



Trends and Future Outlook of AgNP and AuNP-Based Nanosensors for Heavy Metal Identification in Environmental and Biological Systems

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ABSTRACT:

Heavy metal pollution caused by mercury (Hg^{2+}), cadmium (Cd^{2+}), and lead (Pb^{2+}) remains a critical global concern due to their persistence, bioaccumulation, and severe toxicological impacts on ecosystems and human health. Conventional analytical techniques such as AAS, ICP-MS, and voltammetry provide high accuracy but are limited by high cost, complex sample preparation, lack of portability, and unsuitability for rapid on-site detection. In recent years, silver (AgNPs) and gold nanoparticles (AuNPs) have emerged as powerful nanosensing platforms owing to their unique physicochemical properties, including localized surface plasmon resonance (LSPR), high surface-to-volume ratio, tunable optical behavior, and excellent electrochemical responsiveness. These nanomaterials enable sensitive, selective, and rapid detection of toxic metals through colorimetric, fluorescence, electrochemical, and SPR-based mechanisms. Functionalization with biomolecules such as ligands, thiols, DNA, peptides, and aptamers further enhance metal-ion specificity, enabling detection at nanomolar to picomolar levels in complex matrices such as water, soil, food, and biological fluids. Recent innovations include hybrid Ag-Au alloys, graphene- and MOF-based nanocomposites, smartphone-integrated portable sensors, and AI-assisted data interpretation, collectively improving field-deployability and analytical precision. Despite notable advancements, challenges related to nanoparticle stability, interference from coexisting ions, scalability, environmental safety, and regulatory standardization persist. This review highlights the mechanisms, performance, and real-world applicability of AgNP and AuNP based nanosensors, emphasizing their growing role in sustainable monitoring of heavy metal pollution. Future directions include multi-analyte sensor platforms, green nanoparticle synthesis, IoT-enabled systems, and enhanced validation for regulatory acceptance.

1. Introduction

Heavy metal contamination has emerged as one of the most persistent and pressing environmental and public health challenges of the 21st century. Among the toxic metals, mercury (Hg), cadmium (Cd), and lead (Pb) are of particular concern due to their widespread occurrence, high toxicity, and ability to bioaccumulate and biomagnify through food chains. Unlike organic pollutants, these elements are non-biodegradable, allowing them to persist in ecosystems for decades and continuously threaten human health. Industrial activities such as mining, smelting, battery production, pigment and fertilizer manufacturing, e-waste recycling, and fossil fuel combustion remain major contributors to environmental releases, while legacy uses like lead-based paints and mercury in artisanal gold mining exacerbate ongoing exposure risks. With no safe threshold identified for chronic exposure to these metals, their toxicological impacts span multiple organ systems

affecting neurological development, renal and cardiovascular function, skeletal integrity, and immune regulation. The global disease burden linked to Hg, Cd, and Pb highlights the urgent need for sensitive, cost-effective, and field-deployable detection strategies to support early intervention, risk assessment, and regulatory compliance.

Heavy metals such as mercury, cadmium and lead remain persistent environmental contaminants that bioaccumulate through food webs and cause multi-system toxicity in humans. Industrial drivers, mining, smelting, battery and pigment manufacturing, e-waste recycling as well as combustion and legacy uses like leaded paints and lead-acid batteries, continue to elevate exposure risks; in low- and middle-income countries (LMICs), informal sectors and lax controls exacerbate the burden. While global policies such as the Minamata Convention are reducing some mercury inputs, the disease burden particularly for lead remains substantial,



emphasizing the critical need for sensitive, selective, and field-deployable sensors. [1–3] Mercury occurs in elemental, inorganic, and organic forms; methylmercury, produced via aquatic microbial methylation, biomagnifies in fish chains, becoming a dominant exposure route and contributing to neurodevelopmental deficits, cardiovascular disease, and immunological impacts in adults. [1,2] Artisanal and small-scale gold mining (ASGM) remains the largest anthropogenic source of mercury globally, and atmospheric transport leads to widespread contamination. [2,3] Cadmium originates from non-ferrous metal production, phosphate fertilizers, waste incineration, and tobacco smoke accumulating in soils and entering the human food chain through crops like rice and leafy greens. With a long biological half-life, cadmium concentrates in the kidney cortex and is linked to tubular dysfunction, chronic kidney disease, bone demineralization, and cardiovascular risks. [4–6]

Mechanistic insights highlight oxidative stress, calcium signaling disruption, and epigenetic alterations consistent with epidemiological findings. [5,6] Lead exposure remains pervasive—through contaminated consumer goods, informal battery recycling, residual paint and dust, soil, water system corrosion, and industrial emissions. With no known safe blood lead level, Pb impairs neurodevelopment in children and contributes significantly to adult cardiovascular disease. [7–9] In 2021, over 1.5 million deaths were attributed to lead, primarily due to cardiovascular causes [7] and updated estimates suggest substantial under-recognition of mortality and IQ losses globally. WHO highlights lead in drinking water, consumer products, and outdoor air as continuing public health challenges, especially in LMICs. [8–10] Health and environmental hazards of these metals

Mercury, cadmium and lead are among the most hazardous heavy metals due to their persistence, bioaccumulation, and severe toxicological impacts. The side effects are also represented in figure 1. The Mercury, particularly in its methylmercury form, readily biomagnifies in aquatic food webs and poses serious risks to human health, including neurodevelopmental deficits, immune dysfunction, cardiovascular disorders, and renal damage, with prenatal and early-life exposures being most critical.[1,11] Cadmium, a non-essential metal with a biological half-life exceeding two decades,

accumulates mainly in the kidney and bone, leading to renal tubular dysfunction, osteoporosis, and increased risks of cardiovascular disease and cancer; its main environmental sources include non-ferrous metal smelting, phosphate fertilizers, and contaminated crops such as rice and leafy vegetables.[5,6] Lead remains a potent neurotoxin with no safe threshold, causing cognitive impairment, learning disabilities, behavioral problems in children, and cardiovascular and renal diseases in adults, while recent global assessments have highlighted its role as a major contributor to premature mortality and cardiovascular burden worldwide.[7,8] Environmentally, all three metals are highly persistent and mobile: mercury undergoes long-range atmospheric transport and microbial methylation in aquatic systems, cadmium accumulates in agricultural soils and food chains, and lead persists in soils, sediments, and water systems due to industrial emissions, legacy paint, pipes, and informal battery recycling. Their combined ecological and human health impacts underscore the urgent need for sensitive, selective and field-deployable nanosensor-based detection technologies. Need for rapid, sensitive, and selective detection methods

The accurate monitoring of mercury, cadmium and lead is of paramount importance due to their persistence, bioaccumulation, and severe health consequences even at trace levels, yet conventional techniques such as atomic absorption spectroscopy (AAS), inductively coupled plasma mass spectrometry (ICP-MS), and voltammetry, while highly sensitive, are costly, require complex sample preparation, trained personnel, and lack portability for field deployment.[12,13] Moreover, interference from coexisting ions and the need for real-time monitoring in environmental and biological matrices highlight the limitations of traditional laboratory-based methods.[14,15] To address these challenges, there is a growing demand for rapid, sensitive, and highly selective detection technologies capable of on-site analysis with minimal sample pretreatment. Nanomaterial-based sensors, particularly those employing silver and gold nanoparticles, have emerged as powerful alternatives because of their unique optical, electrochemical, and plasmonic properties, enabling low detection limits, visual colorimetric responses, and integration into portable and cost-effective platforms for real-world applications.[16–18] This paradigm shift toward nanosensor-based



approaches supports the development of point-of-care and field-deployable devices, aligning with global efforts for effective monitoring and management of heavy metal pollution.

Role of nanosensors (advantages over conventional methods)

Nanosensors have emerged as transformative tools for heavy metal detection owing to their exceptional sensitivity, selectivity, and portability compared to conventional analytical methods such as ICP-MS or AAS, which, despite their accuracy, are expensive, require sophisticated instrumentation, skilled operators, and are unsuitable for rapid on-site monitoring.[13,14] Noble metal nanoparticles such as gold (AuNPs) and silver (AgNPs) possess unique optical and electrochemical properties, including localized surface plasmon resonance (LSPR), fluorescence quenching/enhancement, and catalytic activity, enabling ultra-trace detection with visual color changes or electrochemical signals that are easily measurable.[16,17] Their high surface-to-volume ratio allows effective functionalization with ligands, DNA, peptides, or polymers, imparting enhanced selectivity toward specific metal ions while maintaining low detection limits in complex environmental and biological matrices.[19] Furthermore, nanosensors are cost-effective, enable rapid response times, and can be integrated into portable devices and smartphone-based platforms, facilitating real-time, in situ monitoring of mercury, cadmium, and lead in water, food, and biological samples.[18,20] These advantages make nanosensors a promising alternative to traditional laboratory-based assays and a crucial component in advancing sustainable environmental monitoring and public health protection.

