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Potential of gold nanoparticles for detecting heavy metal under varying conditions

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Abstract

Heavy metal contamination has been a global environmental issue, posing severe risks to human health and ecosystems. Conventional detection methods, such as atomic absorption spectroscopy and inductively coupled plasma mass spectrometry, have been costly, time-intensive, and require specialized equipment. Gold nanoparticle (AuNP)--based sensors emerged as an alternative due to their unique optical and chemical properties. These sensors functioned on the principle of localized surface plasmon resonance (LSPR) and colorimetric detection, where interactions with heavy metal ions resulted in the aggregation or dispersion of AuNPs, leading to distinct shifts in absorption spectra. For instance, AuNP-based sensors achieved detection limits as low as 0.1 nM for mercury (Hg^{2+}) and 0.5 nM for lead (Pb^{2+}), significantly improving sensitivity over traditional methods. Various detection techniques, including spectrophotometry, fluorescence, and electrochemical methods, were employed to quantify these changes. The review discussed the selectivity and sensitivity of different AuNP-based sensors, emphasizing their applications in environmental monitoring, food safety, and biomedical diagnostics. Challenges such as stability, reproducibility, and real-world implementation were addressed, underscoring the necessity for interdisciplinary collaboration. Future advancements in AuNP sensor technology aimed to enhance detection capabilities while ensuring cost-effectiveness and environmental sustainability in tackling heavy metal contamination

1. Introduction

Heavy metal contamination is a widespread environmental problem that poses serious threats to human health and the environment (Amen *et al.,* 2020; Bashir *et al.,* 2022; Hussain *et al.,* 2021). Heavy metals such as lead, cadmium, mercury, and arsenic are persistent pollutants that can accumulate in the food chain and cause various health problems, including cancer, neurological disorders, and developmental abnormalities. Therefore, the development of sensitive and reliable methods for the detection of heavy metals is of great importance (Farooqi, *et al.,* 2021; Hussain *et al.,* 2017).

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Gold nanoparticles (AuNP) have emerged as a promising platform for the detection of heavy metals due to their unique optical and electronic properties. AuNP exhibit strong surface plasmon resonance (SPR) absorption and scattering, which can be tuned by changing their size, shape, and surface chemistry (Abdollahiyan *et al.,* 2021) . This makes them highly sensitive to changes in their local environment, including the presence of heavy metals. Additionally, AuNP are biocompatible, stable, and easily functionalized, making them ideal for a wide range of sensing applications (Kumar *et al.,* 2019).

This review article aims to provide a comprehensive overview of the use of AuNP for the detection of heavy metals. This review also elaborates the properties and synthesis of gold nanoparticles, current methods for heavy metal detection, and the advantages and limitations of gold nanoparticle-based sensors (Rai *et al.,* 2015). Also, this review will provide a detailed insight for the applications of gold nanoparticle-based sensors in environmental monitoring, food safety, and biomedical applications. Finally, future directions and challenges for the development of gold nanoparticle-based sensors for heavy metal detection have been elaborated.

2. Background on heavy metal contamination

Heavy metal contamination is a global environmental problem that poses serious threats to human health and the environment (Alloway, 2012). Heavy metals are naturally occurring elements that can accumulate in the environment due to human activities such as mining, industrial processes, and improper waste disposal. These heavy metals include lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), chromium (Cr) (Næss *et al.,* 2020). Heavy metals can enter the food chain through contaminated soil, water, and air. Consumption of contaminated food and water can cause various health problems, including cancer, neurological disorders, and developmental abnormalities. Heavy metals can also affect the environment by contaminating water bodies, soil, and air, which can have a detrimental effect on the ecosystem (Ali *et al.,* 2021). Various methods have been developed for the detection and quantification of heavy metals in the environment, including atomic absorption spectroscopy, inductively coupled plasma mass spectrometry, and voltammetry. However, these methods are often expensive, time-consuming, and require sophisticated instrumentation and trained personnel. Therefore, there is a need for simple, cost-effective, and reliable methods for the detection of heavy metals (Jin *et al.,* 2020). In recent years, AuNP have emerged as a promising platform for the detection of heavy metals due to their unique optical and electronic properties (Wu *et al.,* 2020). AuNP can be synthesized with different sizes and shapes, and their surface chemistry can be easily modified to create sensors that are highly sensitive to changes in their local environment. These sensors have the potential to provide a simple and cost-effective solution for the detection of heavy metals in the environment (Oyewole *et al.,* 2019). Figure 1: Shows the different types of heavy metals detected by gold nanoparticles. AuNP can detect various heavy metals due to their unique optical and surface properties. They are commonly used for sensing cadmium (Cd), arsenic (As), chromium (Cr), iron (Fe), lead (Pb), mercury (Hg), zinc (Zn), and copper (Cu). The detection mechanism involves colorimetric, fluorescence, or electrochemical changes upon metal ion binding. These methods offer high sensitivity, selectivity, and rapid detection in environmental and biological samples.

