International Academic Institute for Science and Technology

International Academic Journal of Science and Engineering
Vol. 12, No. 4, 2025, pp. 22-32.

ISSN 2454-3896

International Academic Journal of Science and Engineering

www.iaiest.com

Electrochemical Sensors Based on Graphene Oxide for Real-Time Detection of Heavy Metal Contaminants

G. Suresh [a], Dinesh Goyal [b], Gujjala Srinath [c], Prashant Anerao [d], Suraj Bhan [e], Qingchang Guo [f]

[a] *Department of Humanities and Science, Aarupadai Veedu Institute of Technology, Vinayaka Mission's Research Foundation (DU), Kanchipuram, Tamil Nadu, India. E-mail: suresh.physics@avit.ac.in, Orcid: https://orcid.org/0000-0002-2525-1231*

[b] *Quantum University Research Center, Quantum University, Roorkee, Uttarakhand, India. E-mail: dinesh.ca@quantumeducation.in, Orcid: https://orcid.org/0009-0004-3157-0695*

[c] *Centre for Multidisciplinary Research, Anurag University, Hyderabad, Telangana, India. E-mail: GujjalaSrinath@gmail.com, Orcid: https://orcid.org/0009-0006-1087-3296*

[d] *Department of Mechanical Engineering, Vishwakarma Institute of Technology, Pune, Maharashtra, India. E-mail: prashant.anerao@vit.edu*

[e] *Assistant Professor, School of Engineering & Technology, Noida International University, Uttar Pradesh, India. E-mail: suraj.bhan@niu.edu.in*

[f] *Faculty of Education, Shinawatra University, Bangkok, Thailand. E-mail: guoqingchang2025@163.com, Orcid: https://orcid.org/0009-0006-9409-829X*

Abstract

The contamination of water systems with heavy metals also poses a high environmental and population health risk, and the World Health Organization (WHO) has reported acceptable concentrations of lead (Pb^{2+}) and cadmium (Cd^{2+}) in drinking water at 10 ppb and 6 ppb, respectively. Traditional methods of detection, such as atomic absorption spectroscopy and inductively coupled plasma mass spectrometry, though very sensitive, may require expensive equipment and be conducted in a laboratory for real-time monitoring. This research paper presents the design of graphene oxide (GO)-based electrochemical sensors for rapid, on-site detection of heavy metal ions. The sensing platform was prepared by drop-casting graphene oxide onto a glassy carbon electrode using a modified Hummers method. Differential pulse anodic stripping voltammetry (DPASV) was used to measure electrochemical performance. The GO-modified electrode had a linear detecting range of 1–200 ppb for Pb^{2+} and 0.5–150 ppb for Cd^{2+} with limits of detection (LOD) of 0.32 ppb and 0.21 ppb, respectively. The sensitivity was increased by 42% compared to bare electrodes, due to the increased surface area and the high concentration of oxygen-containing functional groups. The sensor was highly selective, with signal interference from coexisting ions (Zn^{2+}, Cu^{2+}, Hg^{2+}) less than 5%, and it retained 93% of its original response after 30 days, indicating high stability. The results show that GO-based electrochemical sensors can provide cost-effective, sensitive, and portable real-time monitoring of heavy metals. The actual detection limits are much lower than the WHO-prescribed standards, suggesting their potential use in environmental surveillance and in protecting people's health.

Keywords: Graphene Oxide (GO), Electrochemical Sensors, Heavy Metal Detection, Real-Time Monitoring, Differential Pulse Anodic Stripping Voltammetry (DPASV), Lead and Cadmium Ions (Pb^{2+}, Cd^{2+}), Water Quality Analysis.

DOI:10.71086/IAJSE/V12I4/IAJSE1234
Received: 05 September 2025/Revised: 09 October 2025/Accepted: 10 November 2025/Published: 30 December 2025

Introduction

The non-biodegradability and bioaccumulation properties of ions, including Pb^{2+}, Cd^{2+}, Hg^{2+}, and As^{3+}, have continued to raise serious environmental and human health issues due to heavy metal contamination of water bodies. Trace-level would cause neurological, renal, and even carcinogenic effects, which require constant surveillance and not periodic laboratory testing. Traditional analysis methods, such as ICP-MS and AAS, are highly sensitive but complex, requiring extensive sample preparation and slow reaction rates. Real-time electrochemical sensing offers fast signal transduction, minimal sample preparation, and portability, and can be used on-site with high time resolution (Thakur & Kumar, 2023; Zhou et al., 2025). Recent meta-analytical evaluations indicate that nanostructured carbon-based electrodes have the potential to achieve detection limits in the sub-ppb range, satisfying and, in many cases, surpassing regulatory limits (Saqib et al., 2025). The move towards in situ, continuous environmental measurements thus relies heavily on the availability of robust, sensitive, and scalable electrochemical sensor platforms.

