hydroxide | Cd^{2+} | 1 μM | Moderate (ammonia hydroxide enhances | Moderate (aqueous compatibility) | Aqueous solutions | Industrial effluents | Improved aqueous detection | Moderate LOD, lead toxicity | 72 |
| Lead-free | $\mathrm{Cs}_3\mathrm{Bi}_2\mathrm{Br}_9\mathrm{:Eu}^{3+}$ | Cu^{2+} | 98.3 nM | High (Eu ³⁺ doping enhances specificity) | High (stable in seawater) | Aqueous solutions (seawater) | Marine monitoring | Lead-free, high photostability | Lower PLQY (42.4%) than lead-based | 09 |
| Lead-free | MASnBr ₃ with PEI | Fe^{3+} , Cr^{6+} | Nanomolar range | High (PEI chelation enhances selectivity) | Moderate (ligand-dependent) | Aqueous and organic solutions | Environmental monitoring | Lead-free, multi-ion detection | Limited stability in harsh | 89 |
| Lead-free | Cs ₃ Bi ₂ Cl ₉ with hydroxypropyl chirosan | Cr^{6+} | 0.27 µM | High (chitosan enhances ion accessibility) | High (aqueous compatibility) | Aqueous solutions (wastewater) | Wastewater treatment | Lead-free, high sensitivity | Moderate LOD compared to lead-based | 71 |
| Lead-free | Cs ₃ Bi ₂ Cl ₆ / Cs ₃ Bi ₂ Cl ₉ :Eu ³⁺ | Cu ²⁺ , Fe ³⁺ | 6.23 μM (Cu ²⁺), 3.6 μM (Fe ³⁺) | Moderate (Eu ³⁺ doping aids selectivity) | High (stable crystal structures) | Aqueous | Environmental monitoring | Lead-free, multi-ion detection | Higher LOD than lead-based | 80 |

for applications demanding ultra-high sensitivity and rapid response, such as industrial solvent monitoring, but require advanced stabilization to overcome toxicity and aqueous instability. Lead-free PQDs excel in eco-friendly applications, particularly in aqueous environments like wastewater treatment, despite their lower sensitivity. Single-ion sensors offer high specificity, while multi-ion and ratiometric sensors provide versatility for complex systems. Future advancements should focus on enhancing the PLQY of lead-free PQDs, improving stability through novel ligands, and integrating computational tools to optimize sensor design for industrial scalability (Table 4).

4.4. Strategies for enhancing sensor performance

Several strategies have been developed to optimize the performance of PQD-based sensors, addressing limitations in stability, sensitivity, and selectivity for heavy metal detection.

- **4.4.1.** Surface passivation and ligand engineering. Surface passivation with tailored ligands enhances stability and selectivity. Hydroxypropyl chitosan-passivated $Cs_3Bi_2Cl_9$ PQDs improve selectivity for Cr^{6+} by facilitating ion coordination, achieving an LOD of 0.27 μ M in aqueous media. APTES-coated $CsPbBr_3-CsPb_2Br_5$ PQDs enhance Fe^{3+} detection by reducing non-specific interactions, with an LOD of 10^{-5} M and a response time of 8 s. Poly(ethylenimine) ligands in MASnBr_3 PQDs introduce chelating groups, improving Fe^{3+} selectivity through stable complex formation, critical for industrial fluid analysis. These ligand designs optimize ion accessibility while maintaining PQD stability.
- **4.4.2. Encapsulation in stable matrices.** Encapsulation in robust matrices, such as metal-organic frameworks (MOFs) or silica, protects PQDs from environmental degradation while maintaining analyte accessibility. CsPbBr₃ PQDs encapsulated in ZIF-8 MOFs achieve an LOD of 2.64 nM for Cu²⁺ and retain stability in water for 15 days, suitable for industrial wastewater monitoring.⁷⁹ PCN-333(Fe) MOF encapsulation enhances CsPbBr₃ stability, achieving an LOD of 1.63 nM for Cu²⁺ with a 6.5-fold PL enhancement.⁷⁸ Silica-encapsulated CsPbBr₃@-SiO₂ systems support ratiometric Cu²⁺ detection with high stability in aqueous environments, ideal for industrial applications.⁶⁴ These matrices balance protection and sensitivity, enabling robust sensor performance.⁸¹
- **4.4.3. Doping with metal ions.** Doping with metal ions like Mn²⁺ or Eu³⁺ enhances PL stability and enables advanced sensing modalities. Mn²⁺-doped CsPbCl₃ PQDs exhibit dual emission for ratiometric Cu²⁺ detection, achieving an LOD of 22.12 nM with a PLQY of 52.48%. ¹⁹ Eu³⁺-doped Cs₃Bi₂Br₉ PQDs detect Cu²⁺ and Fe³⁺ with LODs of 6.23 μ M and 3.6 μ M, respectively, benefiting from improved photostability and polychromatic emission. ⁸⁰ Doping introduces additional emission bands, enhancing detection accuracy in industrial settings. ⁶⁶
- **4.4.4.** Ratiometric and visual sensing approaches. Ratiometric sensing improves accuracy by using dual-emission signals to mitigate environmental noise. $CsPbBr_3$ PQDs combined with Au nanoclusters enable ratiometric Cu^{2+}

detection, with visual color changes enhancing usability in industrial quality control.⁶⁴ Cs₃Bi₂Cl₉ PQDs facilitate visual detection of Cr⁶⁺ at 0.27 μ M through distinct PL changes, suitable for on-site industrial monitoring.⁷¹

4.5. Industrial applications of PQD-based nanosensors for heavy metal detection

PQD-based nanosensors have demonstrated significant potential in industrial settings for detecting heavy metal ions in various matrices, ensuring quality control and preventing contamination. These applications are particularly relevant in industries such as chemical processing, manufacturing, and waste management, where heavy metal pollutants pose significant risks to product integrity and environmental safety. CsSnX₃ PQDs are highly effective for detecting Pb2+ in lubricants and organic solutions, achieving an LOD of 3.5 nM through optimized synthesis methods that enhance PL stability.75 Their design leverages the high compatibility of lead-free PQDs with non-aqueous media, making them ideal for monitoring industrial fluids used in machinery and automotive applications. The rapid response time (<15 s) and high selectivity over competing ions like Zn²⁺ or Ca²⁺ ensure reliable detection of trace Pb²⁺, which is critical for maintaining lubricant quality and preventing equipment corrosion. 75 The robustness of CsSnX3 PQDs in organic solvents, combined with their eco-friendly composition, positions them as a sustainable solution for industrial monitoring.

CsPbX₃ PQDs are employed to detect Cu²⁺ in organic solvents used in chemical processing, achieving a detection range of 2 \times 10^{-9} to 2×10^{-6} M. Their high PLQY (up to 90%) and sensitivity make them suitable for monitoring trace Cu2+ in solvents used for catalysis or material synthesis, where even low concentrations can affect product quality.76 For instance, Cu2+ contamination in organic solvents can catalyze unwanted side reactions, and PQD-based nanosensors provide a rapid and precise method to ensure solvent purity. The use of OAm ligands in these systems enhances selectivity by facilitating Cu2+ coordination, minimizing interference from other metal ions.62 In industrial wastewater treatment, Cs₃Bi₂Br₉ PQDs are utilized to detect Cu2+ with an LOD of 98.3 nM, leveraging their high photostability and resistance to aqueous degradation. 60 These lead-free PQDs are particularly valuable in monitoring effluent streams from metal plating or electronics manufacturing, where Cu²⁺ contamination is a common concern. Their ability to function in aqueous environments without significant PL degradation makes them suitable for continuous monitoring systems, ensuring compliance with environmental regulations.60 Additionally, hydroxypropyl chitosan-passivated Cs3- Bi_2Cl_9 PQDs detect Cr^{6+} in wastewater with an LOD of 0.27 μ M, offering a visual detection method that is practical for on-site industrial applications.71 The distinct PL changes induced by Cr⁶⁺ enable rapid identification of contamination, facilitating timely remediation.

