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Noble Metal Nanoparticles and Their Application as Sensors for Water Quality Monitoring: A Review

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ABSTRACT:

Noble metal nanoparticles, including gold, silver, platinum, and palladium, have garnered significant attention for their potential applications as sensors in water quality monitoring. Despite extensive research on the individual synthesis and properties of these nanoparticles, a comprehensive review focusing on their collective application in detecting water pollutants has been lacking. This review is crucial as it addresses a significant gap in the literature, highlighting the unique capabilities of noble metal nanoparticles in environmental monitoring. We systematically examine various synthesis methods for these nanoparticles, including chemical reduction, electrochemical techniques, and green synthesis, providing a detailed overview of each approach's advantages and limitations. It further explores the unique properties and characteristics of noble metal nanoparticles, such as their high surface area, tunable optical properties, and excellent conductivity, which make them particularly suitable for sensing applications. The detection mechanisms of these nanoparticles as sensors are analyzed, focusing on their ability to detect various water pollutants through techniques such as surface plasmon resonance (SPR), electrochemical sensing, and colorimetric detection. Our comprehensive examination reveals that noble metal nanoparticles exhibit remarkable sensitivity and selectivity towards a wide range of contaminants, including heavy metals, organic compounds, and pathogens, offering promising solutions for real-time and on-site water quality assessment. The major findings underscore the significant potential of these nanoparticles in enhancing the accuracy and efficiency of water quality monitoring systems. This review provides a valuable resource for researchers and policymakers, emphasizing the transformative potential of noble metal nanoparticles in ensuring safe and clean water resources.

1. Introduction

Water is an indispensable resource for life on Earth, yet it faces escalating threats from pollution driven by the growing global population and the concomitant demand for goods and services dependent on water [1]. Water bodies around the world are increasingly contaminated with various pollutants, including heavy metals, insecticides, and organic compounds, originating from both natural sources and human activities (see Figure 1). In many developing nations, poorly treated domestic, industrial, and agricultural wastewater is frequently discharged into the environment, leading to high concentrations of harmful metals [2]. Mercury, classified by the World Health Organization as a neurotoxicant and immunotoxic, has a long half-life in human brains, posing significant public health risks [3]. Similarly, chromium, a toxic metal found in water from both natural and anthropogenic sources, can cause a range of health issues from skin irritation to DNA damage and cancer, depending on exposure levels [4]. Lead contamination in drinking water is associated with severe health risks, including cancer, stroke, and kidney disease in adults, developmental issues, brain damage, and lower IQ levels in children [5]. Research has shown that minor populations in the semi-arid region of East India are particularly vulnerable to both carcinogenic and noncarcinogenic diseases primarily through oral exposure[6]. The unchecked discharge from industrial

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sites and agricultural runoff further exacerbates the problem, rendering water unfit for human consumption [7]. These persistent metals are toxic to aquatic life and humans even at low exposure levels, leading to detrimental effects on aquatic ecosystems such as the death of aquatic organisms, algal blooms, habitat damage from sedimentation and debris, increased water flow, and various short- and long-term toxicities from chemical contaminants [8]. In addition to heavy metals, agricultural practices contribute significantly to water contamination through the use of insecticides, which enter water bodies via leaching and runoff. Over half of the detected pesticide concentrations exceed regulatory thresholds, posing significant risks to aquatic biodiversity and human health [9]. Insecticide exposure can lead to acute and chronic toxicity, affecting various organs and systems in living organisms [10]. Organophosphorus and carbamate insecticides, for instance, inactivate acetylcholinesterase in both insects and mammals, causing toxic effects through structural requirements and metabolic activation or degradation [11]. Furthermore, dithiocarbamates, a category of fungicides, are cytotoxic and should be considered broad-spectrum biocides for aquatic organisms [12]. Groundwater pollution also presents significant challenges, with hydrogen sulfide contamination causing a rotten egg smell and unpleasant taste, leading to nausea and vomiting, and prolonged exposure resulting in severe gastrointestinal and neurological symptoms [13]. Agricultural non-point sources, including fertilizers, pesticides, and animal wastes, seep into the soil, causing health issues for both humans and aquatic life [14]. In Northern India, groundwater pollution is exacerbated by the influx of contaminated Ganga River water and pesticide residues washed into the ground by monsoon rains, highlighting the significant impact of agricultural practices on water quality [15]. To address the issue of water contamination, it is crucial to identify and quantify the pollutants. This necessitates the use of rapid and reliable analytical tools for environmental monitoring. Noble metal nanostructures have garnered significant attention in nanotechnology due to their unique properties, including substantial optical field enhancements that generate intense light scattering and absorption [16]. These nanoparticles are widely used as color labels and signal generators in the fabrication of colorimetric assays and sensors due to their simplicity and practicality [17]. Nanoparticle-based environmental sensors hold significant promise for detecting toxins, heavy metals, and organic pollutants in air, water, and soil. They are expected to play an increasingly important role in environmental monitoring, enhancing the detection and sensing of pollutants and aiding in the development of new remediation technologies [18]. This review will focus on the use of noble metal nanoparticles in sensing contaminants in water sources, including heavy metal ions, insecticides, pesticides, and microbes, demonstrating their potential as effective environmental monitors.