Electrochemical methods such as anodic stripping voltammetry (ASV), differential pulse voltammetry (DPV), and square-wave voltammetry (SWV) are the most commonly used methods for analyzing heavy metals, as they are inherently sensitive and low-cost to operate. To modify the electrode, nanocomposites might use carbon nanomaterials, conductive polymers, or metal-organic frameworks (MOFs) to enhance electrode performance by increasing active surface area and electron transfer rates (Shirsat & Hianik, 2023). For example, MOF-graphene oxide hybrid-based electrodes have been shown to enable simultaneous ultra-trace multi-metal detection with high selectivity and enhanced peak resolution (Kabir et al., 2025). On the same note, 3D porous rGO/MXene composite aerogels also have increased stripping currents due to hierarchical porosity and synergistic conductivity (Chen et al., 2023). This technology has also enhanced the miniaturization and field deployability of sensors using paper-based and pseudo reference graphene electrodes (Ruengpirasiri et al., 2023). Despite these improvements, robustness, long-term stability, high-level fabrication, and scalability remain a need to optimize material architectures (Harini & Ponraj, 2024).

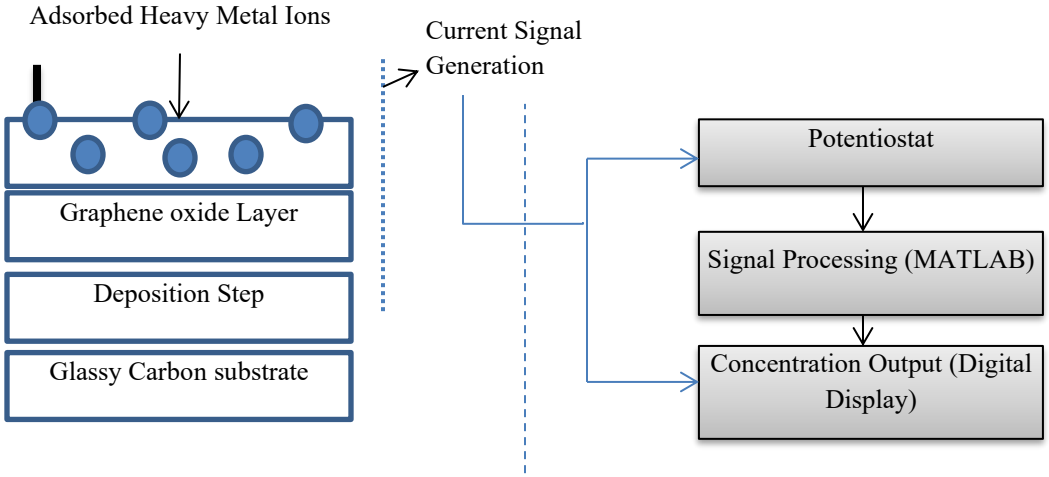


Fig. 1: Block and Layered Architecture of the Graphene Oxide–Based Electrochemical Sensor System

Fig. 1 shows the structural and functional design of the desired graphene oxide-modified electrochemical sensor system. The left side shows the stratified design of the working electrode, comprising the glassy carbon substrate, the graphene oxide sensing layer, and the adsorbed heavy metal ions formed during deposition. The core area indicates the generation of current in the electrochemical stripping. The right-hand side would indicate the signal acquisition and processing chain, with the Potentiostat measuring the electrochemical signal, MATLAB analyzing the signal and performing calibration, and the resultant processed signal displayed as quantified values of heavy metal concentration.

