

Metal Ion Detection by Glutathione

Subjects: [Nanoscience & Nanotechnology](#) | [Engineering, Biomedical](#)

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Low cost, sensitive, selective, and rapid methods for heavy metal ion (HMI) detection are of growing demand, and HMI biosensors have great potential in meeting this need due to their timeliness, cost-effectiveness and convenience in operation. The most widely reported peptide probe for HMI detection is glutathione (GSH), especially in case of lead ion (Pb²⁺) detection. GSH is highly stable, cost-effective, and easy to immobilize on a sensor.

heavy metal ions

glutathione

biosensor

nanoparticle

1. Introduction

In general, heavy metals are the metals with relatively high mass densities (above 5 g/cm³), such as platinum, gold, mercury, and lead. The definition of heavy metals varies from discipline to discipline due to different concerns and perspectives. For physiology and pathology, heavy metals mainly refer to heavy elements with obvious biotoxicity. In terms of toxicity, the most common heavy metals include lead (Pb), mercury (Hg), arsenic (As), cadmium (Cd), and chromium (Cr) [\[1\]\[2\]\[3\]\[4\]](#). These heavy metal ions (HMIs) accumulate in the human body and cause chronic poisoning, resulting in damage to the immune, gastrointestinal, reproductive, and nervous systems [\[5\]\[6\]\[7\]](#). Long-term exposure to heavy metals may even cause cancer in humans [\[8\]](#). Being non-biodegradable, HMIs will continue to exist for decades and even hundreds of years if they are released into the environment [\[9\]](#). With increasing human activities in mining and manufacturing, etc., HMI contamination and pollution pose great risks to ecological and human health [\[10\]\[11\]](#). Therefore, it is of great importance to be able to effectively screen for and quantitatively determine HMIs in a range of situations, including food safety, environmental pollution, and clinical diagnosis. Many international organizations and regulatory bodies, such as the World Health Organization (WHO) and the U.S. Environmental Protection Agency (EPA), have listed heavy metals as priority substances for intensive monitoring [\[1\]](#). In practice, most countries have set standards on the permissible limits for HMI concentrations in water or other mediums to protect the environment and public health.

Traditional HMI measurements are mostly performed using spectroscopic techniques, including atomic absorption spectroscopy (AAS) [\[4\]\[12\]](#), X-ray fluorescence spectrometry (XRF) [\[4\]\[13\]](#), and inductively coupled plasma mass spectrometry (ICP-MS) [\[4\]\[14\]](#), which are gold standards in HMI detection. However, they are expensive, difficult to perform, require complicated pretreatment for the samples, and need to be operated in a central laboratory setting. Thus, traditional spectroscopic techniques cannot meet the needs for pervasive HMI monitoring and screening. In contrast, surface-based biosensors are a good candidate to realize low-cost, sensitive HMI detection with a quick turn-around time. Similar to other biochemical sensors, there are three important components in an HMI sensor:

analyte recognition, physical support for probe immobilization, and signal transduction. Various types of sensors have been reported, including nanoparticles [15][16][17], field effect transistors (FETs) [18][19][20], and working electrodes for voltammetric analysis [21]. In terms of signal transduction, there are mainly optical [15] and electrochemical methods [4]. Specific target recognition is always critically important to analyte detection. Antibody [22], nuclei acids [23][24], and peptide/amino acids [25][26] are the most commonly used probes to recognize and bind with HMIs. An antibody as a probe has the best specificity, but faces challenges when detecting HMIs. HMIs are too small to be directly detected with good sensitivity by an antibody, and antibody binding reactions may require a fluid environment different from that HMIs naturally exist in. Two types of functional nuclei acid probes have been developed for metal sensing: aptamers and DNAzymes. It is well-known that screening aptamer sequences to find one that specifically binds with a certain HMI is difficult, in addition to being laborious and time-consuming. Very few metal ions have successfully found their specific aptamers [27][28]. DNAzymes can selectively detect HMIs based on their catalytic activity; however, another nuclei acid sequence is required to be added to work as the substrate–enzyme pair. During metal detection by DNAzyme, additional steps and time are needed to allow for catalytic reactions between the DNAzyme and the substrate. Besides antibodies, aptamers, and DNAzyme, another option is to use a peptide or an amino acid as a probe to bind with HMIs, such as cysteine [29]. The most widely reported peptide probe for HMI detection is glutathione (GSH) [30]. Because there are six possible coordination sites in GSH for binding with metal ions, it has distinct advantages in capturing HMIs when compared with cysteine, especially in case of lead ion (Pb^{2+}) detection. Furthermore, it is highly stable, cost-effective, and easy to immobilize on a sensor. Therefore, GSH, as a promising probe for HMI detection, has received much attention in recent years.