 $CsPbBr_3-CsPb_2Br_5$ PQDs, modified with ammonia hydroxide, are applied to detect Cd^{2+} in industrial effluents, achieving an LOD of 10^{-6} M. These sensors are designed for

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wastewater from industries like battery manufacturing, where Cd²⁺ is a prevalent pollutant. The ammonia hydroxide modification enhances surface accessibility, improving sensitivity in aqueous media, which is critical for real-time monitoring of industrial discharge.72 Similarly, APTES-coated CsPbBr3-CsPb₂Br₅ PQDs detect Fe³⁺ with an LOD of 10⁻⁵ M, suitable for monitoring iron contamination in industrial fluids used in steel production or chemical synthesis. 67 The high stability of APTES coatings ensures reliable performance under harsh industrial conditions. Ratiometric sensing systems, such as CsPbBr₃ PQDs paired with Au nanoclusters, are employed for Cu²⁺ detection in industrial solvents, providing visual color changes that enhance usability for on-site quality control.⁶⁴ These systems are particularly valuable in industries requiring rapid, non-invasive detection methods, such as petrochemical processing, where Cu²⁺ contamination can degrade product performance. The dual-emission signals improve accuracy by mitigating environmental noise, ensuring precise quantification.64

5. Comparative analysis with other sensing materials for heavy metal ion detection

This section evaluates PQDs against alternative sensing materials, including carbon quantum dots (CQDs), graphene quantum dots (GQDs), traditional semiconductor quantum dots (e.g., CdS, CdTe, ZnS-based), and metal-organic frameworks (MOFs), for detecting heavy metal ions. The comparison emphasizes performance metrics such as limit of detection (LOD), selectivity, PLQY, synthesis complexity, and applicability in environmental and industrial contexts. By benchmarking PQDs against these materials, their unique strengths, limitations, and synergistic potential are highlighted, ensuring a distinct perspective from prior mechanistic, design, and application discussions.

5.1. Comparative analysis of PQDs and nanomaterials for heavy metal sensing

Detecting heavy metal ions in environmental, industrial, and biological matrices requires materials with high sensitivity, selectivity, and practical applicability. PQDs, CQDs, GQDs, semiconductor quantum dots, and MOFs each offer distinct properties for this purpose. CQDs, derived from carbon-based precursors, feature surface functional groups (e.g., NH₂, COOH) that enhance metal ion interactions, making them ecofriendly and suitable for aqueous environments.82,83 GQDs, a subset of CQDs, leverage surface plasmon resonance (SPR) for detection, offering high stability in water.84 Semiconductor QDs like CdS and CdTe provide tunable optical properties but are limited by toxicity.85,86 MOFs, often paired with luminescent nanomaterials, enhance stability and selectivity through their porous structures. 78,87 Table 5 provides a comprehensive comparison of these materials' performance metrics, including LOD and PLOY, across various detection environments.

CQDs, synthesized *via* hydrothermal or microwave methods, typically exhibit PLQY of 20–50% and LODs of 5–35.8 nM for

ions like Pb2+ and Hg2+ in water samples.82,93 Their broad emission spectra limit sensitivity compared to PQDs. GQDs, with similar PLQY (20-30%), achieve LODs of 16.32 nM for Hg²⁺ using SPR, but their pyrolysis-based synthesis is less scalable.84 Semiconductor quantum dots, such as CdTe, offer higher PLQY (50-60%) and LODs of 50-179.5 nM, but cadmium toxicity and complex synthesis hinder their use.85,98 MOFs, while not inherently luminescent, enhance the performance of embedded fluorophores, though their fabrication is intricate.78,87 PQDs combine high PLQY, narrow emission, and moderate synthesis complexity, making them versatile for both organic and aqueous applications. The choice of material depends on the application context. CQDs and GQDs excel in eco-friendly aqueous detection, while semiconductor QDs suit highsensitivity needs despite toxicity concerns. MOFs enhance stability but require complex integration. PQDs offer a balanced profile of sensitivity, tunability, and adaptability, positioning them as a leading platform for heavy metal detection across diverse matrices.

5.2. Advantages of PQDs for heavy metal ion detection

PQDs, particularly lead-based variants like CsPbX3 and CH3-NH₃PbX₃, exhibit exceptional optical properties, including high PLQY and narrow emission spectra, enabling ultra-low LODs (e.g., 0.124 nM for Hg2+ with CH3NH3PbBr3).59 This optical precision supports ratiometric sensing, as seen in Mn²⁺-doped CsPbCl₃ (LOD 22.12 nM for Cu²⁺), enhancing accuracy in complex matrices. 69 Their tunable bandgap, adjusted via size or halide composition, allows tailored detection, such as CsPbBr₃ achieving an LOD of 0.1 nM for Cu2+ in hexane through OAm coordination.62 Lead-free PQDs, like Cs3Bi2Br9:Eu3+, offer comparable performance (LOD 98.3 nM for Cu²⁺) with reduced toxicity, ideal for aqueous environments like seawater.89 Their rapid response times (<10 s) stem from efficient quenching mechanisms, such as cation exchange for Hg2+ detection with CH₃NH₃PbBr₃, outperforming CQDs' slower responses.^{59,82} Integration into MOFs, as with CsPbBr₃@PCN-333(Fe) (LOD 1.63 nM for Cu²⁺), enhances aqueous stability, making PQDs suitable for industrial wastewater monitoring.78 Table 5 highlights these advantages, showing PQDs' superior LODs and versatility compared to other materials. PQDs' compatibility with organic solvents (e.g., hexane, lubricants) and aqueous media via phase-transfer techniques (e.g., oleylamine-modified CsPbBr₃, LOD 0.5 nM for Cu²⁺) broadens their industrial applicability.61 In contrast, GQDs are limited to aqueous systems, and CdS QDs struggle with selectivity in complex matrices.84,98 The combination of high PLQY, tunability, and rapid response positions PQDs as a leading choice for highperformance heavy metal detection.

5.3. Limitations of alternative sensing materials

CQDs, despite their eco-friendliness, are constrained by lower PLQY (20–50%) and broader emission spectra, reducing sensitivity. For example, CQDs from blue crab shells achieve an LOD of 5 nM for Pb²⁺, but their PLQY (50%) is lower than CsPbBr₃'s (81%).^{62,83} Their need for complex surface functionalization to