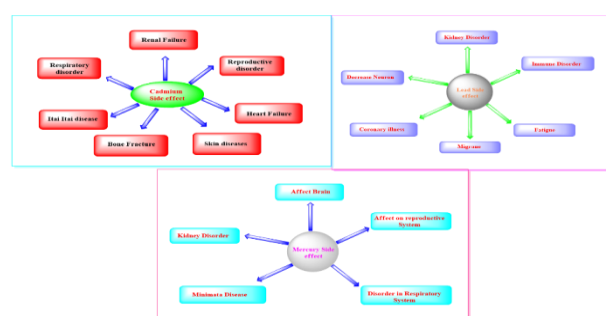


Figure 1: Side effect of Cadmium, Lead and Mercury on human being.

Objectives

The present review focuses on recent advances in the identification of toxic heavy metals mercury, cadmium and lead using silver and gold nanosensors, emphasizing their unique physicochemical properties and sensing mechanisms. While conventional techniques such as AAS, ICP-MS, and voltammetry provide accurate quantification, their limitations in cost, portability, and field applicability necessitate the development of nanosensor-based platforms for rapid, sensitive, and selective detection in real-world matrices.[12,13] This review aims to first summarize the health and environmental risks posed by Hg, Cd, and Pb, highlighting the urgent need for efficient monitoring tools; secondly, critically discuss the design strategies, functionalization approaches, and detection mechanisms of silver- and gold-based nanosensors, including colorimetric, electrochemical, fluorescence, and surface plasmon resonance-based methods; third, evaluate their performance in terms of sensitivity, selectivity, and real-sample applicability; and lastly explore current challenges, emerging hybrid nanostructures, and future perspectives for point-of-care and field-deployable monitoring technologies.[17–20] By consolidating recent developments, this review seeks to provide researchers with an updated understanding of nanosensor-based detection and identify knowledge gaps that can guide next-generation sensor design for environmental and biomedical applications.

2. Methods

Heavy Metal Toxicity and Detection Challenges

Toxicological effects of Mercury, Cadmium, and Lead
Mercury, cadmium and lead exert profound toxicological effects in humans due to their persistence, bioaccumulation, and ability to interfere with critical biological systems. Mercury, particularly methylmercury, readily crosses the blood–brain and placental barriers, leading to neurodevelopmental deficits, impaired cognitive function, cardiovascular toxicity, immunotoxicity, and renal impairment, with prenatal exposure posing the greatest risk.[1,11] Cadmium has an exceptionally long biological half-life (10–30 years), accumulates primarily in the kidneys and bones, and is linked to renal tubular dysfunction, osteoporosis, hypertension, diabetes, and several cancers, largely through mechanisms involving



oxidative stress, disruption of calcium signaling, and epigenetic modifications.[4–6] Lead remains one of the most pervasive neurotoxins, with no safe exposure threshold, and chronic exposure contributes to reduced IQ, learning disabilities, behavioral disorders in children, and cardiovascular disease, hypertension, kidney damage, anemia, and reproductive dysfunction in adults; recent epidemiological modeling underscores its significant contribution to global cardiovascular mortality.[7,8] Collectively, the toxicological profiles of these metals highlight the urgent need for effective monitoring and preventive interventions.

Environmental and regulatory limits (WHO, EPA, BIS standards)

To safeguard public health, international agencies such as the World Health Organization (WHO), the United States Environmental Protection Agency (EPA), and the Bureau of Indian Standards (BIS) have established stringent regulatory limits for mercury, cadmium, and lead in drinking water and food. The WHO Guidelines for Drinking-Water Quality (2022) set maximum permissible concentrations of 0.006 mg/L for mercury, 0.003 mg/L for cadmium, and 0.010 mg/L for lead, values that are aligned with USEPA standards under the Safe Drinking Water Act.[9,21] Similarly, the BIS (IS 10500: 2012, reaffirmed 2020) prescribes acceptable limits of 0.001 mg/L for mercury, 0.003 mg/L for cadmium, and 0.010 mg/L for lead in drinking water supplied in India, reflecting a precautionary approach due to widespread contamination from industrial, agricultural, and domestic sources.[22,23] In the context of food safety, the Codex Alimentarius Commission and WHO/FAO Joint Expert Committee on Food Additives (JECFA) also recommend maximum levels for these metals in cereals, fish, vegetables, and infant foods, acknowledging their bioaccumulative potential and absence of safe exposure thresholds for lead and cadmium.[24,25] Despite these regulations, numerous monitoring studies highlight that concentrations in surface waters, soils, and food products often exceed permissible levels, particularly in regions impacted by mining, e-waste recycling, or inadequate wastewater management, underscoring the need for continuous monitoring and improved detection strategies.

Limitations of conventional detection techniques (AAS, ICP-MS, voltammetry)

Conventional analytical techniques such as atomic absorption spectroscopy (AAS), inductively coupled plasma mass spectrometry (ICP-MS), and electrochemical voltammetry have long been regarded as the gold standards for trace-level detection of heavy metals like mercury, cadmium, and lead; however, each presents significant limitations that restrict their applicability in rapid and on-site monitoring. AAS, while relatively simple, often suffers from low sensitivity for ultra-trace detection, limited multi-element capability, and matrix interferences that necessitate extensive sample preparation.[26] ICP-MS provides exceptional sensitivity (ppt level) and multi-element detection, but its high capital and operational costs, need for skilled personnel, and bulky instrumentation make it unsuitable for field applications.[27] Voltammetric methods offer better portability and relatively low cost, yet they are prone to electrode fouling, poor selectivity in complex matrices, and limited reproducibility, thereby reducing their reliability in real-world environmental samples.[28,29] Moreover, all three methods require laboratory-based infrastructure, hazardous reagents, and lengthy analysis times, which hinders their practical use in continuous monitoring and early warning systems for heavy metal pollution.[30] These drawbacks have motivated the exploration of nanomaterial-based sensors as promising alternatives that combine sensitivity, selectivity, portability, and cost-effectiveness for on-site applications.

Nanosensors: Fundamentals and Principles

Concept of nanosensors and their sensing mechanisms

Nanosensors are analytical devices that exploit the unique physicochemical properties of nanomaterials such as high surface-to-volume ratio, quantum confinement, localized surface plasmon resonance (LSPR), and tunable surface chemistry for the rapid, sensitive, and selective detection of analytes, including toxic heavy metals like mercury, cadmium, and lead. By incorporating noble metal nanostructures (e.g., silver and gold nanoparticles), nanosensors can transduce molecular recognition events into measurable optical, electrochemical, or colorimetric signals with ultra-low detection limits, often at the ppb or ppt level.[31,32] The



sensing mechanisms typically involve changes in the optical absorption (plasmonic shift), fluorescence quenching/enhancement, electrochemical redox activity, or catalytic reactions upon binding of target ions to functionalized nanomaterials.[33] For example, AuNPs functionalized with thiol or amine ligands undergo aggregation in the presence of Hg^{2+} or Pb^{2+} , producing a visible color change, while AgNPs exhibit surface plasmon shifts and enhanced conductivity when interacting with Cd^{2+} ions.[34,35] Compared to conventional techniques, nanosensors provide advantages such as portability, real-time analysis, minimal sample preparation, and potential integration into point-of-care and environmental monitoring platforms, making them highly promising for field-deployable heavy metal detection.[36]

Properties of silver and gold nanoparticles (plasmonic, catalytic, fluorescence, electrochemical properties)

Silver (AgNPs) and gold nanoparticles (AuNPs) possess unique physicochemical properties that make them ideal candidates for nanosensor development in heavy metal detection. Their plasmonic properties, arising from localized surface plasmon resonance (LSPR), enable strong optical absorption and scattering, allowing highly sensitive colorimetric and spectroscopic detection of metal ions through shifts in plasmon bands.[37,38] Both AgNPs and AuNPs also exhibit remarkable catalytic activity due to their large surface-to-volume ratio and active sites, which enhance redox reactions and facilitate signal amplification in sensing platforms.[39] In addition, AuNPs show excellent fluorescence quenching and enhancement effects, often exploited in fluorescence resonance energy transfer (FRET)-based assays, while AgNPs display unique luminescence properties that can further improve detection sensitivity.[40] From an electrochemical perspective, Au and Ag nanostructures demonstrate excellent conductivity, electron transfer kinetics, and stability, making them suitable for developing high-performance electrochemical sensors capable of real-time and on-site monitoring of heavy metals.[41,32] Their biocompatibility, tunable size and shape, and facile surface functionalization with ligands or biomolecules further enhance selectivity and reproducibility in complex environmental matrices, solidifying their role as versatile nanomaterials for environmental sensing applications.[31]

3. Results and Discussion

Mechanisms of detection: Colorimetric response, Fluorescence quenching/enhancement, Electrochemical sensing, Surface plasmon resonance (SPR)