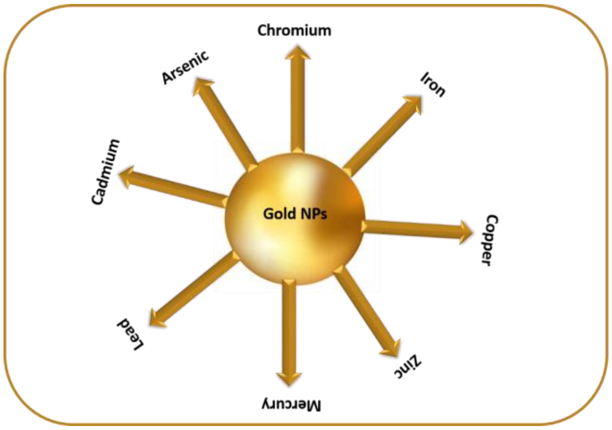

Figure 1. Different types of heavy metal that detect by gold nanoparticles

3. Importance of detecting heavy metal contamination

Detecting heavy metal contamination is important for several reasons. First, heavy metals can have harmful effects on human health and the environment, and their presence in the environment needs to be monitored to ensure public health and safety. Exposure to heavy metals can cause various health problems, including neurological disorders, cancer, and developmental abnormalities (Li *et al.,* 2019). Second, heavy metal contamination can have a significant impact on the environment. Heavy metals can accumulate in soil and water bodies, which can have a detrimental effect on plant and animal life. This can lead to the loss of biodiversity and the disruption of ecosystem services (Mishra *et al.,* 2019). Third, detecting heavy metal contamination is important for compliance with regulatory standards. Many countries have established limits for the levels of heavy metals in food, water, and soil, and it is important to monitor these levels to ensure compliance with these standards (Valente and Durães, 2019). Finally, detecting heavy metal contamination can help identify potential sources of contamination and allow for the development of strategies to prevent further contamination. This can include improved waste management practices, the use of alternative materials, and the development of technologies to remove heavy metals from contaminated soils and water (Selvi *et al.,* 2019).

4. Brief overview of gold nanoparticles

AuNP are clusters of gold atoms that range in size from 1 to 100 nanometers. They exhibit unique optical, electronic, and chemical properties that make them attractive for various applications in biotechnology, nanotechnology, and materials science. AuNP can be synthesized using various methods, including chemical reduction, electrochemical methods, and green synthesis using plant extracts (Ishida *et al.,* 2019).One of the most interesting properties of AuNP is their ability to interact with light. Due to their small size and unique electronic structure, AuNP exhibit a phenomenon known as surface plasmon resonance (SPR), which causes them to strongly absorb and scatter light at specific wavelengths. This property makes them useful for various applications, including biosensing, bioimaging, and drug delivery (Zheng *et al.,* 2021). AuNP can also be functionalized with various molecules, such as antibodies, peptides, and nucleic acids, to target specific biological molecules or cells. This enables them to be used for various biomedical applications, such as cancer diagnosis and therapy, drug delivery, and bioimaging (Cheng and Sun, 2020).

4.1. Synthesis of gold nanoparticles

AuNP can be synthesized using various methods, including chemical reduction, electrochemical methods, and green synthesis using plant extracts.

4.1.1. Chemical reduction

This is one of the most widely used methods for synthesizing gold nanoparticles. In this method, a reducing agent, such as sodium borohydride or hydrazine, is added to a solution of gold salt (e.g., $HAuCl_4$), which results in the reduction of gold ions to gold atoms, which then aggregate to form nanoparticles (Gangwar and Pande, 2021).

4.1.2. Electrochemical methods

Electrochemical methods involve the use of an electrode to reduce gold ions to gold nanoparticles. This method is often used for the synthesis of uniform and monodisperse AuNP (Saldan *et al.,* 2018).

4.1.3. Green synthesis

Green synthesis involves the use of plant extracts or other biological materials as reducing agents for the synthesis of gold nanoparticles. This method is eco-friendly and can be used to produce nanoparticles of various shapes and sizes. Regardless of the method used, the synthesis of AuNP involves the reduction of gold ions to gold atoms, which then aggregate to form nanoparticles. The size and shape of the nanoparticles can be controlled by varying the concentration of the gold salt, the reducing agent, and the reaction conditions (Castillo-Henríquez *et al.,* 2020).

4.2. Properties of AuNP

AuNP exhibit unique physical and chemical properties due to their small size and large surface area to volume ratio. Some of the important properties of gold nanoparticles.

4.2.1. Size and shape-dependent optical properties

AuNP exhibits unique optical properties, such as surface plasmon resonance, which depend on their size and shape. The plasmon resonance results in the absorption and scattering of light, which can be used for various applications, such as biosensing and imaging (Lee *et al.,* 2020).