2. Recognition of HMIs by GSH

Glutathione (GSH) is a ubiquitous tripeptide biomolecule (γ -Glu-Cys-Gly) widely found in animals and plants with a concentration from 0.1 mM to 10 mM [31]. GSH is known as an antidote to prevent cells from toxicosis of heavy metal ions by forming complexes as a key step in biological detoxification processes [30].

The chemical structure of GSH is shown in [Figure 1](#). If oxidized, GSH will form disulfide bonds between themselves, and become what is known as glutathione disulphide (GSSG). GSSG lacks the ability to bind with electrodes or nanoparticles. In practice, GSH in its reduced form is used to bind with HMIs. Reduced GSH is a linear tripeptide of L-glutamine, L-cysteine, and glycine, so reduced GSH is also labeled as L-GSH. GSH contains one amino ($-NH_2$), one sulfhydryl ($-SH$), and two carboxyl ($-COOH$) groups, all with the ability to bind with HMIs. Therefore, GSH is a versatile ligand with several binding modes.

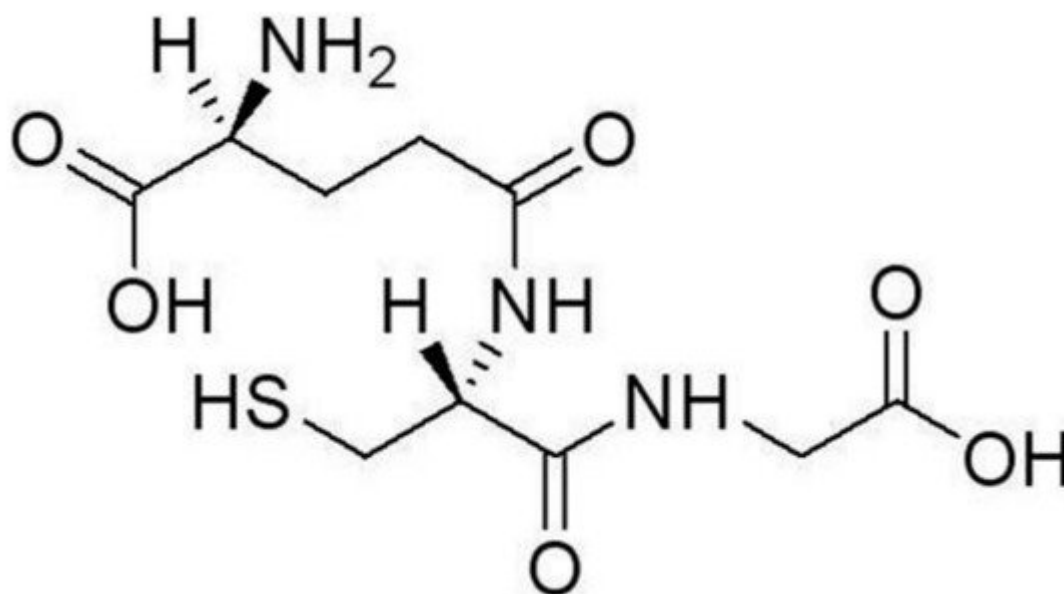


Figure 1. Glutathione's Chemical Structure.

GSH has a sulfhydryl group on the cysteinyl portion. The sulfhydryl group is known to coordinate with a wide range of metal ions. For surface-based or nanoparticle-based HMI sensors, GSH is usually immobilized on gold nanoparticles or electrodes. Numerous experiments indicate that there is a strong binding force between gold and the (-SH) group. It is expected that, during probe immobilization, Au-S bonds are formed to link GSH molecules onto the gold surface [32][33][34][35]. As a result, only one amino (-NH₂) and two carboxyls (-COOH) are still available to bind with metal ions.