Table 5 Comparative performance of PQDs and other sensing materials for heavy metal ion detection

| Material Tanget ion LOD Selectivity PP CH,NH,PbBr, PQD Hg,²* 0.124 nM High (cation exchange) 5.0 CH,NH,PbBr, QMOP-5 Cu²* 0.5 nM High (cation exchange) 5.0 CSPbBr,PMMA FM Cu²* 10 -¹-¹ M High (EREP-based) 88 CSPbBr,PMMA FM Cu²* 2 nM Moderate (transition metal 79 88 CSPbBr, PQD Cu²* 2 nM High (leylamine coordination) 81 CSPbBr, PQD Cu²* 0.1 nM High (leylamine coordination) 42 CSPBBr, PQD Cu²* 0.1 nM High (leylamine coordination) 42 CSBBr, PQD Cu²* 0.1 nM High (leylamine coordination) 42 CSBBr, PQD Cu²* 0.1 nM High (leylamine coordination) 42 CSBBr, PQD Cu²* 0.2 nM High (leylamine coordination) 42 CSBB, Cla, PQD Cu²* 0.2 nM High (leylamine coordination) 42 CSBB, Cla, PQD Cu²* 0.2 nM High (leylamine coordination) | | | | | | |
|---|---|---------------------------|--------------|---|---|----------|
| F-5 Cu ²⁺ Cu ²⁺ 0.124 nM High (ration exchange) Cu ²⁺ Cu ²⁺ 0.5 nM High (MOF-mediated coordination) Cu ²⁺ Yb ³⁺ 2 nM High (MOF-mediated coordination) Cu ²⁺ Cu ²⁺ 2 nM Moderate (transition metal sensitivity) Cu ²⁺ Cu ²⁺ 0.1 nM High (pleylamine coordination) Cu ²⁺ Fe ³⁺ Cr ⁶⁺ 1 nM High (phase transfer elimanes access) Cu ²⁺ Fe ³⁺ 0.5 nM High (phase transfer elimanes access) Cu ²⁺ Fe ³⁺ 0.5 nM High (phase transfer elimanes access) Cu ²⁺ Fe ³⁺ 0.5 nM High (phase transfer elimanes access) Pb ³⁺ Cr ⁶⁺ 1 nM High (phase transfer elimanes access) Cu ²⁺ Fe ³⁺ 6.2 nM High (pand-enhanced elimanes) Se Louin (Igand-enhanced elimanes) 3.5 nM High (MoF enhances elimanes) Fe Cu ²⁺ Cu ²⁺ 3.5 nM High (MoF enhances elimanes) QD Cd ²⁺ M 1.63 nM High (MoF enhances elimanes) QD Cd ²⁺ High (MoF enhances) 10 μM High (MoF enhances) Co ²⁺ Cr ²⁺ Hg ²⁺ 10 nM High (MoF enhan | TOD | | PLQY (%) | Synthesis complexity | Application environment | Ref. |
| Cu ²⁺ C | M | exchange) ediated | 50.28 80 | Moderate (LARP) High (MOF encapsulation) | Organic solvents (toluene) Aqueous solutions | 59 87 |
| Cu ²⁺ , Yb ³⁺ 2 nM Moderate (transition metal sensitivity) Cu ²⁺ 0.1 nM High (lobeylamine coordination) Cu ²⁺ Cu ²⁺ 98.3 nM High (loping specificity) Fe ³⁺ , Cr ⁶⁺ 1 nM High (loping specificity) Cu ²⁺ 52.12 nM High (loping specificity) Cu ²⁺ 6.23 μM (Cu ²⁺), Moderate (doping aids coordination) Cu ²⁺ 6.23 μM (Fe ³⁺) Moderate (doping aids coordination) F Cu ²⁺ 6.23 μM (Fe ³⁺) Selectivity Cu ²⁺ 7.5 nM Specificity Cu ²⁺ 7.5 nM Specificity Cu ²⁺ 7.5 nM High (ligand-mediated specificity) Cu ²⁺ 7.5 nM Specificity Cu ²⁺ 7.5 nM Specificity Cu ²⁺ 7.5 nM High (MOF enhances coordination) F Cu ²⁺ 1.μM Moderate (loping aids specificity) Cu ²⁺ 7.5 nM Specificity Cu ²⁺ 7.5 nM Specificity Cu ²⁺ 7.5 nM High (MOF enhances access) ts Pb ²⁺ Ni ²⁺ 10 nM Moderate (colorimetric changes) Ag ²⁺ 8.3 nM (Fb ²⁺), Moderate (colorimetric changes) Ni ²⁺ 10 nM Moderate (colorimetric changes) Ni ²⁺ 10 nM Moderate (Solvacancy interactions) Ni ²⁺ 10 nM Moderate (Solvimetric changes) | | | 82 | High (electrospinning) | Aqueous/organic (ethanol | 88 |
| Cu ²⁺ 0.1 nM High (oleylamine coordination) Cu ²⁺ Cr ⁶⁺ 98.3 nM High (phase transfer enhances access) Cu ²⁺ Cr ⁶⁺ 1 nM High (phase transfer enhances) Cu ²⁺ Fe ³⁺ , Cr ⁶⁺ 1 nM High (PEI chelation) Cu ²⁺ Fe ³⁺ 22.12 nM High (PEI chelation) Cu ²⁺ Fe ³⁺ 6.23 μM (Cu ²⁺), Moderate (doping aids coordination) F Cu ²⁺ Fe ³⁺ 6.23 μM (Cu ²⁺), Moderate (doping aids 3.5 nM Specificity) Pb ²⁺ 3.5 nM High (ligand-mediated specificity) Cu ²⁺ Cu ²⁺ 1.63 nM High (MOF-mediated specificity) QD Cd ²⁺ 10 μM High (MOF-mediated specificity) QD Cd ²⁺ 10 μM High (MOF-mediated specificity) As ³⁺ Pb ²⁺ Ni ²⁺ 6 nM Moderate (colorimetric chances access) Ag ⁴ 8.2 nM High (Su ³ Sensitivity, adsorption) Pb ²⁺ Ag ⁴ 3.83 nM (Pb ²⁺), Anderate (colorimetric changes) Ni ²⁺ 10 nM Moderate (Solorimetric changes) Ni ²⁺ 10 nM Moderate (Solorimetric changes) Ni ²⁺ High (Hoe ²⁺) High (Hoerscence changes) Ni ²⁺ High (Hoe ²⁺) High (Hoe ²⁺) High (Hoerscence chance) High (Inducescence coccupied to the changes) Ni ²⁺ High (Mof-mediate (Sn vacancy interactions)) High (Inducescence coccupied to the changes) High (Mof-mediate (Sn vacancy interactions)) | 2 nM | | 6 | Moderate (hot-injection) | Organic solvents (hexane) | 92 |
| Cu ²⁺ C | | | 1. | Moderate (hot-injection) | Organic solvents (hexane) | 62 |
| Cu ²⁺ Cr ⁶⁺ Cr ⁶⁺ Cu ²⁺ C | | sfer | 0. | High (phase transfer) | Aqueous solutions | 61 |
| Cu ²⁺ Cu ²⁺ Cu ²⁺ High (ratiometric dual emission) Cu ²⁺ , Fe ³⁺ 6.23 μM (Cu ²⁺), Moderate (doping aids 3.5 μM (Fe ³⁺) selectivity) Pb ²⁺ 3.5 μM (Fe ³⁺) High (ligand-enhanced coordination) Cu ²⁺ Cu ²⁺ 1.63 μM (Fe ³⁺) High (ligand-mediated specificity) Cu ²⁺ Cu ²⁺ 1.63 μM High (MOF-mediated coordination) F Cu ²⁺ Cu ²⁺ 1.63 μM High (MOF-mediated specificity) QD Fe ³⁺ 10 μM High (MOF enhances specificity) QD Cd ²⁺ (10 μM High (APTES reduces non-specificity) Co ²⁺ Cu ³⁺ 1 μM Moderate (Iluorescence coordination) Co ²⁺ Cu ³⁺ 10 μM High (APTES reduces non-specificity) As ³⁺ Pb ³⁺ Ni ²⁺ 6 nM Moderate (colorimetric 9 μM (Ag ²) Moderate (solorimetric 9 μM (Ag ²) Moderate (solorimetric 9 μM (Ag ²) High (fluorescence changes) Ni ²⁺ 10 nM Moderate (Sn vacancy interactions) | 98.3 nM 1 nM | city) | 42.4 14.6 | Moderate (hydrothermal) Moderate (LARP) | Aqueous (seawater) Aqueous/organic solutions | 89 |
| Cr ⁶⁺ Cu ²⁺ , Fe ³⁺ Cu ²⁺ , Fe ³⁺ Cu ²⁺ , Fe ³⁺ Cu ²⁺ Fe ³⁺ Cu ²⁺ Cu ²⁺ Fe ³⁺ Cu ²⁺ | | | 52.48 | Moderate (hot-injection) | Aqueous solutions | 69 |