4.2.2. High surface area to volume ratio

AuNP have a large surface area to volume ratio, which makes them ideal for various applications, such as catalysis, drug delivery, and surface-enhanced Raman scattering (SERS) (Lei *et al.,* 2021).

4.2.3. Chemical stability

Gold is a noble metal that is resistant to corrosion and oxidation, which makes AuNP highly stable in various environments (Hassan *et al.,* 2022).

4.2.4. Biocompatibility

AuNP are biocompatible and do not exhibit any toxic effects on cells, making them ideal for various biomedical applications, such as drug delivery, imaging, and therapy (Bansal *et al.,* 2020).

4.2.5. Surface functionalization

AuNP can be easily functionalized with various biomolecules, such as antibodies, peptides, and nucleic acids, which makes them ideal for various diagnostic and therapeutic applications (Choi and Heo, 2021).

4.3. Functionalization of gold nanoparticles

Functionalization of AuNP involves the modification of their surface with various molecules, such as biomolecules, polymers, and small molecules, to enhance their stability, biocompatibility, and specificity towards certain targets. The functionalization process can be achieved through various methods, including covalent and non-covalent bonding (Li *et al.,* 2019).

4.4. Modification and enrichment of nanoparticulate gold

Thiol chemistry involves the attachment of thiolated molecules, such as thiolated DNA or proteins, to the gold nanoparticle surface through a thiol-gold bond. This method is widely used for the functionalization of AuNP in biosensing and bioimaging applications (Liu and Lämmerhofer, 2019). Polymer coating involves the attachment of various polymers, such as PEG, to the gold nanoparticle surface through electrostatic or covalent interactions. This method can improve the stability, biocompatibility, and solubility of gold nanoparticles, making them suitable for various biomedical applications (Mahato *et al.,* 2019). For instance, AuNP can be conjugated with antibodies through covalent or non-covalent interactions, which can enhance their specificity towards certain targets, such as cancer cells (Nejati *et al.,* 2022). Furthermore, aptamers are short single-stranded DNA or RNA molecules that can bind to specific targets with high affinity and specificity. AuNP can be functionalized with aptamers through covalent or non-covalent interactions, making them ideal for various biosensing and diagnostic applications (Gao *et al.,* 2021). Functionalization of AuNP is a critical step in their use for various applications, as it can improve their stability, biocompatibility, and specificity towards certain targets. The choice of functionalization method depends on the intended application and the properties of the molecules to be attached to the nanoparticle surface (Nejati *et al.,* 2022). (Table. 1) Show the heavy metal and detection of gold nanoparticles

5. Heavy Metal Detection

5.1. Importance of heavy metal detection

The importance of heavy metal detection lies in the potential risks that these contaminants pose to human health and the environment. Heavy metals such as lead, mercury, cadmium, arsenic, and chromium can be present in various sources such as soil, water, air, and food, and can accumulate in the body over time, leading to serious health problems (Nejati *et al.,* 2022). Exposure to heavy metals can cause a range of adverse effects, including developmental and neurological disorders, cancer, liver and kidney damage, and respiratory problems. Heavy metals can also have harmful effects on wildlife, ecosystems, and agricultural production (Rehman *et al.,* 2018). Thus, it is important to detect and monitor heavy metal contamination in various sources to prevent exposure and minimize the risks associated with these contaminants. The development of sensitive and selective detection methods for heavy metals is crucial in identifying contaminated sites and assessing the effectiveness of remediation strategies (Rastogi *et al.,* 2022). AuNP have emerged as promising materials for the detection of heavy metals due to their unique optical and electronic properties, high surface area, and biocompatibility. AuNP can be functionalized with various molecules, such as

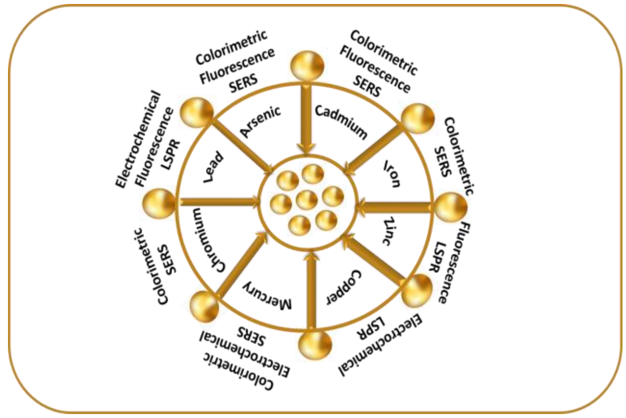

Figure 2: The method used for the detection of heavy metal

ligands or antibodies, to selectively detect heavy metals in different sources with high sensitivity and specificity (Ali *et al.,* 2023). Figure 2 illustrates the methods used for detecting heavy metals using gold nanoparticles. Colorimetric and SERS techniques are used for mercury and iron detection. Colorimetric, fluorescence, and SERS are applied for arsenic, cadmium, and zinc sensing. Electrochemical methods are commonly employed for detecting lead and copper.