A number of published papers have demonstrated that via the two free (-COOH) groups, strong binding with Pb²⁺ is preferred over that with other HMIs [35][36][37]. It was found that the solution pH has a strong effect on the affinity of the GSH-Pb²⁺ complex. At around pH 7, (-COOH) is deprotonated to (-COO⁻). Known as an oxyphilic ion, Pb²⁺ can combine with four acetate molecules or eight oxygen atoms [33]. Within a pH range of 4–8, binding between Pb²⁺ and (-COO⁻) will predominate over other reactions. Under the same pH condition, (-NH₂) is protonated to (-NH₃⁺), which is hypothesized to prevent GSH from combining with other ions due to its charges [33][37]. Therefore, good affinity and selectivity can be achieved for GSH-Pb²⁺ binding. There exist a number of reports on using GSH to specifically detect Pb²⁺ from a mixture of multiple HMIs.

Nevertheless, detection of metal ions other than Pb²⁺ can also be achieved using GSH-based sensors. The GSH support material and the solution pH value play an important role in the HMI-GSH complexation pattern. Research has shown that GSH's conformational structure is strongly influenced by the solution pH [38]. Various functional groups in GSH can participate in complexation under different working conditions, leading to a certain selectivity. For example, GSH-capped quantum dots (QDs) are often used to detect HMIs other than Pb²⁺. In [39], GSH immobilized on sulfur- and nitrogen-co-doped carbon QDs presented free (-SH) groups for binding, which showed strong affinity to Hg²⁺ as opposed to other metal ions (Ag⁺, Al³⁺, Ba²⁺, Cu²⁺, Pb²⁺, etc.) and realized specific detection of Hg²⁺. Simultaneous detection of Cr²⁺ and Pb²⁺ was reported using GSH-coated magnetic

nanoparticles (NPs) [40], as GSH molecules were immobilized onto Fe_3O_4 NPs through a hydrogen bond. In this detection scheme, NH_4^+ , Na^+ , Mg^{2+} , Hg^{2+} and other MIs caused no obvious responses, except for Cd^{2+} and Pb^{2+} . This was attributed in part to the negative charges on the functional groups of GSH [40], since the testing was done at a pH of 4.5. Simultaneous detection of multiple HMIs is thus possible by adjusting the solution pH and the GSH immobilization strategy. However, complexation reactions between GSH and HMIs are complicated and difficult to predict, and the detection outcome under particular conditions usually needs to be verified through experimental results.

The foregoing introduces the interactions and formation of complexes between GSH and HMIs, which are the basis for the specific recognition of certain HMIs by GSH-based detection methods. To convert specific binding between GSH and HMIs into a quantifiable signal, a transducer is needed, which can take many different shapes and forms. Transduction schemes may have effects on the sensor performance as well, especially the plasmon-based detection that depends on the interaction between metal ions and nanoparticles. In next section, various GSH-based detection platforms are presented and discussed, with a focus on optical and electrochemical methods.

3. Heavy Metal Ion Detection Platforms Using Glutathione

Based on a signal transduction strategy, most of the GSH-based HMI detection methods can be categorized into two groups: optical methods and electrochemical methods. Then, each method is further divided into subtypes based on the support materials for GSH.

3.1. Optical Techniques

Metallic nanoparticles (NPs) are between 1–100 nm in size with a high surface charge density, a high surface to volume ratio, and, oftentimes, special optical properties due to a localized surface plasmon resonance (LSPR) effect. For these reasons, metallic NPs have been widely used in diverse biological and chemical applications, especially for biochemical detection. Various types of biochemical molecules can be easily incorporated onto the NPs while retaining their biochemical activity. For HMI detection, most metallic NPs are made of gold and some are silver, with gold NPs (GNPs) being the most widely used material in HMI sensors. Other shapes of NPs, such as nanorods and nanostars, have been adopted for sensing [41][42].