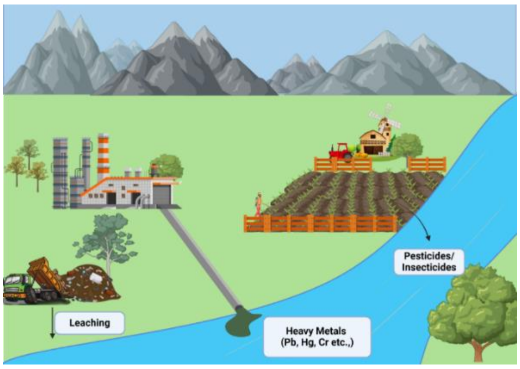

Figure 1 Various Sources of Water Contaminants

2. Synthesis of Noble Metal Nanoparticles

2.1 Gold Nanoparticles

Gold nanoparticles, synthesized via various methods, revolutionize nanotechnology applications [19]. Both top-down and bottom-up approaches enable precise control over nanoparticle properties. Employing a two-step chemical reduction and centrifugation method yielded high-concentration gold nanoparticles with exceptional stability [20]. Continuous flow microreactors provide a versatile platform for direct synthesis of gold nanoparticles, highlighting advancements in nanoparticle fabrication [21]. Biogenic synthesis using plant extracts offers environmentally friendly routes to gold nanoparticle production, as demonstrated with *Sansevieria roxburghiana* and *Pogostemon benghalensis* extracts [22,23]. Additionally, innovative approaches utilizing amino acids and essential oils as reducing agents showcase advancements in green synthesis methods. Furthermore, gold nanoparticles synthesized from tetraauric acid using various amino acids as reducing agents demonstrate the versatility of biogenic synthesis [24]. Green chemistry applications include the catalytic reduction of 4-nitrophenol to 4-aminophenol by gold nanoparticles derived from a glucan derived from an edible mushroom [25].

2.2 Silver Nanoparticles

Robust synthesis of silver nanoparticles from aqueous $AgNO_3$ highlights their promising antimicrobial properties [26]. Various methods, including chemical reduction and plant extract-mediated synthesis, provide versatile routes to silver nanoparticle fabrication [27]. Light-assisted synthesis using LED and sunlight enhances nanoparticle production efficiency, expanding the scope of silver nanoparticle synthesis [28]. Notably, silver nanoparticles exhibit significant inhibitory activity against both Gram-positive and Gram-negative bacteria, indicating their potential in antimicrobial applications [29]. Additionally, silver nanoparticles synthesized from *Withania somnifera* leaf powder under direct sunlight demonstrate the influence of blue light in the reduction process [30]. Green synthesis of silver nanoparticles using *Zosimia absinthifolia* leaf extract provides a cost-effective and eco-friendly alternative to conventional methods [31].

2.3 Platinum Nanoparticles

Precise control over size and properties is achieved in platinum nanoparticle synthesis through photoreduction and plasma-chemical reduction methods [32,33]. Green synthesis approaches, such as utilizing wood nanomaterials and protein cavities, underscore environmentally friendly strategies in nanoparticle fabrication [34,35]. Catalytic activity in Suzuki-Miyaura cross-coupling reactions and hydrogenation positions platinum nanoparticles for diverse industrial processes [36]. Furthermore, the use of dendrimers and phosphine ligands as stabilizing agents enhances nanoparticle catalytic performance and reusability [37]. Quail egg yolk, known for its high vitamin and protein content, serves as a unique medium for green synthesis of platinum nanoparticles [38].