5.2. Current methods for heavy metal detection

Several methods are currently available for heavy metal detection. These methods vary in terms of their sensitivity, selectivity, accuracy, and cost. Some common methods for heavy metal detection. Atomic Absorption Spectroscopy (AAS) is a widely used analytical technique that measures the absorption of light by atoms in a sample. It is a sensitive and accurate method for detecting heavy metals in various samples, such as water, soil, and food (Jin *et al.,* 2020). Inductively Coupled Plasma Mass Spectrometry (ICP-MS) is a highly sensitive and precise technique that measures the abundance of elements in a sample. ICP-MS is widely used for the analysis of heavy metals in various samples, including biological tissues, water, and food (Cohen and Walt, 2018). X-ray fluorescence (XRF) Spectroscopy uses X-rays to excite the electrons in a sample, which emit fluorescent X-rays that can be detected and analyzed. XRF is a non-destructive, fast, and accurate method for detecting heavy metals in various samples, such as soils, rocks, and minerals (Andreo and Poludniowski, 2018). Electrochemical Methods use the electrochemical properties of heavy metals to detect their presence in a sample. Common electrochemical methods include anodic stripping voltammetry (ASV), potentiometry, and amperometry (Li *et al.,* 2018). Colorimetric Methods use the color change of a solution or a surface to indicate the presence of heavy metals. Colorimetric methods are simple, inexpensive, and can be easily adapted for field testing. Examples include paper-based colorimetric sensors, dipsticks, and test strips (Fernandes *et al.,* 2020). Biosensors use biological molecules, such as enzymes or antibodies, to detect heavy metals in a sample. Biosensors are highly selective and sensitive, and can be used for real-time monitoring of heavy metal concentrations in various samples (Šestan and Begić, 2019). Moreover, AuNP have unique optical and electronic properties that make them promising materials for heavy metal detection. They can be functionalized with various molecules, such as ligands or antibodies, to selectively detect heavy metals in different samples with high sensitivity and specificity (Zhou and Zhao, 2018).

5.3. Limitations of current methods

Although there are several methods available for heavy metal detection, each method has its own limitations. Here are some common limitations of current methods. Some methods, such as ICP-MS, can be expensive to operate due to the high cost of instrumentation and consumables (Sader and Ryan, 2020). Atomic absorption spectroscopy, require extensive sample preparation and analysis time, which can limit their applicability for real-time monitoring (Hou *et al.,* 2018). Methods may not be sensitive or selective enough to detect low concentrations of heavy metals or distinguish between different types of heavy metals (Tian *et al.,* 2018). X-ray fluorescence, can be destructive to the sample being analyzed, which can limit their use for certain applications (Zhang and Yu, 2021). Few techniques may be affected by interference from other elements or compounds present in the sample, which can lead to false positives or false negatives (Hu *et al.,* 2020). Some methods require specialized training and expertise to operate, which can limit their use in resource-limited settings or for non-experts (Britton *et al.,* 2019).

6. Gold nanoparticles for heavy metal detection

6.1. Advantages of using AuNP for heavy metal detection

There are several advantages to using AuNP for heavy metal detection. The main advantages. AuNP have unique optical and electronic properties that make them highly sensitive to changes in their environment, such as the presence of heavy metals. This allows for the detection of very low concentrations of heavy metals in a sample (Grasseschi *et al.,* 2018). These can be functionalized with specific ligands or antibodies that selectively bind to certain heavy metals, allowing for the detection of specific heavy metal ions in complex mixtures (Zherdev and Dzantiev, 2019). These AuNP are also known to be highly stable and resistant to oxidation and degradation, which allows for long-term storage and reproducible results (Kim and Lee, 2022). Moreover, it can be easily modified to create different types of sensors, including colorimetric, fluorescent, and electrochemical sensors, allowing for a variety of detection methods and applications (Chang *et al.,* 2019). Compared to other nanomaterials, AuNP are relatively inexpensive and easy to synthesize, making them an attractive option for commercial applications (Hu *et al.,* 2020). AuNP are biocompatible and non-toxic, making them safe for use in biological and environmental applications (Lin *et al.,* 2019).