As an important discovery originally found in the 1990s, semiconductor quantum dots (QDs) have attracted intense research interest for their excellent luminescence properties. In contrast to traditional fluorescence techniques, QDs have advantages in excitation spectra, photo-luminescence quantum efficiency, and so on [43][44]. Reports of new QD-based sensors are on the rise. Most of the reported QD-based HMI detection schemes utilized II–VI semiconductor QDs. As an example, using Mn-doped ZnS QDs, [45] reported a Pb^{2+} detection scheme by phosphorescence measurement. Phosphorescence is generated by the energy transfer from the lowest vibrational energy layer of the excited Mn^{2+} triplet state to the vibrational energy layer of the ground state. Mn–ZnS QDs are a popular II–VI semiconductor QD for biosensor applications. Because Mn–ZnS QDs can be functionalized without using deoxidants and other inducers, they are convenient to work with. Furthermore, Mn–ZnS QDs have a long-

lived doped emission, which can set the signal of Pb²⁺ detection apart from interference by autofluorescence and scattering light.

3.2. HMI Detection Combined with Electrochemical Techniques

Based on our survey of the field, most HMI detection techniques utilized optical techniques to extract the sensing signal. These optical methods have obvious advantages, such as visualization, but may be less advantageous when it comes to field deployability and affordable readout systems. As a result, HMI detection platforms by electrochemical techniques are also worth investigating. Among the electrochemical techniques, field effect transistors (FETs) and working electrodes are the two representative devices.

3.3. Summary of HMI Detection Platforms Using GSH

In summary, GSH has been adopted as the probe molecule in a variety of HMI detection platforms. These detection platforms have demonstrated good detection performance, such as a low LOD and a fast response. Some of them have been applied to practical samples with acceptable outcomes.

The platforms discussed above present commonly reported detection methods, and are not an exhaustive list of all existing GSH-based HMI sensors. [Table 1](#) gives a more comprehensive summary of recently reported HMI detection platforms using GSH. In addition to the examples discussed in the review, [Table 1](#) includes some less-used detection methods with their operational characteristics. As every application has its own unique requirements, different considerations go into choosing a certain detection platform. For example, it is difficult to find a sensor with high sensitivity and a very fast response at the same time. Some trade-off is needed when choosing a detection method. It is our hope that this summary will provide some guidance for choosing a suitable strategy to detect certain HMIs.

Table 1. Recent Achievements in Heavy Metal Ion (HMI) Detection Platforms Using GSH.

Signal Transduction	Sensor Structure	HMI Target	Detection Limit	Linear Range	Response Time	References
Optical methods						
Colorimetry	Gold NPs	Pb	0.1 μM	0.1~50 μM	20 ~ 25 min	[46]
	Silver NPs	Pb	1 nM	Not mentioned	At least 10 min	[32]

Signal Transduction	Sensor Structure	HMI Target	Detection Limit	Linear Range	Response Time	References
Localized surface plasmon resonance	Gold NPs	Cd	4.3 pM	17 pM~16.67 nM	About 17 min	[47]
	Gold NPs	Pb	50 pM	0.1 nM~10 µM	15 min	[33]
	Gold NPs	Pb	0.1 µM	2~350 µM	About 1 min	[48]
Fluorescence	Silver NPs	Pb	0.6 pM (200 ppq)	60 pM~2.4 nM (20~800 ppt estimated)	Less than 20 min	[49]
Surface-enhanced Raman scattering	Silver NPs	As ³⁺	10.2 nM (0.76 ppb)	53.7 nM~4.0 µM (4~300 ppb)	At least 2 min	[50]
Whispering gallery mode	Gold NPs	Pb	0.05 nM	2.40~48.26 nM	About 40 min	[35]
Spectrophotometry	Mn-doped ZnS QDs	Pb	2.2 nM (0.45 µg/L)	4.9 nM~0.49 µM (1.0~100 µg/L)	Not mentioned	[45]
	Mn-doped ZnS QDs	Pb, Cr, Hg	0.93 µM for mixed HMIs	1 µM~1 mM	Not mentioned	[51]
	CdTe QDs	Pb	0.26 nM	0.8~15 nM	About 15 s	[52]