2.4 Palladium Nanoparticles

High catalytic efficiency is demonstrated in palladium nanoparticle synthesis using plant metabolites and polyphenols[39]. Green synthesis methods, including photoassisted citrate reduction and biomolecule-mediated synthesis, offer sustainable routes to palladium nanoparticle production [40]. Functionalization with nitrogen-doped carbon nanostructures enhances catalytic activity and magnetically separable properties of palladium nanoparticles [41]. Protein cavity-mediated synthesis provides a novel approach for stabilizing palladium nanoparticles, showing promise in biocatalysis applications[42]. Phosphine dendrimer-stabilized palladium nanoparticles demonstrate high effectiveness in the Suzuki-Miyaura reaction and hydrogenation, offering superior product yields, turnover numbers, and reusability[43]. Moreover, the hydrothermal synthesis of a novel palladium electrocatalyst using a composite of copper phthalocyanine-3,4′,4″,4‴- tetrasulfonic acid tetrasodium salt functionalized multi-walled carbon nanotubes as the catalyst support for Palladium nanoparticles showcases innovative approaches in palladium nanoparticle synthesis [44].

3. Properties and Characteristics of Noble Metal Nanoparticles

Noble metal nanoparticles, including gold, silver, platinum, and palladium, are notable for their exceptional functional qualities and strong resistance to oxidation and corrosion, making them invaluable in biotechnology and biomedicine [45]. These nanoparticles are characterized by their unique optical, spectroscopic, and physicochemical properties, which significantly enhance bioanalyte detection in biosensing platforms [46]. The exceptional inherent qualities and wide range of applications of noble metal nanoparticles have made metals like gold, silver, platinum, and palladium increasingly significant [45]. For instance, gold and silver nanostructures exhibit substantial optical field enhancements that cause them to scatter and absorb light efficiently, making them ideal for biological, medical, and imaging applications [47]. Noble metal nanoparticles exhibit their well-defined spectroscopic features, such as optical absorption, emission, and luminescence, in the visible-near-infrared window. The fascinating optical characteristics of these nanoparticles are primarily influenced by surface plasmon resonance (SPR), which is affected by factors like the metal type, particle size and shape, and surrounding medium [48]. This resonant oscillation of free electrons in the presence of light, known as localized surface plasmon resonance (LSPR), enhances their optical and photothermal properties [47].

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The unique optical responses of noble metal nanoparticles, due to their superior LSPR characteristics, allow for the visual detection of various analytes with the naked eye [49]. Additionally, the plasmon band in colloidal solutions of gold, silver, or copper contributes to their substantial absorption in the visible spectrum [50]. These properties are particularly beneficial in the detection and treatment of diseases such as cancer, HIV, TB, and Parkinson's disease [51]. Noble metal nanoparticles' size- and shape-dependent plasmon resonance is crucial for the detection of pollutants [52]. For example, proteins and bacteria can be efficiently detected using varying sizes of unaltered noble metal nanoparticles in a colorimetric sensor array, which has significant implications for medical diagnostics [53]. Maintaining the size and form of these nanoparticles during the extraction process is essential for the efficient and selective identification of pollutants in environmental water [54]. Noble metal nanostructures also serve as effective adsorbents for identifying and eliminating contaminants in drinking water due to their size- and shape-dependent characteristics [55]. The surface plasmon resonance of conduction electrons in these nanoparticles, which depends on the particle morphology and shape evolution, plays a key role in their application in visible light harvesting processes and metal-semiconductor composite photocatalysts [56,57]. The distinctive properties of noble metal nanoparticles, including their LSPR and optical enhancements, make them highly suitable for a wide range of applications in detecting contaminants in water bodies. Careful selection of nanoparticle size and composition can significantly improve the effectiveness of color sensing tests, thereby advancing the identification and mitigation of environmental pollutants [58].