The detection of heavy metals such as Hg^{2+} , Cd^{2+} , and Pb^{2+} using silver and gold nanosensors primarily relies on four key mechanisms: colorimetric response represented in Figure 2, fluorescence modulation, electrochemical sensing, and surface plasmon resonance (SPR). In colorimetric sensing, the aggregation or morphological transformation of AgNPs or AuNPs upon binding target ions induces a visible color change, enabling simple and rapid detection without sophisticated instrumentation.[42,35] Fluorescence quenching or enhancement occurs when metal ions interact with fluorophore-labeled or intrinsic luminescent nanoparticles, often via Förster resonance energy transfer (FRET) or electron transfer, leading to highly sensitive detection at trace levels.[40] Electrochemical sensing exploits the excellent conductivity and redox activity of Au and Ag nanostructures, where metal ion binding alters electron transfer rates or current responses, enabling quantitative and real-time measurements in complex samples.[45] Finally, SPR-based sensing utilizes shifts in localized surface plasmon resonance bands of noble metal nanoparticles upon heavy metal adsorption, providing highly sensitive and label-free detection down to parts-per-trillion levels.[37,33] Collectively, these mechanisms allow Au and Ag nanosensors to achieve superior sensitivity, selectivity, and portability compared to conventional methods, positioning them as powerful tools for environmental and health monitoring. The detection work flow of Au/Ag Nanoparticle Nanosensors are represented in figure 3

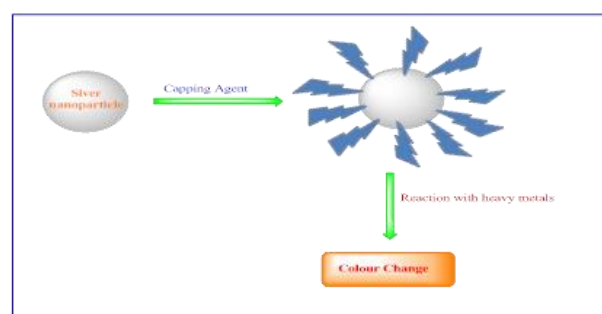


Figure 2: Colorimetric Response of functionalized nanoparticles with Heavy metals.



Silver Nanoparticle Based Nanosensors for Heavy Metal Detection

Optical nanosensors (colorimetric, SPR shifts)

Optical nanosensors based on silver and gold nanoparticles have emerged as highly efficient platforms for detecting toxic heavy metals such as Hg^{2+} , Cd^{2+} , and Pb^{2+} due to their strong optical responses and tunable surface chemistry. Colorimetric nanosensors rely on the aggregation, growth, or morphological changes of nanoparticles upon metal ion binding, which induce visible color transitions and shifts in absorption spectra, enabling rapid and user-friendly detection without sophisticated instrumentation.[42,35] In parallel, surface plasmon resonance (SPR)-based nanosensors exploit the sensitivity of localized SPR bands to changes in the dielectric environment of Au and Ag nanoparticles, where heavy metal adsorption or nanoparticle aggregation leads to measurable spectral shifts with high sensitivity and selectivity.[37,44] These optical strategies are label-free, cost-effective, and amenable to portable sensing devices, making them promising alternatives to traditional laboratory-based techniques for on-site monitoring of environmental contaminants.[33]

Electrochemical nanosensors modified electrodes with AgNPs

Electrochemical nanosensors incorporating silver nanoparticles (AgNPs) on modified electrodes have gained significant attention for the detection of toxic heavy metals such as Hg^{2+} , Cd^{2+} , and Pb^{2+} due to their high conductivity, large surface area, and strong catalytic activity. The integration of AgNPs onto carbon-based (graphene, carbon nanotubes) or polymer-modified electrodes enhances electron transfer kinetics and provides abundant active sites for metal ion adsorption, thereby lowering detection limits and improving sensitivity compared to bare electrodes.[43,45] Techniques such as anodic stripping voltammetry (ASV), differential pulse voltammetry (DPV), and square-wave voltammetry (SWV) are commonly employed, where AgNP-modified electrodes allow simultaneous and selective detection of multiple heavy metals even in complex matrices.[46,47] Furthermore, AgNP-based nanocomposites improve stability, reproducibility, and anti-fouling properties, making them

suitable for portable electrochemical sensing platforms for environmental monitoring.[48]

Fluorescent Ag nanoclusters for metal ion sensing

Fluorescent silver nanoclusters (AgNCs), consisting of a few to tens of silver atoms stabilized by DNA, proteins, or polymers, have emerged as ultrasensitive probes for the detection of toxic heavy metals such as Hg^{2+} , Pb^{2+} , and Cd^{2+} owing to their unique size-dependent fluorescence, high quantum yields, and biocompatibility. Unlike larger silver nanoparticles, AgNCs exhibit strong fluorescence tunable from the visible to near-infrared region, which can be selectively quenched or enhanced upon interaction with heavy metal ions through mechanisms such as metallophilic interactions (e.g., Hg^{2+} - Ag^+), electron/energy transfer, and conformational changes in the stabilizing ligands.[49,50] DNA-templated AgNCs are particularly attractive due to the programmability of DNA sequences, which allows for selective recognition and sensitive detection of individual metal ions at nanomolar or even picomolar levels.[51,52] In addition, AgNCs offer advantages over conventional fluorophores and quantum dots, including lower cytotoxicity, facile synthesis, and strong photostability, making them suitable for environmental monitoring and bioimaging applications.[53] Recent advances also integrate AgNCs with nanocomposites and microfluidic platforms to develop portable fluorescent nanosensors for on-site detection of hazardous metals in water and biological samples.[54]

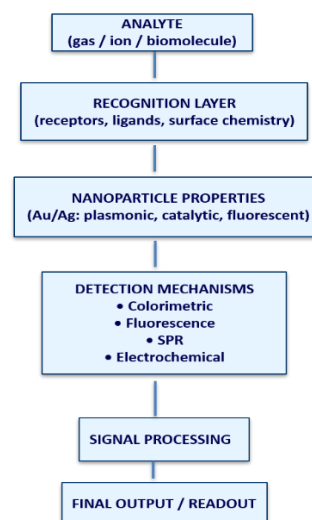


Figure 3: Detection Workflow of Au/Ag Nanoparticle Nanosensors



Case studies for detection of: Mercury (Hg^{2+}) Cadmium (Cd^{2+}) Lead (Pb^{2+})

Mercury detection using silver and gold nanosensors has been extensively reported due to the strong metallophilic interaction between Hg^{2+} and Ag^+/Au^+ . For example, DNA-templated fluorescent silver nanoclusters (AgNCs) have been used for label-free detection of Hg^{2+} , where fluorescence quenching occurs via thymine- Hg^{2+} -thymine coordination, enabling detection down to nanomolar levels in environmental water samples.[51] Similarly, gold nanoparticle (AuNP)-based colorimetric sensors exploit the aggregation of citrate-stabilized AuNPs upon Hg^{2+} binding, leading to a distinct red-to-blue color change that is visible to the naked eye.[55] Electrochemical sensors with AgNP-modified electrodes have also demonstrated ultralow detection limits for Hg^{2+} through anodic stripping voltammetry, offering high selectivity even in the presence of interfering ions.[47]

Cadmium, a highly toxic heavy metal, has been sensitively detected using nanosensors based on AgNP and AuNP composites. A notable example involves AgNP-decorated reduced graphene oxide electrodes, which showed enhanced electrocatalytic response for Cd^{2+} with a detection limit of 0.3 nM using differential pulse anodic stripping voltammetry.[45] Fluorescent AgNCs stabilized by peptides or DNA have also been applied for Cd^{2+} sensing, where the fluorescence intensity changes proportionally with increasing Cd^{2+} concentration due to coordination between Cd^{2+} and stabilizing ligands.[53] Moreover, AuNP-based plasmonic sensors integrated into microfluidic platforms enable rapid, on-site Cd^{2+} detection in water samples, highlighting their potential for field applications.[48]

Lead sensing using Ag and Au nanostructures is widely reported due to its severe neurotoxicity even at trace levels. AuNP-based colorimetric sensors employing DNazymes (Pb^{2+} -dependent catalytic DNA) show high specificity for Pb^{2+} , where Pb^{2+} catalyzes the cleavage of DNA linkers, causing AuNP aggregation and a visible color change.[56] Electrochemical nanosensors using AgNP-modified glassy carbon electrodes have achieved simultaneous detection of Pb^{2+} and Cd^{2+} in environmental samples with excellent sensitivity and reproducibility.[46] Fluorescent AgNCs stabilized by DNA oligonucleotides have also been designed to detect Pb^{2+} via fluorescence quenching/enhancement

mechanisms, achieving picomolar-level sensitivity and applicability in real water samples.[54]