Signal Transduction	Sensor Structure	HMI Target	Detection Limit	Linear Range	Response Time	References
	Carbon QDs	Hg	0.05 nM	1 nM~50 μ M	At least 20 min	[39]
	Silver NPs	Ni ²⁺	75 μ M	About 75 μ M~1 mM	Not mentioned	[53]
	Gold Nanostars	Pb	0.5 μ M	About 0.5~4 μ M	About 30 min	[42]
Dynamic Light Scattering	Gold Nanorod Chains	Pb	0.025 mM	Not mentioned	Not mentioned	[41]
	Electrochemical methods					
Square Wave Anodic Stripping Voltammetry,	Magnetic NPs	Cd, Pb	1.6 nM (0.182 μ g/L); 0.8 nM (0.172 μ g/L)	4.4~879 nM (0.5~100 μ g/L), 2.3~460 nM (0.5~100 μ g/L)	210 s 210 s	[40]
SWASV	Glassy-Carbon Electrode	Cd	0.05 nM	2~20 nM	120 s	[54]
	Carbon Paste Electrode	Cd	8.5 nM (2 ppb)	4.2~420 nM (1~100 ppb)	Longer than 7 min	[55]
Differtial pulsed anodic stripping	Screen-Printed	Pb, Cd	~0.1 nM (~3 μ g/L)	About 0.3~4.5 nM	120 s	[56]

References

1. Bansod, B.K.; Kumar, T.; Thakur, R.; Rana, S.; Singh, I. A review on various electrochemical techniques for heavy metal ions detection with different sensing platforms. Biosens. Bioelectron.

Signal Transduction	Sensor Structure	HMI Target	Detection Limit	Linear Range	Response Time	References
voltammetry, DPASV	Carbon Nanofiber Electrode			(about 10~150 µg/L)		
FET (Drain current)	Field effect Transistor	Pb	10 nM	10 nM~10 µM	1~2 s	[34]
FET (Pulse-driven capacitance)	Gate Capacitance	Pb	<4.8 nM (<1 ppb)	24~96 nM (5~20 ppb)	1~2 s	[19]

antioxidants on absorption, desorption and elimination of lead and iron: An in-vivo study. Eur. J. Biomed. Pharm. Sci. 2016, 3, 528–531.

- Afkhami, A.; Soltanifelehgari, F.; Madrakian, T.; Ghaedi, H.; Rezaeivala, M. Fabrication and application of a new modified electrochemical sensor using nano-silica and a newly synthesized schiff base for simultaneous determination of Cd²⁺, Cu²⁺ and Hg²⁺ ions in water and some foodstuff samples. Anal. Chim. Acta 2013, 771, 21–30.
- Sharma, B.; Singh, S.; Siddiqi, N.J. Biomedical implications of heavy metals induced imbalances in redox systems. BioMed. Res. Int. 2014, 2014, 640754.
- Gong, T.; Liu, J.; Liu, X.; Liu, J.; Xiang, J.; Wu, Y. A sensitive and selective platform based on CdTe QDs in the presence of L-cysteine for detection of silver, mercury and copper ions in water and various drinks. Food Chem. 2016, 213, 306–312.
- Turdean, G.L. Design and development of biosensors for the detection of heavy metal toxicity. Int. J. Electrochem. 2011, 2011, 343125.
- Gao, C.; Yu, X.Y.; Xiong, S.Q.; Liu, J.H.; Huang, X.J. Electrochemical detection of arsenic(III) completely free from noble metal: Fe₃O₄ microspheres-roomtemperature ionic liquid composite showing better performance than gold. Anal. Chem. 2013, 85, 2673–2680.
- Array, G.; Merkoci, A. Nanomaterials application in electrochemical detection of heavy metals. Electrochim. Acta 2012, 84, 49–61.
- Sitko, R.; Janik, P.; Zawisza, B.; Talik, E.; Margui, E.; Queralt, I. Green approach for ultra trace determination of divalent metal ions and arsenic species using totalreflection X-ray fluorescence spectrometry and mercapto-modified graphene oxide nanosheets as a novel adsorbent. Anal. Chem. 2015, 87, 3535–3542.