4. Detection Mechanism as sensors

Nanoparticles serve as versatile sensors, detecting analytes through alterations in colorimetric, fluorescent, or electrochemical properties, enabling specific detection based on analyte concentration [59]. Various methods for heavy metal ion determination include atomic absorption spectroscopy, atomic fluorescence spectrometry, and electrochemical sensing platforms. Among these, colorimetric sensing technology utilizing nanoparticles has emerged as an efficient approach[60]. Noble metal nanoparticles serve as highly accurate and sensitive visual biosensors for detecting various compounds, offering a simple and reliable method for visual quantification [61]. Colorimetric assays employing gold nanoparticles enable ultrasensitive and selective detection of heavy metal ions such as mercury, offering on-site and real-time analysis [62]; [63]. Additionally, the interaction between noble metal nanoparticles and various molecules enables accurate and sensitive detection of toxins, nucleic acids, and proteins [64]. Nanoparticle surface modifications facilitate the determination of analytes, offering broad prospects in sensing pollutants [65]. Electrochemical detection methods utilizing nanomaterials exhibit increased sensitivity and decreased detection limits, promising applications in diagnostics and environmental safety [66]. Furthermore, noble metal nanoparticles serve as plasmonic nanosensors, enabling single-molecule detection through surface-enhanced Raman scattering and fluorescence [67]. Surface functionalization of metal nanoparticles enhances their optical and electronic properties, expanding their applications in sensing [68]. Noble metal nanoparticles, easily functionalized through simple chemistry, offer enhanced capabilities in specific analyte detection [69]. For instance, NADH-functionalized silver nanoparticles provide highly selective optical sensing of mercuric ions[70].The synergy between platinum nanoparticles and single-wall carbon nanotubes enhances sensitivity towards hydrogen peroxide, exemplifying surface functionalization strategies [71]. Overall, noble metal nanoparticles exhibit unique properties and diverse applications in biomedicine, including therapeutics, diagnostics, and sensing[72].

In conclusion, the integration of noble metal nanoparticles into sensing platforms offers remarkable potential for highly sensitive and selective detection of various analytes, spanning environmental monitoring to biomedical applications. These nanoparticles, with their facile functionalization and unique optical and electronic properties, hold promise for advancing sensing technologies in diverse fields.

5. Applications of Noble Metal Nanoparticles as sensors

5.1 Gold Nanoparticles

Various innovative methods leveraging the unique properties of gold nanoparticles have been developed for sensitive and selective detection of contaminants in water

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sources, addressing critical environmental and public health concerns. Label-free gold nanorod-based plasmonic sensing effectively detects arsenic(III) by suppressing the oxidative shortening of gold nanorods, enabling real-time assessment of contamination levels [73]. A colorimetric assay utilizing a DNAzyme sensitive to lead(II) ions has been devised for lead contamination detection in water [74]. Lead exposure poses severe health risks, particularly for children, affecting neurological development and causing long-term cognitive impairments. Moreover, gold plasmon nanoparticles functionalized with 3-mercaptopropionic acid (3-MPA) present a promising approach for water quality monitoring, offering selective detection and quantification of chromium(III) [75]. Chromium contamination in water sources, often stemming from industrial activities, can have serious health implications, including carcinogenic effects, underscoring the importance of sensitive detection methods for effective environmental remediation. Mercury(II) ions, another hazardous contaminant in water, can be detected using gold nanoparticles functionalized with label-free oligonucleotide sequences via thymine-Hg(II)-thymine coordination chemistry[76]. Ultrasensitive detection of mercury ions in water is achieved using a DNA-functionalized Molybdenum Disulfide nanosheet/gold nanoparticle hybrid sensor, surpassing EPA-recommended levels[77]. Furthermore, a gold-nanoparticle-Rhodamine 6 G-based fluorescence sensor enables sensitive and selective detection of mercury(II) ions in water[78]. Various other applications include detection of ractopamine using a molecular imprinting polymer (MIP)--based electrochemical sensor [79], copper ion detection with high sensitivity using an electrochemical sensor[80], and low detection limits for mercury and ziram in water using gold nanoparticle-based microfluidic sensors [81]. Gold nanoparticles derived from *Solanum trilobatum* leaf extract exhibit high sensitivity in detecting cadmium(II) ions [82] , while ultrasensitive silver ion detection is achieved using gold nanoparticles [83]. Cyanide detection in water is enabled by gold-nanocluster-based fluorescence sensors [84] and hazardous anions can be detected using gold nanoparticle-based nanosensors [85] . Moreover, nitrite ions in drinking water can be detected using gold nanoparticles based on their plasmonic properties and catalytic effect [86]. Thiolated azido derivatives and active esters modify gold nanoparticles for hydrogen sulfide detection in lake water [87] and a colorimetric sensor array composed of citrate-capped gold nanoparticles is proposed for detecting and distinguishing various organophosphate pesticides in water sources [88]. *Escherichia Coli* O157:H7 may be quickly and accurately detected in water samples by employing an electrocatalytic gold nanoparticle immunosensing assay [89]. Lastly, organophosphorus and carbamate pesticide detection in complex solutions can be achieved using a rhodamine B-covered gold nanoparticle-based assay [90]. These innovative methods represent significant advancements in nanotechnology and analytical chemistry, offering versatile approaches to address diverse challenges in water quality monitoring.