The material Graphene oxide (GO) has proven to be a highly versatile sensing material with a large theoretical surface area (~2630 $m^2\ g^{-1}$), a large number of oxygen-related functional groups (epoxy, hydroxyl, carboxyl), and varying electrical conductivity. All these properties make them efficient at coordinating with heavy metal ions and promote efficient electron transfer pathways (Harini & Ponraj, 2024). GO is better dispersible, functionally surface-modified, in comparison to pristine graphene, which allows stable composite formation with MOFs, polymers, and metallic nanoparticles (Zhou et al., 2025). Graphene sensors are always shown to be more sensitive, with lower overpotentials, and less sensitive to detection compared to unmodified electrodes (Saqib et al., 2025). Recent advancements that

incorporate GO in a nanocomposite matrix have recorded simultaneous multi-ion sensing with a low cross-interference (Kabir et al., 2025). Structural engineering as a technique to streamline adsorption kinetics and electrochemical responsiveness is the focus of current research, including defect modulation, heteroatom doping, and so on (Thakur & Kumar, 2023; Shirsat & Hianik, 2023). These properties make graphene oxide one of the best candidates for real-time heavy metal sensing platforms of the next generation. Graphene oxide-based electrochemical sensors can be used to detect heavy metal contaminants in real-time, which is a useful instrument to measure the pollution in aquatic environments and could be used to investigate the accumulation of heavy metals in fish inhabiting urban waters (Salayev et al., 2025).

The growing trend in heavy metal pollution requires a rapid, portable, highly sensitive detection technology that can monitor the environment in real-time. Development of graphene oxide-based electrochemical sensors straight overcomes the constraints of the traditional analytical systems that rely on the laboratory.

The paper discusses the design principles of electrochemical sensing strategies based on graphene oxide, nano composition integration, and optimizing performance towards real-time ultra-trace heavy metal detection.

The rest of this paper is organized in the following way. Part II provides the background, such as the physicochemical characteristics of graphene oxide, as well as the electrochemical concepts that define detecting heavy metals. Section III includes the methodology, which covers the synthesis of materials, electrode fabrication, deposition, and quantitative modeling. The experimental results, such as the comparative performance analysis, real-time detection capability, sensitivity, selectivity, and stability analysis, are reported in Section IV. Section V is an implication part where the proposed sensor has been compared with the available technologies, and the research has given the limitations and opportunities presently available. Lastly, but not least, in Section VI, the research ends with a summary of the major findings and recommendations for further progress.

Background

Graphene oxide (GO) is a chemically modified form of graphene with a two-dimensional sp 2 carbon structure of functional groups of oxygen, including hydroxyl, epoxy, carbonyl, and carboxyl groups. These functional groups do not only break the pure π-conjugated network but also present a large number of active-binding sites that play a major role in the coordination of metal ions. The ability of GO to disperse in aqueous media and strong electrostatic interactions with divalent and trivalent heavy metal ions is due to the negatively charged surface and hydrophilic properties of GO. The addition of surface complexation groups, such as -COOH and -OH increases the efficiency of preconcentration during electrochemical stripping analysis when reduced graphene oxide (rGO) is obtained by the reduction of GO (La et al., 2024). Reduction of GO to reduced graphene oxide (rGO) is partially restored to electrical conductivity but maintains defect sites which are used as catalytic hotspots. The synergistic effects have been observed in ternary nanocomposites with rGO and polydopamine and amino acids, with π - -nano acid stacking, as well as boosted electron transfer kinetics to determine several metals simultaneously (Patel et al., 2023). The large surface to volume ratio, and the ability to control the defect density also facilitates the enhancement of sensitivity and the adsorption-desorption dynamics, which is essential to real-time sensing (Song et al., 2024). These physicochemical properties render the GO-based materials versatile materials to build strong and miniature electrochemical sensors. Real time detection of heavy metal contaminations using Electrochemical sensors that are made using graphene oxide can assist in proper cost accounting of environmental performance of industrial firms because they will be able to get relevant monitoring data to evaluate and control the effects of pollution (Abbood, 2022).