| Cu ²⁺ , Fe ³⁺ 6.23 μM (Cu ²⁺), Moderate (doping aids 3.5 μM (Fe ³⁺) Figh (ligand-mediated specificity) Pb ²⁺ 3.5 μM (Fe ³⁺) High (ligand-mediated specificity) Cu ²⁺ 1.63 nM High (MOF-mediated coordination) E Cu ²⁺ 2.64 nM High (MOF enhances specificity) QD Fe ³⁺ 10 μM High (MOF enhances specificity) QD Cd ²⁺ Hg ²⁺ , Ni ²⁺ , Mn ²⁺ , 6 nM Moderate (luorescence co ²⁺ Cg ²⁺ , Hg ²⁺ , Ni ²⁺ , 10 nM High (×80% sensitivity, adsorption) Pb ²⁺ Ag ⁺ 3.83 nM (Pb ²⁺), Moderate (colorimetric changes) Ni ²⁺ 10 nM Moderate (colorimetric changes) Ni ²⁺ 10 nM Moderate (solorimetric changes) Ni ²⁺ 10 nM Moderate (solorimetric changes) Ni ²⁺ 10 nM High (ligorescence fag nations) High (fluorescence fag nations) High (fluorescence fag nations) | | | ιĊ | Moderate (hydrothermal) | Aqueous (wastewater) | 71 |
| Pb ²⁺ 3.5 nM High (ligand-mediated specificity) ?e) Cu ²⁺ 1.63 nM High (lMOF-mediated coordination) F Cu ²⁺ 2.64 nM High (MOF-mediated coordination) QD Fe ³⁺ 10 μM High (MOF-mediated coordination) QD Fe ³⁺ 10 μM High (MOF enhances specificity) QD Cd ²⁺ 1 μM Moderate (MI-QH enhances specificity) QD Cd ²⁺ 1 μM Moderate (Increscence quenching) AS ³⁺ Pb ²⁺ 10 nM High (>80% sensitivity, adsorption) Pb ²⁺ Ag ⁴ 3.83 nM (Pb ²⁺), Moderate (colorimetric changes) Ag ⁺ Ag ⁺ 8.2 nM Moderate (colorimetric changes) Ni ²⁺ 10 nM Moderate (sol vacancy interactions) Ni ²⁺ 10 nM Moderate (Sn vacancy interactions) As ³⁺ High (fluorescence for sn M (Ho ²⁺), High (fluorescence for sn M (Ho ²⁺) High (fluorescence for sn M (Ho ²⁺) | 6.23 μ M (Cu ²⁺), | ping aids | ιĊ | Moderate (hydrothermal) | Aqueous solutions | 80 |
| ξe) Cu ²⁺ 1.63 nM High (MOF-mediated coordination) F Cu ²⁺ 2.64 nM High (MOF enhances specificity) QD Fe ³⁺ 10 μM High (APTES reduces nonspecificity) QD Cd ²⁺ 1 μM Moderate (NH ₄ OH enhances access) κs Pb ²⁺ , Ni ²⁺ , Mn ²⁺ , 6 nM Moderate (INt ₄ OH enhances access) κs Cd ²⁺ , Hg ²⁺ , Ni ²⁺ , 10 nM Moderate (fluorescence quenching) Cd ²⁺ , Hg ²⁺ , Ni ²⁺ , Ni ²⁺ 10 nM High (>80% sensitivity, adsorption) Pb ²⁺ , Ag ⁺ 3.83 nM (Pb ²⁺), Moderate (colorimetric changes) Ag ⁺ 8.2 nM Moderate (colorimetric changes) Ni ²⁺ 10 nM Moderate (colorimetric changes) Ni ²⁺ 10 nM Moderate (colorimetric changes) Ni ²⁺ 10 nM Moderate (sn vacancy interactions) S Fe ³⁺ , Hg ²⁺ 35.8 nM (He ²⁺), High (fluorescence flags) | | ıd-mediated | ιύ | Moderate (hot-injection) | Organic solvents | 75 |
| F Cu ²⁺ 2.64 nM High (MOF enhances specificity) QD Fe ³⁺ 10 μM High (APTES reduces non-specificity) QD Cd ²⁺ 1 μM Moderate (NH ₄ OH enhances access) rs Pb ²⁺ , Ni ²⁺ , Mn ²⁺ , 6 nM Moderate (Iluorescence quenching) Cd ²⁺ , Hg ²⁺ , Ni ²⁺ , 10 nM High (>80% sensitivity, adsorption) Pb ²⁺ , Ag ⁺ 3.83 nM (Pb ²⁺), Moderate (colorimetric changes) Ni ²⁺ 10 nM Moderate (colorimetric changes) Ni ²⁺ 10 nM Moderate (sn vacancy interactions) S Fe ³⁺ , Hg ²⁺ 35.8 nM (Fe ³⁺), High (fluorescence for sum of the chinchine) | | | ເວ | High (MOF encapsulation) | Aqueous solutions | 78 |
| QD Fe ³⁺ 10 μΜ High (APTES reduces nonspecificity) QD Cd ²⁺ 1 μΜ Moderate (NH ₄ OH enhances access) its Pb ²⁺ , Mi ²⁺ , Mn ²⁺ , 6 nM Moderate (fluorescence quenching) Cd ²⁺ , Hg ²⁺ , Ni ²⁺ , 10 nM High (>80% sensitivity, adsorption) Pb ²⁺ , Ag ⁺ 3.83 nM (Pb ²⁺), Moderate (colorimetric changes) Ag ⁺ 8.2 nM Moderate (colorimetric changes) Ni ²⁺ 10 nM Moderate (sol vacancy interactions) S Fe ³⁺ , Hg ²⁺ 35.8 nM (Fe ³⁺), High (fluorescence cherchine) | | | 4. | High (MOF encapsulation) | Aqueous solutions | 79 |
| QD Cd²+ 1 μΜ Moderate (NH₄OH enhances access) its Pb²+, Ni²+, Mn²+, 6 nM Moderate (fluorescence quenching) Cd²+, Hg²+, Ni²+, 10 nM High (>80% sensitivity, adsorption) Pb²+, Ag* 3.83 nM (Pb²+), Moderate (colorimetric changes) Ag* 8.2 nM Moderate (colorimetric changes) Ni²+ 10 nM Moderate (colorimetric changes) Ni²+ 10 nM Moderate (sn vacancy interactions) S Fe³+, Hg²+ 35.8 nM (Fe³+) High (fluorescence cuenchine) | | ES reduces non- | ī. | Moderate (hot-injection) | Aqueous (industrial effluents) | 29 |
| ts Pb ²⁺ , Ni ²⁺ , Mn ²⁺ , 6 nM Moderate (fluorescence Co ²⁺ , Cr ³⁺ Cd ²⁺ , Hg ²⁺ , Ni ²⁺ , 10 nM High (>80% sensitivity, As ³⁺ , Pb ²⁺ Pb ²⁺ , Ag ⁺ Sum (Fb ²⁺), Moderate (colorimetric 9 μM (Ag ⁺) Moderate (colorimetric changes) Ni ²⁺ Ni ²⁺ Ni ²⁺ Ni ²⁺ 10 nM Moderate (sn vacancy interactions) Sum (He ³⁺), High (fluorescence 6.8 nM (Ho ²⁺) Guenchine) | 1 μМ | H | 83 | Moderate (hot-injection) | Aqueous (industrial effluents) | 72 |
| Cd ²⁺ , Hg ²⁺ , Ni ²⁺ , 10 nM High (>80% sensitivity, As ³⁺ , Pb ²⁺ 3.83 nM (Pb ²⁺), Moderate (colorimetric 9 μM (Ag ⁺) (Ananges) (A | 6 nM | scence | 0 | High (thin film deposition) | Aqueous (real water samples) | 82 |
| Pb ²⁺ , Ag ⁺ 3.83 nM (Pb ²⁺), Moderate (colorimetric 9 μM (Ag ⁺) changes) Ag ⁺ 8.2 nM Moderate (colorimetric changes) Ni ²⁺ 10 nM Moderate (Sn vacancy interactions) S Fe ³⁺ , Hg ²⁺ 35.8 nM (Fe ³⁺), High (fluorescence 6.8 nM (Ho ²⁺) cuenchine) | 10 nM | | 0 | High (DFT-based design) | Aqueous (wastewater) | 06 |
| Ag* (1.5) | 3.83 nM (Pb ²⁺), 9 IM (Ao ⁺) | olorimetric | 0 | Moderate (hydrothermal) | Aqueous solutions | 91 |
| Ni^{2+} 10 nM Moderate (Sn vacancy interactions) Solve Fe^{3+} , Hg^{2+} 35.8 nM (Fe^{3+}), High (fluorescence 6.8 nM ($H\phi^{2+}$) an enchine) | | colorimetric | 0 | Moderate (hydrothermal) | Aqueous solutions | 91 |
| Fe ³⁺ , Hg ²⁺ 35.8 nM (Fe ³⁺), High (fluorescence 6.8 nM (Hg ²⁺) anenchine) | | | ιū | Moderate (hydrolysis) | Aqueous (deionized, reclaimed. sea) | 92 |
| | 35.8 nM (Fe ³⁺), 6.8 nM (H9 ²⁺) | | O. | High (oxidation) | Aqueous (pond, sea, well) | 93 |
| te crab shells) Pb^{2+} , Hg^{2+} 5 nM | S nM | н ₂ , соон, он | 0 | Moderate (microwave) | Aqueous (aquaculture) | 83 |