Sensitivity, Selectivity, Detection Limits and Practical Applications

Silver and gold nanosensors have demonstrated remarkable sensitivity and selectivity for heavy metal ion detection, often surpassing conventional methods. For instance, DNA-stabilized Ag nanoclusters have achieved detection limits as low as 0.5 nM for Hg^{2+} , with high selectivity over competing ions such as Cu^{2+} and Pb^{2+} due to the formation of thymine- Hg^{2+} -thymine complexes.[51] AuNP-based colorimetric sensors also provide rapid visual detection, with limits of detection (LOD) of 2–5 nM for Hg^{2+} and high field applicability in drinking water monitoring.[55] For Cd^{2+} , AgNP-modified glassy carbon electrodes integrated with graphene oxide have reached LODs of 0.3 nM, enabling sensitive and reproducible detection in soil and river water samples.[45] Similarly, Pb^{2+} detection using DNazyme-functionalized AuNP sensors has achieved picomolar-level sensitivity, with exceptional selectivity against other divalent ions such as Zn^{2+} and Mg^{2+} , making them suitable for biological fluids and tap water analysis.[56] In terms of practical applications, portable electrochemical nanosensors based on AgNP-decorated carbon nanostructures have been developed for on-site field testing of Pb^{2+} and Cd^{2+} in agricultural runoff and industrial effluents, highlighting their potential in environmental monitoring.[56] Moreover, integration of Ag/Au nanosensors into microfluidic and paper-based platforms has advanced real-world usability by offering rapid, low-cost, and user-friendly detection formats for routine monitoring of heavy metals in water, food, and biomedical samples.[48]

Gold Nanoparticle Based Nanosensors for Heavy Metal Detection

Silver and gold nanoparticles exhibit unique optical properties due to localized surface plasmon resonance (LSPR), which arises from the collective oscillation of conduction electrons when excited by incident light. The resonance frequency is highly sensitive to changes in nanoparticle size, shape, interparticle distance, and the refractive index of the surrounding medium, making them excellent candidates for label-free detection of heavy metal ions.[57,58] In the presence of Hg^{2+} , Cd^{2+} , or Pb^{2+} , interactions with the nanoparticle surface induce



aggregation, alloy formation, or charge transfer, leading to measurable colorimetric shifts (visible color changes) or changes in absorption spectra.[59] For example, AuNPs capped with DNA or thiol ligands undergo red-to-blue color transitions upon binding Hg^{2+} due to nanoparticle aggregation, enabling naked-eye detection at nanomolar levels. [55] Similarly, AgNP-based SPR nanosensors have demonstrated enhanced sensitivity to Cd^{2+} and Pb^{2+} by exploiting their strong plasmonic resonance, achieving detection limits down to sub-nanomolar concentrations in aqueous samples. [60] Furthermore, coupling SPR detection with advanced platforms such as fiber-optic sensors, microfluidics, and portable paper-based assays has significantly improved their practical applicability in environmental and clinical monitoring. [61] Thus, the tunable plasmonic responses of Ag and Au nanosensors provide a simple, rapid, and highly sensitive route for heavy metal detection compared to conventional optical methods.

Functionalization with ligands and biomolecules for selective detection

The selectivity of silver and gold nanosensors toward toxic heavy metals such as Hg^{2+} , Cd^{2+} , and Pb^{2+} is greatly enhanced through surface functionalization with specific ligands, DNA sequences, and biomolecules. Thiol-containing ligands, crown ethers, and chelating agents are commonly employed to tailor surface chemistry, as they exhibit strong affinity for soft metal ions like Hg^{2+} and Pb^{2+} , thereby improving binding selectivity and lowering detection limits.[62,63] DNA-functionalized AuNPs and AgNPs have received particular attention due to the programmability of DNA sequences, enabling the design of thymine– Hg^{2+} –thymine and cytosine– Ag^+ –cytosine coordination complexes that serve as highly selective recognition elements.[59,51] These biomolecular interactions not only promote target-induced aggregation or fluorescence modulation but also allow for label-free, colorimetric, and fluorometric detection strategies. Protein- and peptide-functionalized nanoclusters further contribute to biocompatibility and specificity, facilitating applications in real water samples and biological matrices.[53] Moreover, aptamer-modified nanosensors have demonstrated remarkable potential in discriminating between closely related metal ions, achieving nanomolar to picomolar sensitivity under environmentally relevant conditions.[64] The integration of biomolecule-functionalized Ag/Au nanomaterials

with microfluidic chips and portable sensing platforms is pushing these nanosensors closer to practical applications in environmental monitoring and point-of-care diagnostics.

Electrochemical and fluorescence based AuNP sensors

Gold nanoparticles (AuNPs) have emerged as versatile nanosensors for detecting toxic heavy metals through electrochemical and fluorescence-based approaches, owing to their excellent conductivity, surface plasmon resonance, and facile surface modification. In electrochemical sensing, AuNPs are commonly integrated into modified electrodes to enhance electron transfer, amplify current responses, and improve sensitivity in stripping voltammetry and impedimetric assays.[65,66] For example, AuNP-modified glassy carbon and screen-printed electrodes have been used for simultaneous detection of Pb^{2+} , Cd^{2+} , and Hg^{2+} , achieving nanomolar detection limits with high reproducibility and selectivity, even in complex environmental samples.[67] In fluorescence-based sensing, AuNPs act as quenchers or enhancers due to their strong distance-dependent Förster resonance energy transfer (FRET) and surface plasmon-coupled emission effects.[68,69] DNA- or aptamer-functionalized AuNPs enable selective recognition of Hg^{2+} via thymine- Hg^{2+} -thymine binding or Pb^{2+} via guanine-rich DNAzyme activation, leading to fluorescence recovery or quenching as the signal transduction mechanism.[70,71] Such designs offer ultrasensitive detection down to picomolar levels and are applicable for monitoring trace metals in water, food, and biological fluids. More recently, dual-mode nanosensors combining electrochemical and fluorescence readouts with AuNPs have been developed, enhancing detection accuracy and reliability for field-deployable applications.[72]

Case Studies for Detection of Mercury (Hg^{2+}), Cadmium (Cd^{2+}), and Lead (Pb^{2+})

Mercury ions are among the most toxic heavy metals, and numerous nanosensor platforms have been reported for their detection. For instance, DNA-functionalized AuNPs exploiting thymine- Hg^{2+} -thymine (T– Hg^{2+} –T) coordination have been widely applied, enabling colorimetric and fluorescence turn-on responses with high selectivity. A dual-mode colorimetric/fluorescent nanosensor based on AuNPs achieved a detection limit



as low as 0.5 nM Hg²⁺ in river water samples.[68] Similarly, AgNP-based colorimetric assays functionalized with thymine-rich oligonucleotides demonstrated sensitive detection with distinct visible color changes, making them promising for field applications.[73]

Cd²⁺ is a carcinogenic pollutant often detected in food and water samples. Electrochemical sensors based on AuNP-modified glassy carbon electrodes have enabled simultaneous detection of Cd²⁺ with Pb²⁺ and Hg²⁺ using anodic stripping voltammetry, with detection limits in the low nanomolar range. [67] In addition, a fluorescence nanosensor employing Ag nanoclusters stabilized with DNA templates has been reported for Cd²⁺ sensing, where fluorescence quenching occurs via Cd²⁺ coordination, achieving a detection limit of 2.3 nM in real food matrices.[74]

Pb²⁺ has been extensively studied using AuNP-based nanosensors due to the availability of Pb²⁺-specific DNazymes. For example, a DNzyme–AuNP construct enabled rapid colorimetric detection of Pb²⁺ down to 0.3 nM with high selectivity over other metal ions.[70] Electrochemical platforms have also demonstrated superior performance; a AuNP–graphene oxide composite electrode exhibited excellent sensitivity for Pb²⁺, with detection limits of 0.1 nM, and was successfully applied to contaminated tap water analysis.[72] Furthermore, fluorescent Ag nanoclusters functionalized with G-rich sequences displayed Pb²⁺-induced emission quenching, offering picomolar detection sensitivity.[75]

These case studies demonstrate the versatility of AgNPs and AuNPs in designing colorimetric, fluorescence, and electrochemical nanosensors for Hg²⁺, Cd²⁺, and Pb²⁺, showing potential for real-world environmental and food safety monitoring.