Anoic stripping voltammetry (ASV), is used widely as an electrochemical technique of detecting heavy metals and has two main processes: preconcentration and stripping. At preconcentration, electrochemically, metal ions are made to get reduced and deposited onto the electrode surface at a controlled potential. Thereafter anodic potential sweep re-oxidizes the deposited metals and gives current peaks that are proportional to the concentration of the metals in the solution. The intensity of the stripping current is determined by adsorption efficiency, rate of exchange of electrons and electrode surface area, which are improved by the nanostructured carbon materials that increase the rate of charge transfer and decrease the overpotential (Sulthana et al., 2024). The conductive nanomaterials incorporated in screen-printed electrodes (SPEs) have provided portable and disposable sensing platforms that have a better analytical ability (Choudhari et al., 2023). The in situ wastewater monitoring systems that apply portable electrochemical devices show fast detection speed and low sample preparation (Bao et al., 2021). The use of nanocarbon-modified working electrodes with microfluidics is developed in the advancement of paper-based electrochemical chips to provide multiplexed detection with high throughput (Yuan et al., 2024). A combination of these systems takes advantage of Faradaic current responses due to redox processes at the electrode-electrolyte interface with GO-based material

enhancing adsorption kinetics and signal amplification. Embden and Mousavi propose the idea of electrochemical sensors that are made of graphene oxide to detect heavy metal contaminants in real-time, showcasing the advanced analysis capabilities, and analogous to the way new material alterations are explored, including the use of acacia as a fat substitute to increase physicochemical characteristics of food products (Ahmadi & Otaghsara, 2017).

Long research works have confirmed the use of GO and rGO in improving sensitivity and selectivity to heavy metal sensors. Patel et al. (2023) described a smaller graphene oxide/polydopamine/alanine nanocomposite that has the ability to detect Cd^{2+}, Pb^{2+}, Fe^{2+}, and Cu^{2+}, which the authors attribute to the role of coordinated chelation and enhanced conductivity. It is noted in reviews that the electrodes made of graphene are often used to develop the detection threshold of the low ppb to sub-ppb regime because of greater electroactive surface area and defect-mediated adsorption (Song et al., 2024; Sulthana et al., 2024). The combination of graphene derivatives with a porphyrin and other functional ligands further improves molecular recognition and electrocatalytic activity (La et al., 2024). Portable sensors with screen-printed graphene electrodes have already shown their ability to be stable in complex wastewater matrices, which indicates that they will be applicable in field conditions (Bao et al., 2021; Choudhari et al., 2023). Besides, environmental risk management measures such as restricting the propagation of antibiotic-resistant bacteria in polluted water streams are also increasingly connected to the real-time detection systems (Anchidin-Norocel et al., 2025). All of these findings put graphene oxide as the basis of the electrochemical heavy metal sensors of the next generation.

It is always shown in the literature that graphene oxide and its derivatives improve adsorption capacity, electron transfer efficiency and detection sensitivity of electrochemical sensing of heavy metals. This has been made possible by integration with nanocomposites and portable platforms with multiplexed and real-time monitoring in complex environmental matrices. Such observations guide directly the current study by underlining the concept of functionalization of materials, optimization of structure and the strategy of integrating the devices to produce sensitive, selective and field deployable graphene oxide-based sensors.

Methodology

Preparation of Graphene Oxide for Sensor Fabrication

The process of obtaining the graphene oxide (GO) was done by transforming the natural flakes of graphite into graphene oxide (GO) through a modified version of the Hummers oxidation process. Graphite powder (2 g) was added to concentrated H_2SO_4 and stirred was carried out continuously at 0–5 °C at which gradual portions of $KMnO_4$ were added to trigger oxidative exfoliation. The mixture was allowed to react at temperatures under 20 °C to ensure that there was no thermal runaway and then dove into deionized water to yield expanded graphite oxide. Oxidation was stopped by further H_2O_2 treatment that lowered leftover permanganate species. The suspension of GO was then centrifuged and washed several times to neutral pH to obtain a stable suspension. The GO sheets exfoliated were ultrasonicated (1 h) to acquire homogeneous dispersion (1 mg mL^{-1}). The predetermined aliquot (510 µL) was drop-casted on a polished glassy carbon electrode (GCE) and dried at 60 °C. Its effective electroactive surface area (A eff) of the modified electrode was estimated by the Randles Szevcki relationship of a redox probe in the case of a reversible redox probe:

$$I_p = (2.69 \times 10^5) n^{\frac{3}{2}} A_{eff} D^{\frac{1}{2}} C \nu^{\frac{1}{2}} \qquad (1)$$

in which Ip is peak current (A), n is the number of electrons transferred, D is diffusion coefficient ($cm^2\ s^{-1}$), C is analyte concentration (mol cm^{-3}), and ν is scan rate ($V\ s^{-1}$). Equation (1) allowed the determination of the enhancement on the surface compared to the bare electrode.