14. Liu, X.; Zhu, Z.; Li, H.; He, D.; Li, Y.; Zheng, H.; Gan, Y.; Li, Y.; Belshaw, N.S.; Hu, S. Liquid spray dielectric barrier discharge induced plasma-chemical vapor generation for the determination of lead by ICPMS. *Anal. Chem.* 2017, 89, 6827–6833.
15. Feng, W.; Xue, X.; Liu, X. One-step, room-temperature, colorimetric detection of mercury (Hg^{2+}) using DNA/nanoparticle conjugates. *J. Am. Chem. Soc.* 2008, 130, 3244–3245.
16. Li, S.; Xu, L.; Ma, W.; Kuang, H.; Wang, L.; Xu, C. Triple raman label-encoded gold nanoparticle trimers for simultaneous heavy metal ion detection. *Small* 2015, 11, 3435–3439.
17. Skotadis, E.; Tsekenis, G.; Chatzipetrou, M.; Patsiouras, L.; Madianos, L.; Bousoulas, P.; Zergioti, I.; Tsoukalas, D. Heavy metal ion detection using dnazyme-modified platinum nanoparticle networks. *Sens. Actuators B Chem.* 2017, 239, 962–969.
18. Kullick, T.; Quack, R.; Röhrkasten, C.; Pekeler, T.; Scheper, T.; Schügerl, H.C.K. Pbs-field-effect-transistor for heavy metal concentration monitoring. *Chem. Eng. Technol.* 2010, 18, 225–228.
19. Maity, A.; Sui, X.; Tarman, C.R.; Pu, H.; Chang, J.; Zhou, G.; Ren, R.; Mao, S.; Chen, J. Pulse-driven capacitive lead ion detection with reduced graphene oxide field-effect transistor integrated with an analyzing device for rapid water quality monitoring. *ACS Sens.* 2017, 2, 1653–1661.
20. Hang, R.; Kang, Y.; Gladwin, E.; Claus, R.O. Selective detection of heavy metal ions by self assembled chemical field effect transistors. *Appl. Phys. Lett.* 2015, 106, 402647.
21. March, G.; Nguyen, T.D.; Piro, B. Modified electrodes used for electrochemical detection of metal ions in environmental analysis. *Biosensors* 2015, 5, 241–275.
22. Blake, D.A.; Jones, R.M.; Li, R.C.B.; Pavlov, A.R.; Darwish, I.A.; Yu, H. Antibody-based sensors for heavy metal ions. *Biosens. Bioelectron.* 2001, 16, 799–809.
23. Saidur, M.R.; Aziz, A.R.; Basirun, W.J. Recent advances in dna-based electrochemical biosensors for heavy metal ion detection: A review. *Biosens. Bioelectron.* 2017, 90, 125–139.
24. Zhan, S.; Wu, Y.; Wang, L.; Zhan, X.; Zhou, P. A mini-review on functional nucleic acids-based heavy metal ion detection. *Biosens. Bioelectron.* 2016, 86, 353–368.
25. Ritchie, S.M.C.; Kissick, K.E.; Bachas, L.G.; Sikdar, S.K.; Parikh, C.; Bhattacharyya, D. Polycysteine and other polyamino acid functionalized microfiltration membranes for heavy metal capture. *Environ. Sci. Technol.* 2001, 35, 3252–3258.
26. Neupane, L.N.; Oh, E.T.; Park, H.J.; Lee, K.H. Selectively and sensitively detection of heavy metal ions in 100% aqueous solution and cells with a fluorescence chemosensor based on peptide using aggregation induced emission. *Anal. Chem.* 2016, 88, 3333–3340.
27. Farzin, L.; Shamsipur, M.; Sheibani, S. A review: Aptamer-based analytical strategies using the nanomaterials for environmental and human monitoring of toxic heavy metals. *Talanta* 2017, 174, 619–627.