6.2. Types of gold nanoparticle-based sensors

Gold nanoparticle-based sensors can be classified into different categories based on the mechanism of detection, signal readout, and surface functionalization. Main types of gold nanoparticle-based sensors for heavy metal detection. Colorimetric sensors rely on the change in color of AuNP upon exposure to heavy metals. The color change is due to the aggregation or disaggregation of the nanoparticles, which is controlled by the interaction between the heavy metal ions and the surface ligands on the nanoparticles (Zhou and Zhao, 2018). Fluorescent sensors use AuNP as energy acceptors or donors to modulate the fluorescence signal of a fluorophore in the presence of heavy metals. The fluorescence signal can be enhanced or quenched depending on the proximity and energy transfer between the nanoparticles and the fluorophore (Wang *et al.,* 2008). Electrochemical sensors use AuNP as catalytic or conductive materials to enhance the electrochemical signal of heavy metal ions. The AuNP can act as mediators or catalysts to facilitate the redox reaction of the heavy metal ions, or as conductive materials to increase the surface area and electron transfer efficiency of the electrode (Kim *et al.,* 2022). Surface-enhanced Raman scattering (SERS) sensors use AuNP as substrates to amplify the Raman signal of molecules in the presence of heavy metals. The Raman signal is enhanced by several orders of magnitude due to the electromagnetic and chemical enhancement effects of the AuNP (Song and Xia, 2021). Magnetic sensors use AuNP coated with magnetic materials to allow for magnetic separation and concentration of heavy metal ions from complex mixtures. The magnetic properties of the nanoparticles also enable the detection of heavy metal ions by magnetoresistance or magneto-optical methods (Gangwar and Pande, 2021).

6.3. Mechanisms of detection

Gold nanoparticle-based sensors for heavy metal detection operate through different mechanisms, including colorimetric, fluorescent, electrochemical, and surface-enhanced Raman scattering (SERS) sensing. Colorimetric sensing involves a change in the color of the solution in the presence of heavy metal ions. This change is due to the aggregation or dispersion of AuNP caused by the binding of heavy metal ions to the surface of the nanoparticles (Song and Xia, 2021).

Fluorescent sensing uses the change in fluorescence intensity or lifetime of AuNP in the presence of heavy metal ions. The binding of heavy metal ions to the surface of the nanoparticles affects the energy transfer between the AuNP and the fluorophores attached to them, leading to changes in fluorescence (Yusoff et al., 2015). Electrochemical sensing uses the change in current or voltage across the surface of the AuNP when exposed to heavy metal ions. The binding of heavy metal ions to the surface of the nanoparticles affects the electron transfer reactions, leading to changes in current or voltage (Yu et al., 2021). Surface-enhanced Raman scattering (SERS) sensing involves the enhancement of Raman scattering signals due to the interaction of the heavy metal ions with the surface of the gold nanoparticles. The presence of heavy metal ions enhances the Raman scattering signals, providing a sensitive detection method (Song and Xia, 2021). (Table 1) presents the heavy metals detected using AuNP along with their respective detection methods. These include colorimetric, fluorescence, SERS, and electrochemical techniques for metals like cadmium, arsenic, chromium, iron, lead, mercury, zinc, and copper. AuNP enhance sensitivity and selectivity in metal ion detection. (Table 2) presents various nanoparticles used for heavy metal detection along with their methods and accuracy. These include gold, silver, iron oxide, titanium dioxide, and graphene oxide nanoparticles, among others. Detection techniques range from spectroscopy and electrochemical methods to fluorescence and potentiometry for improved sensitivity.

Table. 1. Advanced Gold Nanoparticle-Based Detection of Heavy Metals in Environmental and Biological Systems

Sr. No	Heavy Metal	Gold Nanoparticle-Based Sensor	Reference
1	Lead	LSPR-based colorimetric sensor	(Singh *et al.,* 2021)
		Electrochemical sensor	
		Fluorescence-based sensor	
2	Cadmium	Colorimetric sensor	(Ren *et al.,* 2021)
		Fluorescence-based sensor	
		SERS-based sensor	
3	Mercury	Colorimetric sensor	(Shrivas *et al.,* 2021)
		Electrochemical sensor	
		SERS-based sensor	
4	Arsenic	Colorimetric sensor	(Motalebizadeh *et al.,* 2018)
		Fluorescence-based sensor	
		SERS-based sensor	
5	Chromium	Colorimetric sensor	(Jaiswal and Uttam, 2021)
		SERS-based sensor	
6	Copper	LSPR-based colorimetric sensor	(Nikkhah and Masroor, 2023)
		Electrochemical sensor	
7	Zinc	LSPR-based colorimetric sensor	(Singh *et al.,* 2021)
		Fluorescence-based sensor	
8	Iron	SERS-based sensor	(Muhammad *et al.,* 2020)

Table No: 2. Different types of nanoparticles have been utilized for the detection of heavy metal