5.2 Silver Nanoparticles

Silver nanoparticles, a type of noble metal, are important in various applications due to their aesthetic appeal, corrosion resistance, and high thermal stability [91]. They are particularly useful in contamination sensing due to their broad linearity range and excellent selectivity towards cationic Ag^+ ion activity [92]. These nanoparticles can interact with heavy metals in water samples in a highly effective and selective manner, contributing to potential water remediation applications [93]. They provide reliable data for risk assessment and environmental monitoring when detecting heavy metals in surface water [94]. In conjunction with nitrogen-doped graphene, they form a highly sensitive biosensing platform with a low detection limit, enabling the identification of pesticides [95]. They can also employ UV light scattering and post-sample fluorescence detection to identify heavy metal ions in water, such as mercury, lead, and methylmercury [96]. Furthermore, they can detect potentially dangerous Hg(II) ions in water at micromolar concentrations and across a wide pH range [97]. When coated on chitosan foam, they can actively collect analytes in solution and on solid surfaces, proving useful for sensing pollutants [98]. With a linearity of 0.97 and a limit of detection of 1.5 ppb, they are effective for sensing pollutants like mercury [99]. They can rapidly degrade water contaminants like methylene blue, methyl orange, and naphthol green B, and detect harmful dithiocarbamate fungicide [100]. Aromatic polyphenols such as gallic acid, pyrogallol, and tannic acid can be visually detected in water samples using silver nanoparticles [101]. Silver nanoparticles stabilized with

cysteamine are highly sensitive and selective for the rapid colorimetric detection of Hg(II) ion in water, with a limit of detection of 0.273 nM [102]. At low concentrations, heavy metals in water can be effectively detected using an electronic tongue that combines silver nanoparticles with electrospun nanofibers [103]. Silver nanoparticles capped with 3-mercapto-1propanesulfonic acid sodium salt, also known as AgNPs-3MPS, exhibit a specific sensitivity of 500 ppb for the detection of heavy metal ions Ni(II) and Co(II) in water [104]. By enhancing bulk conductance and differentiating between various heavy metal ions through sensor and frequency modifications, silver nanoparticles in ternary nanocomposites can detect heavy metals in water [103]. They detect heavy metals by observing changes in the aggregation of the nanoparticles in solution through optical transduction [105]. In conclusion, silver nanoparticles offer a versatile and effective approach for the detection and remediation of water contaminants.

5.3 Platinum nanoparticles

Platinum nanoparticles, known for their diverse sizes and forms, find extensive applications in various fields in sensing [106,107]. Particularly notable are their biomedical uses, especially in angiogenesis and cancer-related illnesses, where they play pivotal roles in detection [102]. Leveraging their unique properties, platinum nanoparticles are integral components in highly sensitive impedimetric aptasensors, facilitating the selective detection of pesticides such as acetamiprid and atrazine [108]. Moreover, nanoelectrodes fashioned from platinum demonstrate efficacy in detecting heavy metals, while glassy carbon electrodes coated with platinum nanoparticles exhibit promising arsenic detection capabilities, with a notable limit of detection of 2.1 +/- 0.05 ppb [109]. Enhanced sensitivity is further exemplified by platinum nanoparticles combined with DNAzymes, boasting a detection limit of 25 nM for heavy metal ions [110]. Notably, the sensitivity of platinum nanoparticle electrodes for heavy metal ion detection is augmented by increased layer electrode thickness, showcasing commendable repeatability and reusability [111]. Furthermore, boron-doped diamond microelectrodes enhanced with platinum nanoparticles enable the detection of arsenite in water with remarkable precision, achieving a detection limit of 0.5 ppb [112]. Beyond heavy metal detection, platinum nanoparticle-modified electrodes prove instrumental in rapidly detecting *Escherichia Coli*, with a detection limit of 20 cfu/mL and a detection time of less than 4 hours [113]. Similarly, these nanoparticles exhibit prowess in identifying hypoxanthine, a sensitive indicator of aquatic product freshness, with exceptional selectivity and recovery rates [114]. Notably, platinum nanoparticles capped with citrate emerge as promising candidates for field detection in various samples, including environmental, biological, and dietary matrices, capable of detecting Hg(II) ions with an impressive detection limit of 8.5 pM [115].