Detection performance and real sample applications

The effectiveness of nanosensors for heavy metal detection is often evaluated in terms of sensitivity, selectivity, detection limits, reproducibility, and applicability in real matrices. AgNP- and AuNP-based nanosensors have consistently demonstrated ultrasensitive detection limits in the nanomolar to picomolar range, surpassing many conventional analytical techniques. For example, a DNzyme–AuNP

colorimetric nanosensor detected Pb²⁺ at 0.3 nM with high selectivity, even in the presence of competing metal ions, and was successfully applied to contaminated drinking water samples. [70] Similarly, thymine-rich DNA-functionalized AuNP probes have enabled Hg²⁺ detection down to 0.5 nM in river water, with visible color changes allowing naked-eye detection.[68]

Electrochemical nanosensors also offer significant advantages for real sample monitoring. AuNP–carbon nanocomposite electrodes enabled simultaneous detection of Pb²⁺, Cd²⁺, and Hg²⁺ in lake water and industrial wastewater, achieving detection limits of 0.1–1.0 nM with excellent recovery rates (95–105%).[67] Fluorescent Ag nanoclusters stabilized with DNA templates have shown selective detection of Cd²⁺ with a detection limit of 2.3 nM, and were applied in the analysis of rice and milk samples, demonstrating their potential for food safety applications.[76]

Importantly, these nanosensors are also being adapted for portable and on-site detection. Smartphone-based readouts integrated with colorimetric AuNP probes have enabled field-deployable testing of Pb²⁺ and Hg²⁺ in drinking water, providing results within minutes without sophisticated instrumentation.[77] Such advancements highlight the potential of nanosensors to bridge the gap between laboratory-based analyses and real-world monitoring.

Overall, Figure 4 represent the Functional and Transduction Mechanisms of AgNP and AuNP Nanosensors for Hg²⁺, Cd²⁺ & Pb²⁺. The nanosensors based on silver and gold nanoparticles provide not only ultrasensitive detection performance but also practical applicability in environmental water, food matrices, and biological samples, making them promising candidates for future regulatory and field applications. Comparative Analysis of Silver vs. Gold Nanosensors

Sensitivity and detection limits

The sensitivity of silver and gold nanoparticle-based nanosensors primarily stems from their high surface-to-volume ratio, unique plasmonic and catalytic properties, and facile surface functionalization, which enable strong signal amplification for trace metal ion detection. AgNP and AuNP based platforms have consistently demonstrated ultrasensitive detection limits (LOD), often reaching nanomolar (nM) to picomolar (pM)



ranges, significantly outperforming conventional spectroscopic and electrochemical methods. For instance, a thymine-AuNP probe exhibited an LOD of 0.5 nM for Hg^{2+} , allowing reliable detection in natural water samples.[68] A DNAzyme-AuNP colorimetric system achieved Pb^{2+} detection as low as 0.3 nM, with high selectivity against interfering cations.[70] Similarly, DNA-templated Ag nanoclusters have been reported for Cd^{2+} sensing with an LOD of 2.3 nM, enabling application in food samples such as rice and milk.[76] Electrochemical sensors based on AuNP-graphene composites have also shown simultaneous detection of Pb^{2+} , Cd^{2+} , and Hg^{2+} in environmental water samples, with LODs in the range of 0.1–1.0 nM.[67] Furthermore, integration with microfluidic and portable readout systems has enabled on-site testing with detection limits meeting or even surpassing WHO and EPA regulatory standards.[48]

Stability and reproducibility

The stability and reproducibility of silver and gold nanoparticle (AgNP/AuNP) nanosensors are critical parameters determining their practical applicability in environmental monitoring and biomedical diagnostics. While noble metal nanoparticles exhibit excellent chemical stability due to their inert core, their sensing performance may be affected by aggregation, oxidation, and ligand desorption, leading to signal fluctuations and reduced reproducibility in real samples.[78] To address these challenges, surface functionalization with DNA, thiols, polymers, or biomolecules has been widely employed, which not only enhances colloidal stability but also preserves sensitivity under varying ionic strengths and complex matrices.[77] For instance, DNA-stabilized AuNP colorimetric probes for Hg^{2+} detection demonstrated stable performance for over one month of storage without significant signal loss, while maintaining batch-to-batch reproducibility ($\text{RSD} < 5\%$).[79] Similarly, protein- and peptide-capped Ag nanoclusters have shown robust fluorescence stability against photobleaching and pH variations, ensuring consistent detection of Cd^{2+} and Pb^{2+} across multiple measurements.[53] Electrochemical sensors incorporating AuNP-modified electrodes also report high reproducibility, with current responses showing relative standard deviations (RSDs) below 3% across at least 10 replicates, making them suitable for real-world water quality assessment.[80] Despite these advances,

ensuring long-term operational stability under field conditions remains a challenge, driving ongoing research into hybrid nanocomposites and encapsulation strategies to minimize nanoparticle degradation and variability.[48] Cost-effectiveness and ease of synthesis

The cost-effectiveness and ease of synthesis of silver and gold nanoparticle (AgNP/AuNP) nanosensors are key factors driving their widespread adoption for heavy metal detection and Figure 5 demonstrate the Various Types of nanosensor manufactured from Green and Chemical synthesis. Silver nanoparticles are generally considered more economical than gold due to the lower cost of silver precursors, making AgNP-based nanosensors attractive for large-scale environmental monitoring applications.[81,82] In contrast, AuNPs, while more expensive, offer superior stability and tunable surface chemistry, which justifies their use in applications requiring high reproducibility and long-term performance.[83] Both nanoparticles can be synthesized using straightforward chemical reduction methods, employing reducing agents such as sodium borohydride or citrate, which enable rapid, low-cost, and scalable

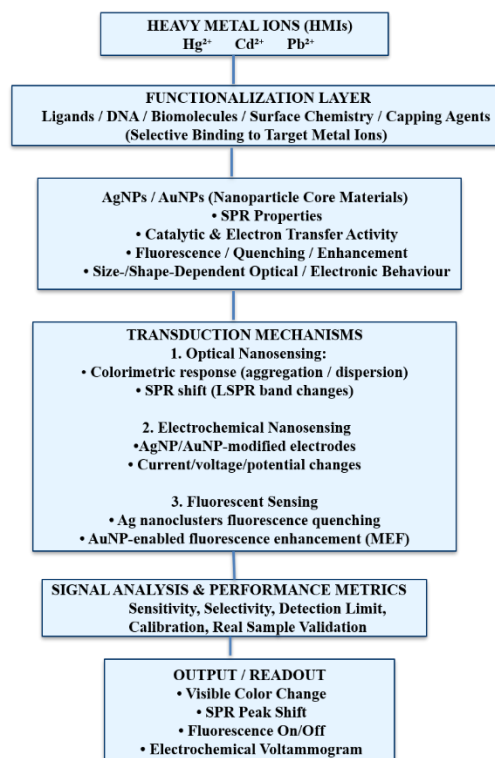


Figure 4: Functional and Transduction Mechanisms of AgNP and AuNP Nanosensors for Hg^{2+} , Cd^{2+} & Pb^{2+}



production.[84] Moreover, green synthesis approaches using plant extracts, polysaccharides, and microbial routes have emerged as sustainable alternatives, eliminating the need for toxic reagents while reducing costs and enhancing biocompatibility.[85] The simple surface modification of AuNPs and AgNPs with ligands, DNA, or polymers further enhances selectivity without requiring complex fabrication procedures, thus making these nanosensors practical for field-deployable platforms.[86] Overall, the balance between the low cost of AgNPs and the high stability of AuNPs allows researchers to tailor nanosensor design according to the cost-performance requirements of specific environmental and biomedical applications.

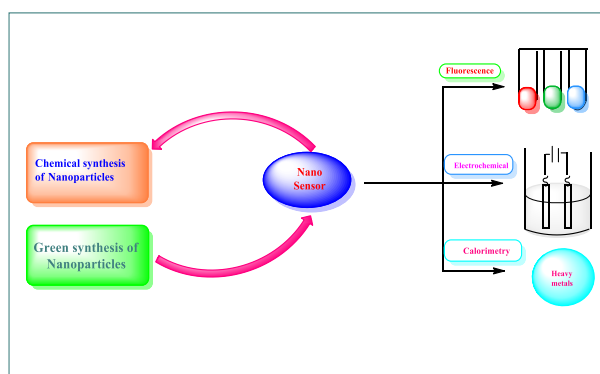


Figure 5: Various Types of nanosensor manufactured from Green and Chemical synthesis.

Biocompatibility and environmental considerations

The biocompatibility and environmental safety of silver and gold nanoparticles (AgNPs/AuNPs) are critical aspects for their practical deployment in sensing applications. AuNPs are generally regarded as highly biocompatible and chemically inert, making them suitable for in vivo applications and biosensing without inducing significant cytotoxicity.[87,88] In contrast, AgNPs, while cost-effective and highly sensitive, exhibit potential toxicity due to the release of Ag^+ ions, which can generate reactive oxygen species (ROS), induce oxidative stress, and disrupt microbial ecosystems.[89,90,] To mitigate these effects, surface functionalization with biocompatible ligands, polymers, proteins, or green-synthesized coatings has been employed to reduce nanoparticle toxicity while maintaining sensitivity.[91,92] Environmentally, improper disposal of AgNPs poses risks of bioaccumulation and ecotoxicity in aquatic systems,

whereas AuNPs are more environmentally benign due to their stability and resistance to dissolution [93,94] Recent advances in green synthesis using plant extracts, microbial routes, and biopolymers [95] have further enhanced the sustainability of nanosensor fabrication, minimizing the ecological footprint Thus, balancing the superior biocompatibility of AuNPs with the economic feasibility of AgNPs, while adopting eco-friendly synthesis and safe disposal strategies, remains essential for large-scale implementation in environmental and biomedical monitoring.