Table 5 (Contd.)

| | | | | | | | ĺ |
|--|---|--|---|---------|--------------------------------|------------------------------------|------|
| Material | Target ion | LOD | Selectivity | PLQY(%) | Synthesis complexity | Application environment | Ref. |
| Graphene QDs (S.N-GODs) | Hg^{2^+} | 16.32 nM | High (SPR-based) | 30 | Moderate (pyrolysis) | Aqueous (tap, river) | 84 |
| CdS QDs (DMSO-capped) | $Cu^{2^+}, Hg^{2^+}, Pb^{2^+}$ | 179.5 nM (Cu ²⁺), 58 μ M (Hg ²⁺), 60 μ M (Pb ²⁺) | High (colorimetric) | 30 | Moderate (chemical synthesis) | Aqueous (polluted samples) | 82 |
| CdTe QDs (TGA, GSH, L-cyst.) | ${ m Cr}^{3+}, { m pb}^{2+}$ | 100 nM | High (turn-on for Cr^{3+} , Pb^{2+}) | 28 | Moderate (aqueous phase) | Aqueous/organic solutions | 94 |
| CdTe QDs (TGA-capped) | Cu^{2+} | 50 nM | High (1:1 complexation) | 09 | Moderate (one-step aqueous) | Aqueous solutions | 95 |
| CdTe/CdS/ZnS QDs | ${ m Hg}^{2+}$ | 16.32 nM | High (fluorescence quenching) | 59 | High (multi-step aqueous) | Aqueous (tap, river, agricultural) | 96 |
| CdSe/ZnS QDs (TGA-capped) | Cr^{3+} , Cu^{2+} | 100 nM | High (turn-off fluorescence) | 09 | Moderate (aqueous phase) | Aqueous solutions | 26 |
| CdS QDs (GSH-capped) | $Cu^{2+}, Hg^{2+}, Mg^{2+}$ | 100 nM | Moderate (fluorescence quenching) | 29 | Moderate (one-pot) | Foods (aqueous media) | 86 |
| CuInS2/ZnS QDs (GSH-capped) | Cu^{2+} | 63 nM | High (aggregation-based quenching) | 55 | Moderate (aqueous) | Aqueous solutions | 66 |
| Co/Ag@ZnS QDs | ${ m Hg}^{2+}$ | 130 nM | High (fluorescence quenching) | 27.6 | Moderate (co-precipitation) | Aqueous (real water samples) | 100 |
| $ m g	ext{-}C_3N_4/CeO_2$ heterostructure | Cu^{2+}, Hg^{2+}, Ag^{+} | 26.2 μM, 17.5 μM, 14.9 μM | Moderate (binding affinity) | 10 | High (co-precipitation) | Aqueous solutions | 101 |
| Starch-capped CdS QD | ${\rm Hg}^{2+}$, ${\rm Cu}^{2+}$ | 100 nM | High (cation exchange reaction) | 30 | Moderate (aqueous) | Aqueous solutions | 98 |

enhance selectivity increases synthesis complexity. 91,93 GQDs, with PLQY of 20–30%, achieve an LOD of 16.32 nM for Hg²⁺, significantly higher than PQDs' 0.124 nM, and their pyrolysis synthesis is less scalable. 59,84 Semiconductor QDs like CdS and CdTe offer PLQY of 50–60% and LODs of 50–179.5 nM, but cadmium toxicity limits their environmental applications. 94–98 Their multi-step synthesis is more complex than PQD hotinjection or LARP methods, and selectivity often requires multiple capping agents. 94,97 MOFs, while enhancing stability when paired with PQDs, lack intrinsic luminescence and require intricate fabrication, limiting standalone use. 78,79 Table 5 underscores these limitations, showing higher LODs and synthesis challenges for alternative materials compared to PQDs' superior performance.

5.4. Synergistic approaches combining PQDs with other nanomaterials

Combining PQDs with MOFs, CQDs, or metal nanoclusters creates synergistic systems that enhance detection performance. Encapsulation in MOFs, such as CsPbBr₃@PCN-333(Fe) (LOD 1.63 nM for Cu²⁺) or CsPbBr₃@ZIF-8 (LOD 2.64 nM), improves aqueous stability and analyte accessibility, ideal for wastewater monitoring.^{78,79} These composites leverage MOF porosity and PQD optical properties, overcoming the aqueous instability of lead-based PQDs. Hybrid systems with CQDs or Au

nanoclusters enable ratiometric sensing, as seen with CsPbBr₃ and Au nanoclusters for visual Cu²⁺ detection *via* FRET, enhancing accuracy in industrial solvents.⁶⁴ CsPbBr₃/PMMA fiber membranes achieve an LOD of 10⁻¹⁵ M for Cu²⁺, combining PQD fluorescence with polymer matrix stability.⁸⁸ Doping with Eu³⁺ or Mn²⁺, as in Cs₃Bi₂Br₉:Eu³⁺ (LOD 98.3 nM for Cu²⁺), enhances PLQY and selectivity in aqueous settings.^{69,89} These synergistic approaches address PQD limitations, offering performance superior to standalone CQDs or semiconductor quantum dots.