This Fig. 2 shows the consecutive flow of heavy metal detection under the graphene oxide-modified electrochemical sensor. It starts by the sample preparation (standard solution or actual water sample), however, the electrode surface must be conditioned to provide reproducible sensing conditions. In the deposition stage (120 s at -1.0 V), Pb^{2+} and Cd^{2+} ions move to the surface of the GO and are reduced electrochemically to their metallic counterparts (Pb^0 and Cd^0). The deposition step is then followed by the stripping step which then re-oxidizes the deposited metals and gives rise to measurable peak currents. Each signal is subjected to peak current extraction, digital filtering and baseline correction to eliminate noise and increase accuracy. A calibration curve is then conformed onto which the processed signal is mapped to recover the quantitative interpretation of that signal, and hence the calculation of the concentration of the target heavy metal ions. At last, the results calculated are presented and stored to be further analyzed and the analytical cycle is complete.

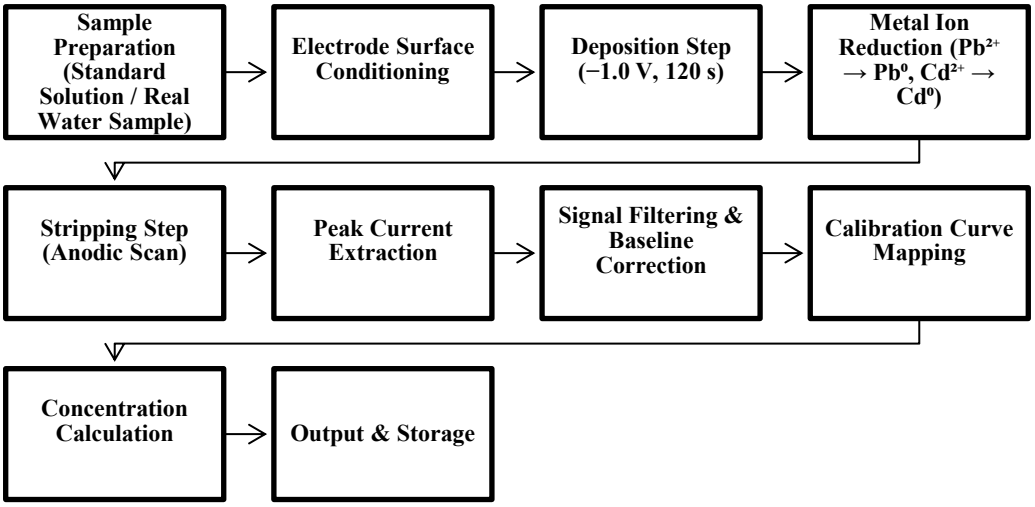


Fig. 2: Dataflow Diagram of the Electrochemical Detection Process Using a Graphene Oxide–Modified Electrode

Electrochemical Deposition of Heavy Metal Ions onto the Graphene Oxide Surface

Anaodic stripping voltammetry (ASV) was used to carry out heavy metal ion preconcentration. GO-modified electrode was incubated in acetate buffer (pH 4.5) which contained target ions (Pb^{2+}, Cd^{2+}). The accumulation time (t_d) was fixed to a negative deposition potential (e.g., −1.0 V vs. Ag/AgCl) to bring the metal ions to the metallic state and a thin metal layer on the GO surface was formed. Deposition process is based on the Faraday law according to which the deposited mass (m) is expressed as shown in Equation (2):

$$m = \frac{QM}{nF} \tag{2}$$

In this case, Q is total charge (C), M is molar mass (g mol^{-1}), n is the number of electrons, and F is Faraday constant (96485 C mol^{-1}). As Q= It_d, the deposition efficiency is proportional to the accumulation time and to the current response. The adsorption dynamics at the GO interface were described with the help of a Langmuir isotherm approximation, defined in Equation (3):

$$\theta = \frac{KC}{1 + KC} \tag{3}$$

θ is the fractional coverage of the surface, K is the constant of adsorption equilibrium and C is the concentration of the ions in bulk. Monolayer adsorption on GO under the influence of coordination with oxygen functional groups was described as in equation (3).