Nanoparticles	Heavy Metal Elements	Detection Method	Accuracy	References
Gold nanoparticles	Lead	Spectroscopy	98%	(Chadha *et al.,* 2021; Skotadis *et al.,* 2017)
Silver nanoparticles	Cadmium	Electrochemical	95%	(Amare *et al.,* 2020)
Iron oxide nanoparticles	Mercury	Colorimetric	90%	(Jain *et al.,* 2018)
Titanium dioxide nanoparticles	Arsenic	Immunoassay	92%	(Chinnaperumal *et al.,* 2018; Keasberry and Ahmed, 2023)
Zinc oxide nanoparticles	Chromium	Voltammetry	94%	(Hilali *et al.,* 2020)
Silica nanoparticles	Copper	Fluorescence	96%	(Peng *et al.,* 2018)
Carbon nanotubes	Nickel	Mass spectrometry	97%	(Zhang *et al.,* 2020; Zhang *et al.,* 2020)
Quantum dots	Aluminum	Atomic absorption	93%	(Wegner *et al.,* 2019; Yu *et al.,* 2021)
Lipid nanoparticles	Zinc	Magnetic resonance	91%	(Narmani *et al.,* 2018; Hildebrand *et al.,* 2020)
Polymer nanoparticles	Barium	X-ray fluorescence	89%	(Qian and Nie, 2017)
Cerium oxide nanoparticles	Selenium	Potentiometry	88%	(Sagadevan *et al.,* 2022)
Palladium nanoparticles	Thallium	Ion chromatography	85%	(Mehri and Hassannia, 2017; Zhou *et al.,* 2017)
Platinum nanoparticles	Beryllium	Laser-induced breakdown spectroscopy	87%	(Kumar and Basumatary, 2023; Poggialini, 2022)
Magnetic nanoparticles	Antimony	Inductively coupled plasma	86%	(Öztürk Er *et al.,* 2022; García-Mesa *et al.,* 2019)
Graphene oxide nanoparticles	Cadmium	Surface-enhanced Raman spectroscopy	92%	(Hu *et al.,* 2022; Heidari, 2018)

6.4. Sensitivity and selectivity of gold nanoparticle-based sensors

The sensitivity and selectivity of gold nanoparticle-based sensors for heavy metal detection are influenced by several factors, including the size and shape of the nanoparticles, functionalization, and detection mechanism (Kusuma et al., 2023). AuNP with smaller sizes and well-defined shapes generally exhibit higher sensitivities due to their increased surface area and better control over the surface properties (Yu et al., 2021). The functionalization of the nanoparticles with specific ligands can enhance their selectivity by promoting the binding of heavy metal ions while reducing interference from other substances (Yu et al., 2021). The detection mechanism also plays a crucial role in determining the sensitivity and selectivity of gold nanoparticle-based sensors.

For example, colorimetric and fluorescent sensing methods may suffer from interference due to the presence of other substances that can affect the color or fluorescence of the solution. In contrast, electrochemical and SERS sensing methods can provide higher selectivity by measuring specific changes in the electrical or spectral properties of the nanoparticles (Hoener et al., 2018).

7. Applications of Gold Nanoparticle-based Sensors

7.1. Environmental monitoring

Gold nanoparticle-based sensors have shown great potential for environmental monitoring due to their high sensitivity, selectivity, and portability. These sensors can detect a wide range of heavy metal ions, including lead, cadmium, mercury, arsenic, and chromium, which are common environmental pollutants (Rastogi et al., 2022). One application of gold nanoparticle-based sensors in environmental monitoring is the detection of heavy metal ions in water sources. The sensors can be designed to detect specific heavy metal ions, and their portability allows for on-site testing, reducing the time and cost of sample collection and analysis (Halkare et al., 2019). Another application of gold nanoparticle-based sensors is the detection of heavy metal ions in soil samples. Soil contamination with heavy metal ions can have serious environmental and health impacts, and traditional methods for soil analysis can be time-consuming and require expensive equipment. Gold nanoparticle-based sensors offer a more rapid and cost-effective alternative for detecting heavy metal ions in soil (Singh et al., 2021). Gold nanoparticle-based sensors can also be used for air pollution monitoring. Heavy metal ions can be released into the air from industrial processes and vehicle emissions, and their detection can help identify sources of pollution and inform regulatory measures. Gold nanoparticle-based sensors have been developed for the detection of heavy metal ions in air samples, offering a sensitive and selective method for air pollution monitoring (De and Kalita, 2021).

7.2. Food safety

Gold nanoparticle-based sensors have shown great potential for food safety monitoring due to their high sensitivity, selectivity, and rapid detection. Food contamination with heavy metal ions can have serious health impacts, and traditional methods for detecting heavy metal ions in food samples can be time-consuming and require expensive equipment (Liu et al., 2018). One application of gold nanoparticle-based sensors in food safety is the detection of heavy metal ions in seafood. Seafood is a major source of protein and nutrients for many people, but it is also a common source of heavy metal contamination, particularly with mercury and lead. Gold nanoparticle-based sensors have been developed for the rapid detection of heavy metal ions in seafood samples, providing a sensitive and reliable method for monitoring seafood safety (Rastogi et al., 2022; Umair et al., 2022). Another application of gold nanoparticle-based sensors in food safety is the detection of heavy metal ions in fruits and vegetables. Contamination of fruits and vegetables with heavy metal ions can occur using contaminated water or soil, as well as through the use of pesticides and fertilizers containing heavy metals. Gold nanoparticle-based sensors have been developed for the detection of heavy metal ions in fruits and vegetables, offering a fast and sensitive method for monitoring the safety of these foods (Rastogi *et al.,* 2022). Gold nanoparticle-based sensors can also be used for the detection of other contaminants in food, such as pesticides and bacterial toxins. For example, gold nanoparticle-based sensors have been developed for the detection of chlorpyrifos, a common pesticide used in agriculture, as well as for the detection of bacterial toxins such as Staphylococcal enterotoxin (Rastogi *et al.,* 2022; Altaf *et al.,* 2024).