The provided figure illustrates key optical and energetic properties of Eu^{3+} -doped $Cs_3Bi_2Br_9$ PQDs combined with PeQD. Panel (a) presents the excitation spectra monitored at 446 nm and 620 nm, revealing distinct peaks at 365 nm and broader emissions influenced by Eu^{3+} doping, with emission wavelengths at 446 nm and 620 nm corresponding to transitions from the conduction band to the valence band and specific Eu^{3+} energy levels ($^5D_0 \rightarrow ^7F_j$). This highlights the enhanced PL properties due to Eu^{3+} incorporation, which boosts PLQY and selectivity, as noted for $Cs_3Bi_2Br_9$: Eu^{3+} with an LOD of 98.3 nM for Cu^{2+} . Panel (b) depicts the energy level diagram, showing the alignment of Eu^{3+} levels (5D_0 to 5D_4 and 7F_0 to 7F_6) with the conduction and valence bands of $Cs_3Bi_2Br_9$, facilitating efficient ET and FRET mechanisms that underpin the improved detection performance in hybrid systems. Panels (c) and (d) further

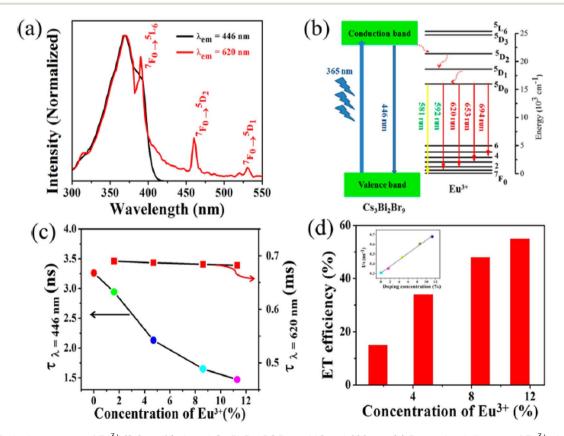


Fig. 10 (a) Excitation spectra of Eu^{3+} (8.6 mol%)-doped $Cs_3Bi_2Br_9$:PQDs at 446 and 620 nm. (b) Energy level diagram of Eu^{3+} -doped $Cs_3Bi_2-Br_9$:PQDs. (c) Time-resolved PL decay at 446 nm and 620 nm ($^5D_0 \rightarrow ^7F_j$) for undoped and Eu^{3+} (1.6–11.3 mol%)-doped samples. (d) Energy transfer efficiency from $Cs_3Bi_2Br_9$:PQDs to Eu^{3+} vs. concentration (inset: 446 nm decay constants). Reprinted with permission from ref. 89. Copyright 2019, American Chemical Society.

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elucidate the concentration-dependent behavior of Eu³⁺ doping. Panel (c) shows the decay time (τ) at 446 nm decreasing from 3.5 ns to 1.5 ns with increasing Eu³⁺ concentration (0-12%), indicating enhanced non-radiative energy transfer to Eu³⁺ ions, as supported by the inset's reverse exciton emission decay constants. Panel (d) quantifies the ET efficiency (η_{ET}) and coefficient (α), peaking at 0.7 and 0.6, respectively, at 12% doping, alongside a bar graph of η_{ET} , which underscores the optimal doping level for maximizing PLQY and sensing accuracy in aqueous environments. These findings reinforce the synergistic potential of Eu³⁺-doped PQDs with nanomaterials like MOFs or CQDs, enhancing stability and detection limits as demonstrated in systems like CsPbBr₃@PCN-333(Fe) and CsPbBr₃/PMMA fiber membranes (Fig. 10).

5.5. Benchmarking PQD performance against established sensors

PQDs consistently outperform alternative sensors in key metrics. For Hg²⁺, CH₃NH₃PbBr₃ achieves an LOD of 0.124 nM, surpassing CdTe/CdS/ZnS (16.32 nM) and GQDs (16.32 nM) due to efficient cation exchange.84,96 For Cu²⁺, CsPbBr₃ reaches an LOD of 0.1 nM, compared to CdS (179.5 nM) and CuInS₂/ZnS (63 nM), leveraging rapid quenching mechanisms.85,99 Lead-free Cs₃Bi₂Cl₉ detects Cr⁶⁺ at 0.27 μM, competitive with CdTe (100 nM), with added eco-friendliness.71,94 PQDs' selectivity, enhanced by tailored ligands and doping, matches or exceeds that of CdTe and CdS, which require complex functionalization. 62,94 Their moderate synthesis complexity (hot-injection, LARP) contrasts with the multi-step processes of CdTe/CdS/ ZnS or GQDs. 59,84 PQDs' versatility across organic and aqueous environments, particularly when integrated with MOFs, positions them as a robust platform for industrial and environmental monitoring, outperforming alternative materials in sensitivity and applicability.

Challenges, future directions, and pathways to industrial adoption

PQDs have emerged as a transformative platform for heavy metal ion detection, offering exceptional sensitivity, tunable optical properties, and versatility across diverse matrices. Despite their promise, several challenges hinder their practical implementation and scalability, particularly in environmental, industrial, and biomedical applications. Addressing these obstacles is essential to fully harness the potential of PQDs for detecting heavy metal ions such as Hg²⁺, Cu²⁺, Cd²⁺, Fe³⁺, Cr⁶⁺, and Pb²⁺. This section delineates the primary challenges associated with PQD-based nanosensors and proposes future directions to overcome these limitations, paving the way for advanced, reliable, and commercially viable detection systems.

6.1. Challenges in PQD-based heavy metal ion detection

6.1.1. Stability in aqueous and humid environments. The instability of PQDs, particularly lead-based variants like CsPbX₃ and CH3NH3PbX3, in aqueous and humid environments remains a significant barrier. Exposure to moisture can degrade

the perovskite lattice, leading to phase transitions or decomposition that diminish PLQY and sensing performance. 59,61 For instance, CH3NH3PbBr3 PQDs exhibit reduced stability due to the volatility of organic cations, limiting their use in aqueous media such as wastewater or biological fluids.59 While encapsulation in matrices like metal-organic frameworks (MOFs) or silica enhances stability, as seen with CsPbBr₃@ZIF-8 (stable for 15 days in water),⁷⁹ these approaches increase synthesis complexity and may compromise analyte accessibility, reducing sensitivity for ions like Cu²⁺ or Cr⁶⁺. 78,79 Lead-free PQDs, such as Cs₃Bi₂X₉, offer improved moisture resistance but often at the cost of lower PLQY (20-50%), impacting detection limits. 60,71 Achieving robust stability without sacrificing optical performance remains a critical challenge for practical applications in industrial effluents and environmental monitoring.