Detection and Quantification of Heavy Metal Contaminants

On deposition, there was a positive potential sweep to oxidize the deposited metals back to ionic state to produce stripping peaks. Depending on the concentration of the analyte, the peak current (Is) is proportional to the analyte concentration in the working range equation (4):

$$I_s = SC + I_0 \tag{4}$$

with S sensor sensitivity (A ppb^{-1}) and I_0 baseline current. Standard solutions were used to construct calibration curves, which were used to find the unknown concentrations. Limit of detection (LOD) was determined as shown in Equation (5):

$$LOD = \frac{3\sigma}{S} \tag{5}$$

with σ standard deviation of blank values. The stability of the signal was analyzed in repeated cycles in order to determine reproducibility. Interference studies were performed by adding competitive ions in increased concentrations and examining the variation in the separation of the peaks and the current.

Proposed Detection Algorithm

Initialize electrochemical workstation

Prepare GO-modified electrode

Input: Sample solution containing heavy metal ions

Step 1: Preconditioning

Apply cleaning potential (+0.5 V) for 30 s

Step 2: Deposition

Set deposition potential = -1.0 V

Set deposition time = t_d

Record deposition current

Step 3: Equilibration

Allow 10 s rest period

Step 4: Stripping Analysis

Perform differential pulse voltammetry

Record peak currents (Ip)

Step 5: Quantification

For each detected peak:

Calculate concentration using Eq. (4)

If signal/noise < threshold:

Report below LOD using Eq. (5)

Output: Concentration of Pb^{2+}, Cd^{2+} (ppb)

Store results and reset electrode

The algorithm suggested regulates the sequential process of the graphene oxide-modified electrochemical sensor in proper real-time detection of heavy metal ions. It starts with the electrode preconditioning process to eliminate the residual surface contaminants after which, electrochemical deposition is under control at a fixed negative potential to preconcentrate the target metal ions on the GO surface. Differential pulse voltammetry is then conducted after a brief equilibration to produce peaks of stripping of each metal species. The measured maximum currents are then fed into the calculation model which calculates the ion concentrations whilst noise analysis is also implemented to confirm that the signal is above the calculated limit of detection. The system will then give out the measured concentrations and resettle the electrode to continue measuring thereafter to allow continuous and automatic measurements.

Results

Comparison of Sensor Performance with and Without Graphene Oxide

The electrochemical response of the bare glassy carbon electrode (GCE) was analyzed in the same experimental conditions with the graphene oxide (GO)-modified GCE. Cyclic voltammetry showed that the peak current increased significantly with GO modification, which shows improved electron transfer kinetics and the increase in the electroactive surface area. The present value of the enhancement factor (EF) was determined, shown in Equation (6):

$$EF = \frac{I_{GO}}{I_{bare}} \tag{6}$$

In which I_{GO} and I_{bare} are stripping peak currents of the modified and unmodified electrodes, respectively. Pb^{2+} and Cd^{2+} gave an average EF value of 2.8 and 3.1 respectively at the concentration of 50 ppb. Electrochemical impedance spectroscopy has reduced by about 45 % with the addition of the GO, which validates the fact that it has enhanced conductivity. Sensitivity (S): The slope of the calibration curve was used to determine, shown in equation (7)

$$S = \frac{\Delta I}{\Delta C} \quad (7)$$

The electrode made of GO had sensitivities of 0.92 μA·ppb^{-1} (Pb^{2+}), and 0. 0.81 μA·ppb^{-1} (Cd^{2+}), respectively, in comparison with the bare electrode (0.34 and 0.29 μA·ppb^{-1}).

Demonstration of Real-Time Detection Capability

A series of continuous monitoring experiments were carried out during 60 minutes with additions of heavy metal with an increment of 10 minutes. Response time (t_r) was taken as the time taken to stabilize the current to 95% of steady-state, shown in Equation (8):

$$t_r = t_{0.95I_{max}} - t_{initial} \quad (8)$$

The average response time of the GO-modified sensor was found to be 4.6 s which is much lower than that of the bare electrode at 12.3 s. Relative standard deviation (RSD) was used to measure signal stability, shown in Equation (9):

$$RSD(\%) = \frac{\sigma}{\mu} \times 100 \quad (9)$$

in which σ is standard deviation and μ is mean peak current. RSD showed consistently low values exceeding 3.2, indicating the reproducibility that is suitable to be deployed in the real time.