7.3. Biomedical applications

Gold nanoparticle-based sensors also have important biomedical applications. Some examples include i) Disease diagnosis: AuNP can be functionalized with specific biomolecules (such as antibodies or DNA probes) that recognize and bind to disease biomarkers in biological fluids, allowing for the sensitive and specific detection of diseases such as cancer or infectious diseases (Sibuyi *et al.,* 2021), ii) Drug delivery: AuNP can be functionalized with drugs or other therapeutic molecules and delivered to specific cells or tissues using targeting molecules such as antibodies. This targeted delivery approach can increase drug efficacy and reduce side effects (Amina and Guo, 2020), iii) Imaging: AuNP have unique optical properties that make them useful for biomedical imaging. They can be functionalized with targeting molecules and imaging agents to visualize specific cells or tissues in vivo (Gangwar and Pande, 2021) iv) Photothermal therapy: AuNP can convert light into heat, making them useful for photothermal therapy. When AuNP are targeted to cancer cells and irradiated with light, they can heat up and kill the cancer cells while leaving healthy tissue unharmed (Vines *et al.,* 2019).

8. Future Directions and Challenges

8.1. Opportunities for further development of nanoparticulate gold-based sensors

There are several opportunities for further development of gold nanoparticle-based sensors, including.

i. Multiplexed detection using gold nanoparticle-based sensors can allow for the simultaneous detection of multiple targets in a single sample. This can be achieved by functionalizing different AuNP with different targeting molecules or by using different-sized AuNP that can be distinguished based on their optical properties (Pei *et al.,* 2020).

ii. Nanoparticulate gold-based sensors have the potential to be developed into simple and portable point-of-care testing devices. This could be particularly useful for detecting heavy metals or other contaminants in low-resource settings (Wang *et al.,* 2021).

iii. Nanoparticulate gold-based sensors can be integrated with other technologies such as microfluidics or biosensors to create more complex and versatile detection systems (Su *et al.,* 2019).

iv. Nanoparticulate gold-based sensors have shown promise for in vivo detection of disease biomarkers or environmental contaminants. Further development of these sensors could lead to non-invasive diagnostic tools or real-time monitoring of environmental exposures (Pinheiro *et al.,* 2021).

V. There is a need for standardization of gold nanoparticle-based sensors to ensure reproducibility and comparability of results between different studies and devices (Rastogi *et al.,* 2022).

8.2. Challenges

There are several challenges that need to be addressed to further develop gold nanoparticle-based sensors for heavy metal detection. Some of these challenges include.

i. There is a need for standardization of protocols and procedures for the synthesis, functionalization, and detection of AuNP to ensure consistency in results across different studies (Tomás *et al.,* 2019).

ii. Many real-world samples, such as environmental and food samples, can contain complex matrices that can interfere with the detection of heavy metals using gold nanoparticle-based sensors. There is a need to develop methods to minimize or eliminate such interference (Manjubaashini and Thangadurai, 2023).

iii. While gold nanoparticle-based sensors have shown high sensitivity for heavy metal detection, there is still a need to further improve the detection limits to detect low concentrations of heavy metals (Gangwar and Pande, 2021) .

iv. The cost of synthesis, functionalization, and detection using gold nanoparticle-based sensors can be high compared to traditional methods. There is a need to develop cost-effective methods to make the technology accessible to a wider range of users (Mahato *et al.,* 2019).

V. Most current gold nanoparticle-based sensors require several steps and time for detection, which can be a limitation in some applications. There is a need to develop real-time detection methods that can be used in the field. Colorimetric detection relies on color changes caused by nanoparticle aggregation, indicating the presence of heavy metals. Fluorescence detection works by enhancing or quenching fluorescence signals when metal ions bind to nanoparticles. Surface-enhanced Raman spectroscopy (SERS) increases Raman signal intensity, allowing for trace metal ion detection. Electrochemical detection measures electrical signals generated by interactions between metal ions and nanoparticles. Spectroscopy techniques such as UV-Vis, atomic absorption, and ICP-MS determine metal concentration based on light absorption or emission. Voltammetry detects metal ions by measuring current changes during redox reactions. Magnetic resonance imaging (MRI) employs magnetic nanoparticles to identify metal ions in biological systems. X-ray fluorescence (XRF) identifies metals by analyzing emitted X-ray signals after excitation. Ion chromatography separates and quantifies metal ions using a charged column, ensuring precise analysis (Li *et al.,* 2022).