- 6.1.2. Toxicity concerns of lead-based PQDs. The toxicity of lead-based PQDs, such as CsPbX3 and CH3NH3PbX3, poses significant environmental and health risks, particularly in applications involving water quality monitoring or biomedical diagnostics. The release of Pb2+ ions during degradation can contaminate the tested matrix, rendering these PQDs unsuitable for eco-sensitive applications. 59,62 Although lead-free alternatives like Cs3Bi2X9 and CsSnX3 mitigate toxicity concerns, their lower PLQY and stability issues, such as Sn²⁺ oxidation in CsSnX₃, limit their competitiveness.^{68,75} For example, Cs₃Bi₂-Br₉:Eu³⁺ achieves an LOD of 98.3 nM for Cu²⁺ in seawater, but its PLQY (42.4%) is significantly lower than that of CsPbBr₃ (81%).60,62 Balancing toxicity reduction with high sensitivity and stability is a pressing challenge for widespread adoption.
- 6.1.3. Interference from coexisting ions and complex matrices. Selectivity in complex matrices, such as industrial wastewater or biological fluids, is hindered by interference from coexisting ions (e.g., Na⁺, K⁺, Ca²⁺) and organic species. While ligands like OAm or PE enhance selectivity for specific ions like Cu²⁺ or Fe³⁺, non-specific interactions can lead to false positives or reduced sensitivity.62,68 For instance, CsPbBr3 PQDs show high selectivity for Cu2+ in hexane but face challenges in aqueous environments with multiple ions, where LODs increase from 0.1 nM to 0.8 µM.⁷⁷ Ratiometric designs, such as CsPbBr₃ with Au nanoclusters, mitigate some interference through dualemission signals, but their complexity limits scalability.64 Developing sensors that maintain high selectivity in real-world, multi-ion environments is a critical hurdle.
- 6.1.4. Scalability and reproducibility of sensor fabrication. The scalability of PQD synthesis and sensor fabrication remains challenging due to batch-to-batch variations in size, crystallinity, and ligand passivation. Methods like hot-injection yield high-quality PQDs with PLQY > 80%, but their hightemperature, inert-atmosphere requirements limit large-scale production.⁶² Ligand-assisted reprecipitation (LARP) is more scalable but produces PQDs with broader size distributions and lower PLQY (50-70%), affecting reproducibility in sensing applications.68 For example, variations in ligand density can alter ion accessibility, impacting the LOD for Cu²⁺ detection.⁶¹ Additionally, integrating PQDs into stable matrices like MOFs or polymers increases fabrication complexity, posing challenges for cost-effective, industrial-scale production.78,79 Ensuring

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consistent sensor performance across large-scale manufacturing is essential for commercial applications.

6.1.5. Lack of standardization for commercial and regulatory applications. The absence of standardized protocols for PQD-based sensor design, calibration, and validation hinders their regulatory approval and commercial adoption. Variations in synthesis methods, ligand types, and detection conditions lead to inconsistent performance metrics, complicating comparisons across studies. For instance, LODs for Cu²⁺ detection range from 0.1 nM (CsPbBr3 in hexane) to 6.23 µM (Cs₃Bi₂Cl₆:Eu³⁺ in aqueous media), reflecting diverse testing environments and sensor designs. 62,80 Regulatory frameworks for environmental and biomedical applications require standardized testing conditions and safety assessments, particularly for lead-based PODs, which face scrutiny due to toxicity concerns.⁵⁹ Establishing universal standards for PQD-based nanosensors is critical to ensure reliability and compliance in practical settings.

6.2. Future directions for PQD-based sensors

To overcome the aforementioned challenges and advance PQD-based nanosensors for heavy metal ion detection, innovative strategies and interdisciplinary approaches are needed. The following directions outline opportunities to enhance stability, sensitivity, selectivity, and scalability, aligning with the demands of industrial, environmental, and biomedical applications.

6.2.1. Development of stable and eco-friendly lead-free PQDs. Advancing lead-free PQDs, such as Cs₃Bi₂X₉, CsSnX₃, or double perovskites (*e.g.*, Cs₂AgInCl₆), is crucial to address toxicity and stability concerns. Enhancing the PLQY of lead-free PQDs through doping with ions like Eu³⁺ or Mn²⁺ can improve sensitivity, as demonstrated by Eu³⁺-doped Cs₃Bi₂Br₉ (LOD 98.3 nM for Cu²⁺).⁶⁰ Novel synthesis methods, such as microwave-assisted or solvothermal approaches, can improve crystallinity and reduce defects, enhancing PLQY and stability in aqueous environments.⁷¹ Exploring new compositions, such as germanium-based or antimony-based perovskites, could yield environmentally benign PQDs with optical properties comparable to lead-based systems, enabling sustainable applications in wastewater and seawater monitoring.

6.2.2. Advanced encapsulation and surface engineering. Innovative encapsulation strategies can enhance PQD stability without compromising analyte accessibility. Hybrid matrices combining MOFs with polymers or silica, such as CsPbBr₃@-PCN-333(Fe) (LOD 1.63 nM for Cu²⁺), offer robust protection and high sensitivity. Peveloping stimuli-responsive coatings that allow selective analyte penetration could further improve selectivity in complex matrices. Ligand engineering, such as using zwitterionic or multidentate ligands, can enhance water compatibility and ion-specific interactions, as seen with hydroxypropyl chitosan-passivated $Cs_3Bi_2Cl_9$ for Cr^{6+} detection (LOD 0.27 μM). Machine learning-guided ligand design can optimize surface chemistry, predicting ligand–ion interactions to enhance selectivity and sensitivity for ions like Fe³⁺ or Cd²⁺.

6.2.3. Integration with advanced detection platforms. Integrating PQD-based nanosensors with advanced platforms, such as microfluidics or smartphone-based systems, can enhance portability and real-time monitoring capabilities. Microfluidic devices can enable precise control over sample delivery, improving detection consistency in industrial effluents or biological fluids. For example, CsPbBr3-CsPb2Br5 PQDs integrated into microfluidic chips could detect Cd²⁺ with high reproducibility.72 Smartphone-based sensors, leveraging PQD fluorescence for visual or ratiometric detection, offer costeffective solutions for on-site monitoring in industrial settings, as demonstrated by CsPbBr₃-Au nanocluster systems for Cu2+.64 These platforms can democratize access to highsensitivity detection, particularly in resource-limited environments.

6.2.4. Machine learning and computational approaches. Machine learning (ML) and computational modeling, such as DFT and molecular dynamics (MD), can optimize PQD sensor design. ML algorithms can predict optimal PQD compositions and ligand configurations for specific ions, reducing experimental trial-and-error. For instance, DFT studies have elucidated Hg²⁺-induced mid-gap states in CH₃NH₃PbBr₃, guiding sensor optimization.⁵⁹ ML-driven analysis of quenching mechanisms can enhance selectivity by identifying ion-specific interactions in complex matrices, improving performance for multi-ion detection.⁸⁰ Computational simulations can also model ion diffusion kinetics, informing ligand designs that balance stability and sensitivity, critical for detecting low-concentration ions like Pb²⁺ in lubricants.⁷⁵

6.2.5. Standardization and scalable fabrication. Establishing standardized protocols for PQD synthesis, sensor calibration, and performance evaluation is essential for commercial and regulatory acceptance. Developing scalable synthesis methods, such as continuous-flow hot-injection or automated LARP systems, can improve reproducibility and reduce costs. For example, microwave-assisted synthesis offers rapid, uniform nucleation, suitable for large-scale production of Cs₃Bi₂X₉ PQDs.⁷¹ Standardizing performance metrics, such as LOD and linear range, across diverse matrices (*e.g.*, organic solvents, wastewater) will facilitate comparisons and regulatory approval. Collaborative efforts between researchers, industry, and regulatory bodies can establish guidelines for PQD-based sensors, ensuring safety and reliability in applications like industrial wastewater treatment.