28. Oroval, M.; Coll, C.; Bernardos, A.; Marcos, M.D.; Martínez-Máñez, R.; Shchukin, D.G.; Sancenón, F. Selective fluorogenic sensing of As(III) using aptamer-capped nanomaterials. *ACS Appl. Mater. Interfaces* 2017, 9, 11332–11336.
29. Zhou, S.F.; Wang, J.J.; Gan, L.; Han, X.J.; Fan, H.L.; Mei, L.Y.; Huang, J.; Liu, Y.Q. Individual and simultaneous electrochemical detection toward heavy metal ions based on l-cysteine modified mesoporous MnFe₂O₄ nanocrystal clusters. *J. Alloys Compd.* 2017, 721, 492–500.
30. Zhang, L.; Xu, C.; Li, B. Simple and sensitive detection method for chromium(VI) in water using glutathione-capped CdTe quantum dots as fluorescent probes. *Microchim. Acta* 2009, 166, 61–68.
31. Mah, V.; Jalilehvand, F. Lead(II) complex formation with glutathione. *Inorg. Chem.* 2012, 51, 6285–6298.
32. Anambiga, I.V.; Suganthan, V.; Arunai Nambi Raj, N.; Buvaneswari, G.; Sampath Kumar, T.S. Colorimetric Detection of lead ions using glutathione stabilized silver nanoparticles. *Int. J. Sci. Eng. Res.* 2013, 4, 710–715.
33. Feng, B.; Zhu, R.; Xu, S.; Chen, Y.; Di, J. A sensitive LSPR sensor based on glutathione-functionalized gold nanoparticles on a substrate for the detection of Pb²⁺ ions. *RSC Adv.* 2018, 8, 4049–4056.
34. Zhou, G.; Chang, J.; Cui, S.; Pu, H.; Wen, Z.; Chen, J. Real-time, selective detection of Pb²⁺ in water using a reduced graphene oxide/gold nanoparticle field-effect transistor device. *ACS Appl. Mater. Inter.* 2014, 6, 19235–19241.
35. Panich, S.; Wilson, K.A.; Nuttall, P.; Wood, C.K.; Albrecht, T.; Edel, J.B. Label-free Pb(II) whispering gallery mode sensing using self-assembled glutathione-modified gold nanoparticles on an optical microcavity. *Anal. Chem.* 2014, 86, 6299–6306.
36. Beqa, L.; Singh, A.K.; Khan, S.A.; Senapati, D.; Arumugam, S.R.; Ray, P.C. Gold nanoparticle-based simple colorimetric and ultrasensitive dynamic light scattering assay for the selective detection of Pb(II) from paints, plastics, and water Samples. *ACS Appl. Mater. Interfaces* 2011, 3, 668–673.
37. Kim, I.B.; Dunkhorst, A.; Gilbert, J.; Bunz, U.H.F. Sensing of lead ions by a carboxylate-substituted PPE: Multivalency effects. *Macromolecules* 2005, 38, 4560–4562.
38. Vila-Viçosa, D.; Teixeira, V.H.; Santos, H.A.F.; Machuqueiro, M. Conformational Study of GSH and GSSG Using Constant-pH Molecular Dynamics Simulations. *J. Phys. Chem. B* 2013, 117, 7507–7517.
39. Wang, W.; Lu, Y.C.; Huang, H.; Wang, A.J.; Chen, J.R.; Feng, J.J. Solvent-free synthesis of sulfur- and nitrogen-co-doped fluorescent carbon nanoparticles from glutathione for highly selective and sensitive detection of mercury(II) ions. *Sens. Actuators B Chem.* 2014, 202, 741–747.