Applications in real-world samples (water, soil, food, biological fluids)

Silver and gold nanoparticle (AgNPs/AuNPs)-based nanosensors have demonstrated remarkable potential for detecting toxic heavy metals such as Hg^{2+} , Cd^{2+} , and Pb^{2+} in real-world samples including water, soil, food, and biological fluids. In environmental monitoring, AuNP-based colorimetric assays have been applied for the on-site detection of Hg^{2+} and Pb^{2+} in river and tap water with high sensitivity and without the need for sophisticated instrumentation.[96,77] Similarly, AgNP-modified electrodes have been successfully utilized for Cd^{2+} determination in groundwater and industrial effluents, achieving detection limits below regulatory thresholds.[97] In soil analysis, nanosensors functionalized with thiols or DNA aptamers enable selective detection of Pb^{2+} and Cd^{2+} in agricultural soil extracts, aiding in contamination mapping and risk assessment.[63] Food safety applications include detection of Pb^{2+} and Hg^{2+} in rice, milk, and seafood using AuNP-based surface plasmon resonance (SPR) and fluorescence nanosensors, ensuring compliance with food safety standards.[98,99] Moreover, nanosensors have been applied in biological samples such as urine, serum, and blood, providing non-invasive and ultra-sensitive detection of Hg^{2+} and Pb^{2+} ions for biomonitoring and early diagnosis of heavy metal exposure in humans.100,101 These advancements highlight the versatility of AgNPs and AuNPs in real-sample analysis, bridging the gap between laboratory studies and field-deployable, user-friendly sensing platforms.



Recent Advances and Emerging Trends

Hybrid nanosensors (Ag-Au alloys, core-shell nanostructures)

Hybrid nanosensors based on Ag–Au alloys and core–shell nanostructures have attracted significant attention due to their synergistic properties that combine the high plasmonic activity of silver with the superior stability and biocompatibility of gold. Alloyed Ag–Au nanoparticles exhibit tunable localized surface plasmon resonance (LSPR), improved photostability, and enhanced sensitivity toward heavy metal ions such as Hg²⁺, Cd²⁺, and Pb²⁺ compared to monometallic counterparts.[102,103] Core–shell structures (e.g., Au@Ag, Ag@Au) provide a unique platform where the shell controls surface chemistry and prevents oxidation, while the core dictates strong plasmonic responses, enabling highly stable and selective detection.[104] For instance, Au@Ag nanostructures have been used for colorimetric and surface-enhanced Raman spectroscopy (SERS)-based sensing of Hg²⁺ with picomolar detection limits, while Ag@Au composites have been exploited in electrochemical assays for Pb²⁺ detection in water and food samples.[105,106] The tunability of morphology (nanorods, nanocubes, nanostars) further enhances signal amplification and allows multiplex detection.[107] Importantly, hybrid Ag–Au nanosensors offer higher reproducibility, resistance to environmental degradation, and compatibility with biomolecule functionalization (DNA, aptamers, peptides), making them superior platforms for real-world heavy metal detection in environmental and biological samples.[108,109]

Integration with nanocomposites, graphene, carbon nanotubes, MOFs

The integration of silver and gold nanoparticles (AgNPs, AuNPs) with advanced nanomaterials such as graphene, carbon nanotubes (CNTs), and metal–organic frameworks (MOFs) has significantly enhanced the performance of nanosensors for heavy metal detection. Graphene and reduced graphene oxide (rGO) provide large surface area, high electrical conductivity, and strong adsorption capacity, which facilitate the immobilization of nanoparticles and improve electron transfer in electrochemical sensing of Hg²⁺, Cd²⁺, and Pb²⁺. [110,111] Similarly, CNTs act as excellent conductive scaffolds, enabling signal amplification and

enhanced sensitivity, particularly in voltammetric and impedimetric detection platforms.[112] MOF-based composites offer tunable porosity, functional sites, and selective adsorption, which, when combined with plasmonic or catalytic properties of Ag/Au NPs, yield superior selectivity and lower detection limits in complex environmental and biological matrices.[113,114] For instance, AuNP–graphene composites have achieved sub-nanomolar detection of Pb²⁺ in water samples, while AgNP–MOF hybrids have shown excellent reproducibility in detecting Hg²⁺ via fluorescence quenching.[115,116] Such hybrid nanocomposites not only overcome the aggregation and stability limitations of bare nanoparticles but also enable multifunctional sensing (colorimetric, electrochemical, and fluorescence), making them highly promising candidates for practical heavy metal monitoring applications.[117]

Smartphone-based and portable sensor technologies

The integration of silver and gold nanoparticle-based nanosensors with smartphone platforms and portable devices has emerged as a transformative approach for on-site detection of toxic heavy metals such as Hg²⁺, Cd²⁺, and Pb²⁺. Smartphone-based sensors leverage the high-resolution cameras, computing power, and wireless connectivity of mobile devices to analyze colorimetric or fluorescence responses from Ag/Au nanosensors, enabling real-time, user-friendly, and low-cost monitoring.[118,119] For instance, colorimetric sensors based on AgNP aggregation or AuNP SPR shifts can be directly quantified using smartphone cameras, eliminating the need for sophisticated spectrophotometers.[120] Portable electrochemical devices integrated with AuNP- or AgNP-modified electrodes, coupled with smartphone interfaces, have demonstrated ultrasensitive detection (sub-nanomolar levels) of Pb²⁺ and Hg²⁺ in environmental water and food samples.[121,77] Recent advances also include lab-on-a-chip microfluidic systems linked to smartphones, which enhance portability, reduce sample consumption, and allow multiplexed detection of multiple heavy metals simultaneously. [122,123] These innovations address the limitations of laboratory-based methods by providing rapid, selective, and in-field detection, making them highly relevant for environmental monitoring, food safety, and public health surveillance, especially in resource-limited settings. [124]



Point of care and on site environmental monitoring devices

The development of point-of-care (POC) and on-site environmental monitoring devices using Ag and Au nanoparticle-based nanosensors has significantly advanced the field of heavy metal detection, offering rapid, portable, and cost-effective alternatives to conventional laboratory methods. Such devices are particularly valuable for detecting toxic metals like Hg^{2+} , Cd^{2+} , and Pb^{2+} in water, soil, food, and biological fluids, where timely monitoring is crucial for public health and environmental safety.[124,118] Colorimetric paper-based strips embedded with AgNPs or AuNPs allow visual readout without the need for complex instrumentation, making them highly suitable for field testing in resource-limited settings.[123,120] Similarly, lab-on-a-chip microfluidic platforms coupled with electrochemical or optical readouts provide multiplexed, real-time detection with high sensitivity and selectivity.[122,121] These systems have been successfully employed for on-site testing of contaminated river water and food products, achieving detection limits comparable to ICP-MS and AAS while maintaining portability and affordability.[125,126] Furthermore, the integration of POC devices with wireless data transmission and smartphone applications enhances real-time decision-making and supports environmental surveillance networks.[127] Overall, these POC nanosensor platforms are paving the way toward sustainable, decentralized monitoring systems that ensure compliance with regulatory limits and safeguard human and ecological health.

Artificial intelligence (AI) and machine learning assisted nanosensing

The integration of artificial intelligence (AI) and machine learning (ML) algorithms with nanosensor technologies has emerged as a powerful approach to enhance the sensitivity, selectivity, and predictive capabilities of heavy metal detection. Traditional nanosensors based on Ag and Au nanoparticles generate complex datasets from optical (colorimetric, SPR), electrochemical, or fluorescence signals, which can be difficult to interpret due to environmental noise, cross-sensitivity, and matrix interferences.[128,129] By applying ML techniques such as support vector machines (SVM), random forests, principal component analysis

(PCA), and deep learning models, researchers can process large-scale sensor data to improve analyte classification, optimize calibration models, and predict ultra-trace metal concentrations in real-world samples.[130,131,132] Recent studies have demonstrated AI-assisted colorimetric analysis using smartphone-captured images of AuNP aggregation, enabling accurate on-site quantification of Hg^{2+} and Pb^{2+} in water and food samples.[133] Furthermore, AI-based signal processing has been applied in electrochemical nanosensors to correct background currents and enhance reproducibility, achieving lower detection limits than conventional approaches.[134,135] The synergy of Nano sensors with AI also facilitates automated, portable, and real-time monitoring systems that integrate wireless data transmission and cloud-based analytics, paving the way for next-generation environmental monitoring and smart POC devices.[136] Overall, AI-assisted Nano sensing significantly expands the analytical performance and practical utility of Ag and Au nanoparticle-based platforms for heavy metal detection through modern nanosensing techniques and it is represented in Figure 6