5.4 Palladium Nanoparticles

Palladium nanoparticles showcase remarkable potential in water sensing applications, boasting nearly 100% recovery rates for various pollutants alongside excellent sensitivity, repeatability, and stability [116]. They serve as key components in enhancing analytical performance, such as in simultaneous detection setups for direct yellow 50, tryptophan, carbendazim, and caffeine in water samples, when integrated into graphite pencil electrodes [117]. Moreover, encapsulated palladium nanoparticles offer effective treatment solutions for water contaminated with trichloroethylene, efficiently dechlorinating the chemical in less than an hour [118] Palladium nanoparticles (PdNP's) integrated into porous activated carbons (PACs) enable the creation of electrochemical sensors sensitive enough to detect harmful metal ions like Hg(II), Pb(II), Cu(II), and Cd(II) [119]. They also play crucial roles in electrochemical stripping analysis and ion-selective detection systems, enhancing sensitivity and lowering detection limits for heavy metals [120]. Additionally, palladium nanoparticles demonstrate utility in ultrasonic slurry sampling electrothermal vaporization inductively coupled plasma mass spectrometry for detecting heavy metals like Zn, As, Cd, Sb, Hg, and Pb in biological samples [121]. Furthermore, they serve as highly sensitive and selective sensors for nickel ion detection, with remarkable reliability and detection limits [122]. In the realm of electrocatalytic detection, palladium nanoparticles exhibit promising sensitivity and detection limits, particularly notable in detecting hydrazine [123]. Also, The PdNPs on reduced Graphene oxide Rotating Disk Electrodes(RDE), with a diameter of 3.7 ± 1.4 nm, exhibits a high degree of stability in detecting trace hydrazine in wastewater, indicating its potential utility as an electrochemical sensor [124]. Their catalytic activity

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extends to water-based Sonogashira coupling reactions, showcasing potential for water-based environmental sensing applications [125]. Overall, palladium nanoparticles, with their exceptional recovery rates, stability, and catalytic properties, emerge as valuable assets for environmental sensing in water.

Table 1 Noble metal nanoparticles as sensors for various contaminants with their sensitivity

Nanoparticle Sensor	Contaminant	Sensor type	Sensitivity	Reference
Gold Nanoparticles	Arsenic(III)	Plasmonic sensor	10 – 500 ppb	[73]
	Lead(II)	Colorimetric sensor	100 nM - 200 muM	[74]
	Chromium(III)	Colorimetric sensor	0.34 ppb	[75]
	Mercury(II)	Colorimetric sensor	50nM	[76]
	Mercury(II)	Fluorescence sensor	5 $x10^{-10}$ - 3.5 $x10^{-8}$ mol/L	[78]
	Mercury(II)	Electrochemical sensor	0.1nm	[77]
	Cadmium(II)	Plasmonic sensor	0.058/mM - 0.095/mM	[82].
	Copper(II)	Electrochemical sensor	< 1pm	[80]
	Silver(I)	Electrochemical sensor	470 fM	[83]
	Ractopamine	Electrochemical sensor	0.002 - 0.1 µM	[79]
	Dithiocarbamate	Microfluidic sensor	16 µg/L	[81]
	Anionic fluorosurfactants	Optical Sensors	10 ppb	[85]
	Nitrite Ions	Colorimetric sensor	20 to 35 µM	[86]
	Hydrogen Sulfide	Colorimetric sensor	0.2 µM	[87]
	Organophosphate pesticides	Colorimetric sensor	120-400 ng.m/L	[88]
	Organophosphorus pesticide	Fluorescence sensor	0.1 - 1 µg/L	[90].
	Escherichia Coli O157:H7	Electrochemical (Immunosensing Assay)	309 CFU/mL	[89]
	Escherichia Coli XL1	Electrochemical Sensor	100 CFU/mL	[66]
Silver Nanoparticles	copper(II) and cobalt(II) ions	Fluorescent sensor	40 ppb	[126]
	Organophosphate and carbamate pesticides	Chemiluminescent (CL) sensor array	24 µg/mL	[127]
	Dithiocarbamate fungicide	Spectrophotometric and electrochemical	0.18ppm	[100]
	Cd(II), Cu(II), Ni(II), and Pb(II)	Electrochemical (electronic tongue)	10nM/L	[103]