40. Baghayeri, M.; Amiri, A.; Maleki, B.; Alizadeh, Z.; Reiser, O. A simple approach for simultaneous detection of cadmium(II) and lead(II) based on glutathione coated magnetic nanoparticles as a highly selective electrochemical probe. *Sens. Actuators B Chem.* 2018, 273, 1442–1450.
41. Durgadas, C.V.; Lakshmi, V.N.; Sharma, C.P.; Sreenivasan, K. Sensing of lead ions using glutathione mediated end to end assembled gold nanorod chains. *Sens. Actuators B Chem.* 2011, 156, 791–797.
42. D'Agostino, A.; Taglietti, A.; Bassi, B.; Donà, A.; Pallavicini, P. A naked eye aggregation assay for Pb²⁺ detection based on glutathione-coated gold nanostars. *J. Nanopart. Res.* 2014, 16, 2683.
43. Nightingale, A.M.; deMelloa, J.C. Improving the ensemble optical properties of InP quantum dots by indium precursor modification. *J. Mater. Chem. C* 2016, 4, 8454–8458.
44. Choi, D.B.; Kim, S.; Yoon, H.C.; Ko, M.; Yang, H.; Do, Y.R. Color-tunable Ag-In-Zn-S quantum-dot light-emitting devices realizing green, yellow and amber emissions. *J. Mater. Chem. C* 2017, 5, 953–959.
45. Chen, J.; Zhu, Y.; Zhang, Y. Glutathione-capped Mn-doped ZnS quantum dots as a room-temperature phosphorescence sensor for the detection of pb²⁺ ions. *Spectrochim. Acta A* 2016, 164, 98–102.
46. Chai, F.; Wang, C.; Wang, T.; Li, L.; Su, Z. Colorimetric detection of Pb²⁺ using glutathione functionalized gold nanoparticles. *ACS Appl. Mater. Interfaces* 2010, 2, 1466–1470.
47. Li, L.; Liu, B.; Chen, Z. Colorimetric and dark-field microscopic determination of cadmium(II) using unmodified gold nanoparticles and based on the formation of glutathione-cadmium(II) complexes. *Microchim. Acta* 2019, 186, 37.
48. Zhang, H.; Wang, S.; Chen, Z.; Ge, P.; Jia, R.; Xiao, E.; Zeng, W. A turn-on fluorescent nanoprobe for lead(II) based on the aggregation of weakly associated gold(I)-glutathione nanoparticles. *Microchim. Acta* 2017, 184, 4209–4215.
49. Singh, A.K.; Kanchanapally, R.; Fan, Z.; Senapati, D.; Ray, P.C. Synthesis of highly fluorescent water-soluble silver nanoparticles for selective detection of Pb(II) at the parts per quadrillion (PPQ) level. *Chem. Commun.* 2012, 48, 9047–9049.
50. Li, J.; Chen, L.; Lou, T.; Wang, Y. Highly sensitive SERS detection of As³⁺ ions in aqueous media using glutathione functionalized silver nanoparticles. *ACS Appl. Mater. Interfaces* 2011, 3, 3936–3941.
51. Liu, J.; Lv, G.; Gu, W.; Li, Z.; Tang, A.; Mei, L. A novel luminescence probe based on layered double hydroxides loaded with quantum dots for simultaneous detection of heavy metal ions in water. *J. Mater. Chem. C* 2017, 5, 5024–5030.

52. Wang, H.; Chen, Q.; Tan, Z.; Yin, X.; Lun, W. Electrochemiluminescence of CdTe quantum dots capped with glutathione and thioglycolic acid and its sensing of Pb²⁺. *Electrochim. Acta* 2012, 72, 28–31.
53. Li, H.; Cui, Z.; Han, C. Glutathione-stabilized silver nanoparticles as colorimetric sensor for Ni. *Sens. Actuators B Chem.* 2009, 143, 87–92.
54. Priya, T.; Dhanalakshmi, N.; Thennarasu, S.; Thinakaran, N. Ultra sensitive detection of Cd (II) using reduced graphene oxide/carboxymethyl cellulose/glutathione modified electrode. *Carbohydr. Polym.* 2018, 197, 366–374.
55. Kaabi, R.; Abderrabba, M.; Gómez-Ruiz, S.; Hierro, I.D. Bioinspired materials based on glutathione-functionalized SBA-15 for electrochemical Cd(II) detection. *Microporous Mesoporous Mater.* 2016, 234, 336–346.
56. Pérez-Ràfols, C.; Serrano, N.; Díaz-Cruz, J.M.; Ariño, C.; Esteban, M. Glutathione modified screen-printed carbon nanofiber electrode for the voltammetric determination of metal ions in natural samples. *Talanta* 2016, 155, 8–13.

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