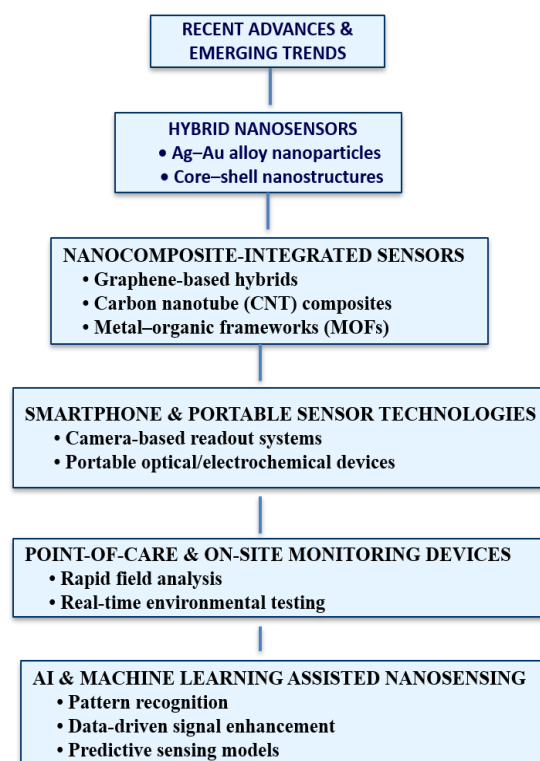


Figure 6: Flow chart of Evolution of Modern Nanosensing Techniques



Limitations and Challenges

Interference from coexisting ions in real samples

One of the major limitations of Ag and Au based nanosensors for heavy metal detection is their susceptibility to interference from coexisting ions and complex matrices present in environmental and biological samples. Although these nanosensors often exhibit high sensitivity under controlled laboratory conditions, the presence of common ions such as Na^+ , K^+ , Ca^{2+} , Mg^{2+} , Fe^{3+} , and Cu^{2+} can significantly alter sensor responses by inducing non-specific aggregation, competing for binding sites, or modifying the surface plasmon resonance (SPR) signals.[137,138] Additionally, natural organic matter (e.g., humic acids, proteins, and polysaccharides) can adsorb onto the nanoparticle surface, leading to signal suppression or false positives.[139,140] For example, AuNP-based colorimetric assays for Hg^{2+} detection have shown reduced selectivity in river water due to competitive binding from Cu^{2+} and Fe^{3+} ions.⁵ Similarly, AgNP sensors designed for Pb^{2+} detection demonstrated cross-reactivity when Zn^{2+} and Cd^{2+} were present in comparable concentrations.[141] To overcome these issues, strategies such as surface functionalization with thiols, DNA aptamers, peptides, or chelating ligands have been explored to improve selectivity; however, these approaches often increase synthesis complexity and cost.[142,143] Thus, minimizing interference from coexisting ions remains a critical challenge in translating nanosensors from proof-of-concept studies to reliable real-world applications.

Stability and reproducibility of nanoparticle-based sensors

The stability and reproducibility of nanoparticle-based sensors, particularly those utilizing silver and gold nanostructures, remain critical challenges for their practical application in heavy metal detection. Nanoparticles are prone to aggregation, oxidation, and surface modification during storage or upon exposure to environmental matrices, leading to changes in their optical, electrochemical, and catalytic properties and thus compromising sensor reliability.[145,146] For instance, AgNPs can undergo surface oxidation or dissolution, causing a drift in colorimetric or electrochemical signals, while AuNPs, though more

chemically stable, may still aggregate in high-salt or protein-rich samples, reducing reproducibility.[147,148]

Additionally, variations in nanoparticle synthesis (size distribution, surface charge, and functionalization efficiency) often result in batch-to-batch inconsistencies, leading to poor reproducibility across experiments and laboratories.[149,150] Some strategies to address these issues include surface coating with polymers, silica shells, or biomolecules, which improve colloidal stability and extend sensor shelf-life, as well as standardized synthesis and storage protocols.[151,152] However, achieving long-term stability and reproducibility while retaining high sensitivity and selectivity remains a key barrier to the commercialization and real-world deployment of nanosensors.

Issues of scalability and commercialization

Despite significant advancements in the design and performance of silver and gold nanoparticle-based nanosensors for detecting heavy metals, their scalability and commercialization remain major hurdles. Laboratory-scale synthesis methods such as chemical reduction, seed-mediated growth, or biomolecule-assisted fabrication often lack the reproducibility, uniformity, and cost-efficiency required for industrial-scale production.[153,154] Batch-to-batch variations in nanoparticle size, shape, and surface functionalization affect sensor reliability and regulatory approval, creating barriers for large-scale deployment.[155] Moreover, challenges related to long-term stability, storage, and integration into portable or automated devices hinder commercialization efforts, especially for point-of-care and field-based applications.[156,157] Another concern is the high production cost of noble metals (Au, Ag), which limits affordability for widespread monitoring in developing regions where heavy metal pollution is most critical.[158,159] Additionally, the lack of standardized protocols, regulatory frameworks, and large-scale validation in real-world samples slows down the transition of nanosensor prototypes from research labs to market-ready products.[160] Addressing these issues requires scalable, green synthesis routes, robust surface modifications, and the development of standardized testing guidelines to ensure commercial viability and regulatory compliance.



Environmental and toxicological concerns of nanomaterials themselves

While silver and gold nanoparticle-based nanosensors show great promise for heavy metal detection, their own environmental and toxicological impacts raise significant concerns. Upon release into ecosystems during synthesis, usage, or disposal, AgNPs and AuNPs can undergo aggregation, dissolution, or surface transformations, influencing their persistence and mobility in soil and aquatic systems.[161,162] Silver nanoparticles, in particular, may release Ag^+ ions, which exhibit antimicrobial properties that can disrupt beneficial microbial communities, soil fertility, and aquatic food chains.[93,163]

Gold nanoparticles are generally considered biocompatible, but studies have shown that prolonged exposure can lead to oxidative stress, inflammation, and cytotoxicity in mammalian cells, depending on their size, shape, and surface chemistry.[164,165] The small size and high reactivity of these nanomaterials also increase the risk of bioaccumulation and trophic transfer, raising concerns about long-term ecological consequences.[166] Furthermore, the lack of standardized ecotoxicological testing protocols and limited data on chronic exposure and environmental fate hinder accurate risk assessment.[167] To ensure sustainable application of nanosensors, future work must focus on green synthesis approaches, biodegradable nanocomposites, and lifecycle assessment studies that evaluate both efficacy and environmental safety.

Future Perspectives

Development of multi-analyte detection platforms

Traditional nanosensors are often designed to detect a single target ion; however, in real-world samples, multiple heavy metals such as Hg^{2+} , Cd^{2+} , and Pb^{2+} frequently coexist, necessitating the development of multi-analyte detection platforms. Recent advances in silver and gold nanostructures, particularly in combination with graphene, DNA-functionalization, and metal-organic frameworks (MOFs), have enabled simultaneous recognition of multiple toxic metals with high sensitivity, selectivity, and minimal cross-interference.[168,169] Multi-analyte detection strategies utilize differential colorimetric responses, unique fluorescence signatures, and electrochemical redox

peaks, allowing parallel monitoring within a single platform.[170,171] For instance, AuNP-based ratiometric colorimetric sensors have been reported for distinguishing Hg^{2+} , Pb^{2+} , and Cd^{2+} based on distinct surface plasmon resonance (SPR) shifts, while Ag nanoclusters conjugated with DNA have been engineered for multiplexed fluorescent detection of coexisting metal ions.[172,173] The integration of nanomaterials with microfluidics and smartphone-based readouts further enhances their potential for rapid, on-site, and low-cost multi-metal monitoring.[174,175] Such platforms are particularly valuable for environmental surveillance and food safety, where simultaneous detection is more practical and efficient than sequential single-analyte testing.

Sustainable and green synthesis of nanoparticles

The conventional chemical synthesis of silver and gold nanoparticles often involves toxic reducing and stabilizing agents, raising environmental and health concerns. In response, green synthesis approaches utilizing biological and eco-friendly resources such as plant extracts, microorganisms, polysaccharides, amino acids, and natural polyphenols have emerged as sustainable alternatives.[176,177] These methods exploit phytochemicals (e.g., flavonoids, terpenoids, phenolic acids) or microbial enzymes as reducing and capping agents, thereby eliminating hazardous chemicals while offering better biocompatibility, stability, and scalability.[178,179] Green-synthesized Ag and Au nanoparticles have demonstrated strong plasmonic, catalytic, and sensing properties comparable to chemically synthesized counterparts, with added benefits of renewability and reduced toxicity.[180,181] Furthermore, recent advances have integrated waste-derived biomass, agricultural by-products, and even food waste extracts for nanoparticle production, aligning with the principles of circular economy and sustainable nanotechnology.[81,182] These eco-friendly nanomaterials not only reduce the ecological footprint of synthesis but also hold promise for real-world applications in heavy metal sensing, environmental remediation, and biomedical diagnostics.