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	Nile Blue A (NBA) Rhodamine 6G (R6G) Pesticides - triazophos, methidathion and isocarbophos	-	5pg, 10ppb	[128]
	Aptamer-based Pesticide	Electrochemical	3.3×10^{-14} M	[95]
	Ni, Zn, Ba, As, Pb, Co, Cr, and Cu			
	Ni(II) and Co(II)	Colorimetric	0.5–2.0 ppm	[104]
	Mercury, lead, and methylmercury	Electro-optical	Mercury - 2ppm Methylmercury – 8ppm Lead – 15ppm	[96]
	Hg(II) ion	optical sensor	0.55ppb	[102]
	Hg(II)	Colorimetric		[97]
	Aromatic ortho-trihydroxy phenols (gallic acid, pyrogallol and tannic acid)	Colorimetric	1–50 mM	[101]
	Cd (II)	Optical	5ppm	[93]
	Hg(II)	Optical	1.5ppb	[99]
Platinum Nanoparticles	As(III)	Electrochemical	0.5ppb	[112]
	Escherichia Coli	Electrochemical	20 cfu/mL	[113]
	Hg(II), Cu(II) and Ag(II)			
	Hg(II)	Colorimetric	50-500 nM	[129]
	Pb(II)	Biosensor	25 nM	[110]
	As(III),	Electrochemical	2.1 ± 0.05 ppb	[109]
	Hg(II)	Colorimetric	8.5 pM	[115]
	Pesticides: acetamiprid and atrazine	Electrochemical	1pM	[108]
	Hypoxanthine	Fluorescent biosensor	2.88 µM	[114]
Palladium Nanoparticles	Hydrazine	Electrochemical	1.8 mM	[123]
	Direct yellow 50, tryptophan, carbendazim and caffeine	Electrochemical	Direct Yellow - 0.99–9.9 µmol/L Tryptophan- 1.2–12 µmol/L Carbendazium -0.20–1.6 µmol/L Caffeine - 25–190 µmol/L	[130]
	Zn, As, Cd, Sb, Hg and Pb		Zn - 1.9 – 3.6 ng/g As - 0.2 – 0.4 ng/g Cd - 0.5 – 0.8 ng/g	[121]

			Sb - 0.1 – 0.2 ng/g Hg - 0.4 – 0.8 ng/g Pb - 0.4 – 0.6 ng/g	
	Cd(II), Pb(II), Cu(II), and Hg(II)	Electrochemical	Cd(II) - 66.7 µA/µM/cm^2, Pb(II) - 53.8 µA/µM/cm^2, Cu(II) - 41.1 µA/µM/cm^2, and Hg(II) - 50.3 µA/µM/cm^2	[119]
	Ni(II)	Fluorescent sensor	7.26 × 10−9 m	[122]
	As(V), As(III)	-	0.029 g/L	[131]
	4-nitroaniline (4-NA)	Electrochemical	0.17 µmol/L	[116]

6. Future scope and conclusion

In conclusion, noble metal nanoparticles have emerged as indispensable tools in water pollutant sensing, offering unparalleled sensitivity, selectivity, and versatility. Their integration into sensor devices has facilitated rapid and accurate detection of pollutants in water sources, enabling proactive measures to safeguard public health and environmental integrity. However, the journey does not end here. The future scope for noble metal nanoparticle-based sensing is vast and promising. Further advancements in nanoparticle synthesis techniques, sensor design, and detection methodologies hold the potential to revolutionize water quality monitoring. Integration with emerging technologies such as artificial intelligence and Internet of Things can enhance sensor capabilities, enabling real-time, autonomous monitoring of water resources. Additionally, interdisciplinary collaborations between researchers, policymakers, and industry stakeholders are essential for translating research findings into practical solutions and addressing the evolving challenges of water pollution. As we strive towards achieving sustainable water management practices, noble metal nanoparticles will continue to play a pivotal role in ensuring safe and secure access to clean water for present and future generations.

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