8.3. Comparison with other emerging technologies

Gold nanoparticle-based sensors are not the only emerging technology for heavy metal detection. There are several other technologies that are being developed for this purpose, including. Carbon nanotube-based sensors: Carbon nanotubes have unique electronic and mechanical properties that make them suitable for the detection of heavy metals. They have been used to develop sensors with high sensitivity and selectivity for heavy metals (Mallakpour and Khadem, 2019). Quantum dot-based sensors: Quantum dots are nanoscale semiconductors that have unique optical properties. They have been used to develop sensors that can detect heavy metals based on changes in their optical properties (Zhou and Leblanc, 2019). Electrochemical sensors: Electrochemical sensors use changes in electrical properties to detect heavy metals. They are often based on metal or metal oxide nanoparticles, which can enhance sensitivity and selectivity (Mansha and Ullah, 2018). Surface-enhanced Raman spectroscopy (SERS): SERS is a technique that uses metal nanoparticles to enhance the Raman scattering signal of analytes. It has been used to detect heavy metals in environmental and food samples (Bell *et al.,* 2020). Compared to these emerging technologies, gold nanoparticle-based sensors have some unique advantages. AuNP have excellent biocompatibility and low toxicity, which makes them suitable for biomedical applications. Gold nanoparticle-based sensors offer high sensitivity, selectivity, and rapid detection, making them more efficient than many conventional techniques. Compared to traditional methods like atomic absorption spectroscopy and inductively coupled plasma mass spectrometry, gold nanoparticle sensors provide a cost-effective and portable alternative without requiring extensive sample preparation. However, inductively coupled plasma mass spectrometry remains more precise for ultra-trace metal detection in complex matrices (Choi and Heo, 2021). They can also be easily functionalized with different ligands to enhance selectivity for different heavy metals. Additionally, gold nanoparticle-based sensors can be easily integrated with other detection techniques, such as colorimetric or fluorescent readouts. When compared to other nanomaterials, silver nanoparticles also exhibit strong plasmonic properties for colorimetric sensing but are less stable and prone to oxidation. Carbon nanotubes and graphene-based sensors offer excellent conductivity for electrochemical detection but may require complex functionalization to achieve high specificity. Iron oxide and magnetic nanoparticles facilitate separation and pre-concentration of metal ions, improving detection in biological and environmental samples. However, gold nanoparticle-based sensors also have some limitations, such as their cost and the need for specialized equipment for their synthesis and detection. Gold nanoparticle-based colorimetric sensors have demonstrated high accuracy in detecting lead, outperforming conventional spectroscopic methods in field applications. Electrochemical detection of cadmium using silver nanoparticles has shown promising results but with lower stability than gold-based sensors. Iron oxide nanoparticles have been used for mercury detection through a colorimetric approach but lack the reproducibility of gold nanoparticle systems (Wang *et al.,* 2022).

9. Conclusion

AuNP have unique physical and chemical properties that make them suitable for various applications, including the detection of heavy metal contamination. Their small size, large surface area, and ability to be functionalized make them ideal for sensing applications. Gold nanoparticle-based sensors offer advantages such as high sensitivity, selectivity, and rapid response times compared to traditional detection methods. They have potential applications in environmental monitoring, food safety, and biomedical fields. However, there are still challenges that need to be addressed, such as reproducibility and cost-effectiveness. Comparisons with other emerging technologies such as carbon nanotube-based sensors, quantum dot-based sensors, electrochemical sensors, and surface-enhanced Raman spectroscopy (SERS) indicate that gold nanoparticle-based sensors have unique advantages and limitations that depend on the specific application. The development of gold nanoparticle-based sensors for heavy metal detection has the potential to revolutionize the way we monitor and control environmental contamination and food safety. With their high sensitivity and selectivity, these sensors could enable real-time monitoring of heavy metal concentrations in the environment and food products. This would help ensure that humans and animals are not exposed to harmful levels of heavy metals. Moreover, additional research is needed to explore the potential applications of gold nanoparticle-based sensors in other fields, such as medicine and industry. This would require collaboration between researchers from different disciplines, including materials science, engineering, and medicine. Further research and development of gold nanoparticle-based sensors for heavy metal detection have the potential to make a significant impact on human health, environmental monitoring, and food safety.

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12. Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

13. Author Contributions

Tasawar Iqbal, Sidra Altaf, and Muhammad Ashir Hameed: Conceptualization, Supervision, Writing- Original draft preparation; Hamna Bashir, Hamza Amin, and Mehreen Malik: Data validation, Investigation, Proofreading, Writing-reviews and Editing; Zilyad Ul Hassan, Jawad Arshad, Mohsin Ali, Moazma Batool, Mantasha Maqbool, Humna Afzal: Proofreading, Writing-reviews and Editing

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