6.2.6. Multi-ion and multiplexed detection systems. Developing PQD-based nanosensors capable of detecting multiple heavy metal ions simultaneously will enhance their utility in complex industrial and environmental matrices. Multi-ion sensors, such as Eu^{3+} -doped $Cs_3Bi_2Cl_6/Cs_3Bi_2Cl_9$ for Cu^{2+} and Fe^{3+} detection (LODs 6.23 μM and 3.6 μM), demonstrate the potential for multiplexed systems. 80 Ratiometric designs with dual-emission PQDs, such as Mn^{2+} -doped CsPbCl $_3$, can improve accuracy by mitigating interference, ideal for industrial solvents or effluents. 69 Combining PQDs with other nanomaterials, like CQDs or metal nanoclusters, can enable multiplexed detection with visual readouts, enhancing usability in real-time quality

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control.64 Future research should focus on optimizing these systems for simultaneous detection of ions like Hg²⁺, Cu²⁺, and Cr⁶⁺, addressing the needs of diverse applications.

6.2.7. Eco-friendly and biocompatible sensor designs. To address regulatory and environmental concerns, future PQDbased nanosensors should prioritize eco-friendly and biocompatible designs. Lead-free PQDs with enhanced PLQY and stability, such as doped Cs₃Bi₂X₉ or Cs₂AgInCl₆, can replace toxic lead-based systems in biomedical and environmental applications.60 Biocompatible ligands, such as peptides or polysaccharides, can improve safety for biological fluid analysis, enabling detection of heavy metals in clinical settings. For instance, integrating Cs₃Bi₂Cl₉ with biocompatible coatings could enable Fe3+ detection in blood samples with minimal toxicity. 71 These advancements will broaden the applicability of PQD-based sensors, aligning with global sustainability goals.

6.3. Commercialization pathways and industrial integration

The transition of perovskite quantum dot (PQD)-based nanosensors from laboratory research to industrial applications requires strategic pathways to ensure scalability, costeffectiveness, and seamless integration into existing industrial workflows. While PQD sensors demonstrate exceptional sensitivity and selectivity for heavy metal ion detection, their commercial adoption hinges on addressing economic, regulatory, and operational challenges, distinct from their technical performance in specific applications.

6.3.1. Cost-effective synthesis and manufacturing. Scaling up PQD synthesis for industrial use demands cost-effective methods that maintain high PLQY and reproducibility. Techniques like ligand-assisted reprecipitation (LARP) and continuous-flow hot-injection offer scalable alternatives to batch-based methods, reducing production costs while ensuring uniform PQD quality.68 For instance, automating LARP processes could lower the cost of producing lead-free PQDs like Cs₃Bi₂X₉, making them economically viable for large-scale environmental monitoring.60 Collaborative partnerships with chemical manufacturing industries can optimize precursor sourcing and waste management, further reducing costs. Additionally, developing modular synthesis platforms that integrate quality control metrics, such as real-time PLQY monitoring, can enhance batch consistency, addressing reproducibility concerns for commercial production.

6.3.2. Integration into industrial monitoring systems. Integrating PQD-based nanosensors into existing industrial systems, such as continuous monitoring platforms for wastewater treatment or quality control in chemical processing, requires compatibility with automated and IoT-enabled infrastructures. For example, embedding CsPbBr₃@ZIF-8 sensors into inline water quality analyzers can enable real-time detection of Cu²⁺ in industrial effluents, with data transmitted to centralized control systems.79 Developing plug-and-play sensor modules that interface with standard industrial equipment, such as spectroscopy units or microfluidic systems, can streamline adoption. These modules should incorporate robust encapsulation (e.g., MOFs or silica) to ensure stability under

harsh industrial conditions, such as high temperatures or corrosive environments, without compromising analyte accessibility.78

6.3.3. Regulatory compliance and market readiness. Achieving regulatory approval for PQD-based nanosensors involves addressing safety and environmental concerns, particularly for lead-based PQDs. Lead-free PQDs, such as Cs3-Bi₂Br₉:Eu³⁺, align better with environmental regulations due to their reduced toxicity, making them more viable for markets with stringent standards, such as the European Union's REACH framework.60 Establishing standardized testing protocols for sensor performance, including LOD, selectivity, and stability under diverse conditions, is critical for regulatory acceptance. Collaborations with regulatory bodies can facilitate the development of certification pathways, ensuring POD sensors meet industry standards for applications in wastewater treatment, chemical manufacturing, and environmental monitoring. Market readiness also requires demonstrating long-term reliability through field trials, such as deploying CsSnX₃ sensors in lubricant quality control systems to validate performance over extended periods.75

6.3.4. Economic viability and market differentiation. To compete with established sensing technologies, such as carbon QDs or semiconductor quantum dots, PQD-based nanosensors must offer clear economic advantages. Their high sensitivity (e.g., LOD of 0.1 nM for Cu²⁺ with CsPbBr₃) and versatility across organic and aqueous media provide a competitive edge.62 Positioning PQD sensors as cost-effective solutions for highprecision applications, such as detecting trace Pb2+ in lubricants, can attract industries seeking to minimize equipment downtime and contamination risks.75 Developing portable, user-friendly devices, such as smartphone-integrated PQD sensors for on-site Cu²⁺ detection, can target niche markets like small-scale chemical processing or environmental consulting, enhancing market penetration.64 Strategic partnerships with sensor manufacturers and distributors can accelerate market entry, leveraging existing supply chains to reduce time-tomarket.

Conclusion

This comprehensive review underscores the transformative potential of PQDs as advanced platforms for heavy metal ion detection, marking the first systematic evaluation of their application in this domain. PQDs, with their high photoluminescence quantum yield, narrow emission spectra, and tunable optical properties, offer unparalleled sensitivity and selectivity for detecting ions such as Hg²⁺, Cu²⁺, Cd²⁺, Fe³⁺, Cr⁶⁺, and Pb²⁺. Their efficacy, driven by mechanisms like cation exchange and electron transfer, is enhanced by advanced synthesis methods and integration with stable matrices like metal-organic frameworks. Lead-based PQDs achieve subnanomolar detection limits, while lead-free variants address environmental concerns, broadening their applicability. The versatility of PODs enables their use in industrial wastewater treatment and lubricant quality control, ensuring compliance with environmental regulations and product integrity. Despite

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these advancements, challenges such as aqueous instability, toxicity of lead-based PQDs, and scalability of synthesis methods remain. Future research should focus on developing stable, eco-friendly PQDs through novel encapsulation techniques and ligand designs, alongside computational modeling to optimize ion-PQD interactions. Comparative studies with other nanomaterials, such as carbon quantum dots, will further elucidate their unique advantages. By addressing these challenges, PQDs can transition from laboratory innovations to practical sensing solutions, offering rapid, cost-effective, and portable detection for environmental and industrial applications. This review lays a foundation for advancing PQD-based sensors, guiding researchers toward innovations that enhance sensitivity, selectivity, and scalability, ultimately contributing to sustainable monitoring of heavy metal ion contamination.

Author contributions

Ahmad Mohebi and Suleiman Ibrahim Mohammad conceptualized the study. Asokan Vasudevan, I. B. Sapaev, and Munthar Kadhim Abosaoda developed the methodology. Chou-Yi Hsu, Malatesh Akkur, and Alok Kumar Mishra conducted the investigation. Gaganjot Kaur and Rajesh Singh handled data curation. Suleiman Ibrahim Mohammad and Ahmad Mohebi drafted the original manuscript, while Ahmad Mohebi, Asokan Vasudevan, and Chou-Yi Hsu reviewed and edited it. I. B. Sapaev and Munthar Kadhim Abosaoda contributed to visualization. Ahmad Mohebi supervised and managed the project. Suleiman Ibrahim Mohammad secured funding. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

There are no conflicts to declare.

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

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