Regulatory acceptance and standardization of nanosensors

Despite the rapid progress in nanosensor technologies for heavy metal detection, their regulatory acceptance and



integration into official monitoring frameworks (WHO, EPA, BIS, ISO) remain limited due to the absence of standardized validation protocols, safety evaluations, and reproducibility criteria. Current regulatory bodies such as the U.S. Environmental Protection Agency (EPA) and the World Health Organization (WHO) primarily rely on well-established analytical techniques (AAS, ICP-MS) for compliance testing, while nanosensors are still largely considered emerging or complementary tools.[183,184] A major challenge lies in the lack of harmonized standards for nanoparticle synthesis, surface functionalization, calibration, and performance benchmarking across different laboratories and real matrices.[185,186] Furthermore, issues of toxicological risk assessment, environmental safety of nanomaterials, and long-term stability must be addressed to gain regulatory confidence.[167,187] Recent initiatives by ISO (International Organization for Standardization) and OECD (Organization for Economic Co-operation and Development) are working towards frameworks for nanomaterial characterization, environmental risk assessment, and validation of nano-enabled sensors, which may pave the way for their broader acceptance in water, soil, and food quality monitoring.[188,189] Thus, achieving global regulatory approval and standardization will require interdisciplinary efforts involving scientists, policymakers, and industry to ensure safety, reproducibility, and comparability of nanosensor-based methods with conventional gold-standard techniques.

Integration with IoT for real-time monitoring

The integration of nanosensors with the Internet of Things (IoT) has emerged as a transformative approach for real-time, remote, and continuous monitoring of toxic heavy metals such as mercury, cadmium, and lead in environmental and biological systems. By coupling nanosensor platforms (optical, electrochemical, or fluorescence-based) with wireless communication modules, cloud storage, and mobile interfaces, IoT-enabled sensing networks can provide rapid data transmission, geospatial mapping, and predictive analytics, overcoming the limitations of conventional offline laboratory-based techniques.[190,191] For example, AgNP- and AuNP-based colorimetric and electrochemical nanosensors have been successfully integrated into IoT architectures for on-site water quality monitoring, enabling rapid detection of Pb^{2+} and Hg^{2+} at

sub-ppb levels with smartphone readout and Bluetooth connectivity.[192,193] Furthermore, IoT-enabled nanosensors allow large-scale environmental surveillance, early warning systems for contamination events, and integration with machine learning algorithms for trend analysis and decision support.[194,195] Challenges remain in terms of sensor stability, power consumption, data security, and interoperability with regulatory frameworks, but ongoing developments in 5G-enabled networks, flexible electronics, and cloud-based analytics are paving the way for the widespread deployment of IoT-nanosensor systems in water, soil, food, and biomedical monitoring.[196,197]

Opportunities in healthcare, food safety, and environmental monitoring

Silver and gold nanoparticle-based nanosensors offer immense opportunities across healthcare, food safety, and environmental monitoring, owing to their high sensitivity, selectivity, and adaptability for portable detection platforms. In healthcare, AuNP and AgNP sensors have been employed for monitoring toxic metal exposure in biological fluids (blood, urine, saliva), enabling early diagnosis of heavy metal poisoning and supporting personalized medicine.[197,198] In food safety, nanosensors provide rapid detection of trace Hg^{2+} , Cd^{2+} , and Pb^{2+} in fruits, vegetables, seafood, and dairy products, ensuring compliance with regulatory standards and preventing chronic dietary exposure to heavy metals.[199,200] Moreover, the integration of nanosensors into packaging materials and smartphone-based systems enhances real-time food quality assessment and consumer safety. In the domain of environmental monitoring, AgNP- and AuNP-based nanosensors allow on-site detection of contaminants in water, soil, and air, offering advantages over conventional laboratory-based methods through portability, lower costs, and real-time data transmission when integrated with IoT technologies.[192,195] These versatile applications highlight nanosensors as multi-sectoral tools that bridge gaps between diagnostics, food security, and environmental sustainability, paving the way for next-generation monitoring and decision-making systems.[194,196]



Summary of current status and key findings

Research on silver and gold nanoparticle-based nanosensors has made significant progress in recent years, establishing them as promising alternatives to conventional heavy metal detection techniques. Current studies demonstrate that optical nanosensors, particularly those based on colorimetric and surface plasmon resonance (SPR) responses, provide rapid, visible, and instrument-free detection of Hg^{2+} , Cd^{2+} , and Pb^{2+} at trace levels with high sensitivity and selectivity.[202,203] Similarly, electrochemical nanosensors, often utilizing modified electrodes with AgNPs or AuNPs, offer ultra-low detection limits and enhanced reproducibility, making them suitable for real-world applications in water and food testing.[204,205] Advances in fluorescent Ag nanoclusters and AuNP-based quenching/enhancement mechanisms further improve detection sensitivity, enabling applications in biological fluids for monitoring heavy metal exposure.[206,207] Importantly, recent studies highlight the integration of nanosensors with graphene, carbon nanotubes, and MOFs, as well as the development of hybrid Ag–Au nanostructures, which enhance stability, surface functionality, and multiplexed detection capabilities.[208,209] In practical applications, these nanosensors have been successfully deployed in detecting trace heavy metals in drinking water, milk, seafood, soil, and human urine, showing strong agreement with standard laboratory techniques and confirming their translational potential.[210] Despite challenges such as interference from coexisting ions, stability issues, and limited regulatory standardization, the field is rapidly moving toward portable, smartphone-based, and IoT-integrated sensing platforms, supported by AI-assisted data analysis for real-time monitoring.[212] Collectively, these advancements highlight nanosensors as cost-effective, sensitive, and sustainable tools with broad applicability in healthcare, food safety, and environmental protection, while ongoing efforts are focused on improving scalability, biocompatibility, and commercialization.

Importance of silver and gold nanosensors in addressing global heavy metal pollution

Heavy metal contamination, particularly by mercury, cadmium and lead, poses a severe threat to environmental sustainability and human health due to their toxicity, persistence, and bioaccumulation,

necessitating sensitive and rapid monitoring tools worldwide. Conventional analytical methods such as atomic absorption spectroscopy (AAS), inductively coupled plasma mass spectrometry (ICP-MS), and voltammetry, though accurate, are expensive, time-consuming, and unsuitable for on-site detection. In this context, silver and gold nanoparticle (AgNPs and AuNPs)-based nanosensors have emerged as powerful alternatives due to their unique optical (surface plasmon resonance), electrochemical, and fluorescence properties, which enable ultrasensitive, selective, and portable detection of trace metals in complex matrices. Their ease of functionalization with ligands, DNA, or biomolecules enhances specificity, while integration into smartphone-based and IoT-enabled sensing platforms supports real-time monitoring in resource-limited settings. Importantly, AgNPs and AuNPs offer cost-effectiveness, rapid response times, and adaptability for diverse real-world applications, including thermal stability [201], water quality monitoring, chemical oxygen demand, food safety testing, and biological fluid analysis, thereby addressing critical gaps in global heavy metal surveillance and contributing to sustainable environmental management and public health protection. [202,203,208, 211]

Future outlook and potential research directions

The future of silver and gold nanoparticle-based nanosensors lies in their transition from laboratory demonstrations to robust, field-deployable platforms that can address the pressing global challenge of heavy metal pollution. Current research highlights the need to overcome challenges of stability, reproducibility, interference from coexisting ions, and large-scale manufacturing, which remain barriers to commercialization. Future directions include the development of multi-analyte detection systems capable of simultaneously monitoring mercury, cadmium, and lead in real-world samples, as well as integration with graphene, carbon nanotubes, and metal–organic frameworks (MOFs) to enhance sensitivity and selectivity. Advances in green and sustainable nanoparticle synthesis using plant extracts, biopolymers, and waste-derived precursors can improve environmental compatibility, while machine learning and AI-assisted nanosensing will accelerate data processing, pattern recognition, and predictive analytics in complex matrices. Moreover, the integration of



nanosensors with Internet of Things (IoT)-enabled portable and smartphone-based devices will facilitate real-time environmental and biomedical monitoring in resource-limited settings. Future studies must also address the toxicological implications of nanomaterials themselves, ensuring regulatory acceptance and standardization. By bridging nanotechnology, materials science, artificial intelligence, and environmental engineering, AgNP and AuNP-based nanosensors are poised to play a transformative role in sustainable monitoring of heavy metals, contributing significantly to global efforts aligned with UN Sustainable Development Goals (SDGs) for clean water, food safety, and public health [202,208,125]

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