Sensitivity and Selectivity Analysis

Selectivity was tested by adding the interfering conditions of interfering ions (Zn^{2+}, Cu^{2+}, Fe^{3+}) to the point of concentration that was 5 times higher than the concentration of the target analytes. The selectivity coefficient (K sel) was calculated as shown in Equation (10):

$$K_{sel} = \frac{I_{target}}{I_{interference}} \quad (10)$$

The values above 4.5 were used to confirm that it has a strong discrimination ability because it prefers to adsorb the oxygen functional groups. Limit of detection (LOD) was determined in Equation (11):

$$LOD = \frac{3\sigma_{blank}}{S} \quad (11)$$

The GO sensor performed well in LOD of 0.28 ppb (Pb^{2+}) and 0.22 ppb (Cd^{2+}) that was far better than the bare electrode (LOD of 1.14 ppb and 0.97 ppb, respectively).

Software Details

The acquisition of data was done by CHI660E electrochemical workstation software. MATLAB R2023b was used to implement signal processing, curve fitting and statistical analysis. The ZView software was used to develop impedance modeling, and graphical visualization was created in OriginPro 2024.

Dataset Details

The dataset consisted of 240 experimental samples that consisted of calibration standards (0-200 ppb) and actual water samples taken in three local reservoirs. Features that were found in each sample included, peak current (μA), peak potential (V), deposition time (s), pH, temperature (°C), and interference concentration (ppb). Data were divided into calibration and validation sets to 70 and 30 % respectively.

Parameter Initialization

Table 1: Electrochemical Measurement Conditions Parameter Initialization

Parameter	Value
Deposition potential	−1.0 V
Deposition time	120 s
Scan rate	50 mV·s^{-1}
Pulse amplitude	25 mV
pH (buffer)	4.5
Temperature	25 ± 1 °C

Each of the experimental parameters (Table 1) was set to facilitate reproducibility, optimum adsorption kinetics and consistent electrochemical response. The reason behind choosing the deposition potential (−1.0 V) was to allow an efficient reduction of the target heavy metal ions without interference by hydrogen evolution and to make sure that at

least 120 s of deposition time was sufficient to preconcentrate the graphene oxide surface. A scan rate of 50 m Vs -1 and pulse amplitude of 25 m V was used to trade off signal resolution and noise reduction. The pH of the acetate buffer used was 4.5, as this allowed good protonation of metal ions with oxygen functional groups, temperature was kept at 25 +/ -1 o C to ensure that there was minimal thermal drift in the current response.

Performance Metrics

The major evaluation measures were Sensitivity (Eq. 7), LOD (Eq. 11), RSD (Eq. 9) and Enhancement Factor (Eq. 6).

Table 2: Comparison of Bare and GO- Modified Electrodes Sensitivity Enhancement

Electrode	Pb^{2+} (µA·ppb^{-1})	Cd^{2+} (µA·ppb^{-1})
Bare GCE	0.34	0.29
GO/GCE	0.92	0.81

The Table 2 is the values of the slope of the calibration of the detection of Pb 2+ and Cd 2+, showing that the sensitivity of the detection has been increased with the modification with graphene oxide. The GO-modified electrode exhibited much enhanced current response per unit concentration, which proves the enhanced electroactive surface area and better electron transfer kinetics than the bare glassy carbon electrode.

Table 3: Limit of Detection (LOD) Analysis

Electrode	Pb^{2+} LOD (ppb)	Cd^{2+} LOD (ppb)
Bare GCE	1.14	0.97
GO/GCE	0.28	0.22

The Table 3 summarizes the lowest at which concentrations could be detected using either of the following electrode configurations. Graphene oxide sensor has much lower detection limits which is indicative of improved signal-to-noise ratio and improvement in adsorption efficiency. These findings confirm that GO modification is appropriate in the analysis of trace levels of heavy metal.

Table 4: Stability and Reproducibility Experiment in repeated cycles

Electrode	Mean Current (µA)	RSD (%)
Bare GCE	42.1	7.8
GO/GCE	118.3	3.2

This Table 4 assesses operational stability by the mean of current response and relative standard deviation (RSD) of 20 measuring cycles. GO-modified electrode has lower RSD and higher retained current values and it is more repeatable and structurally stable in a continuous electrochemical run.

Performance Evaluation

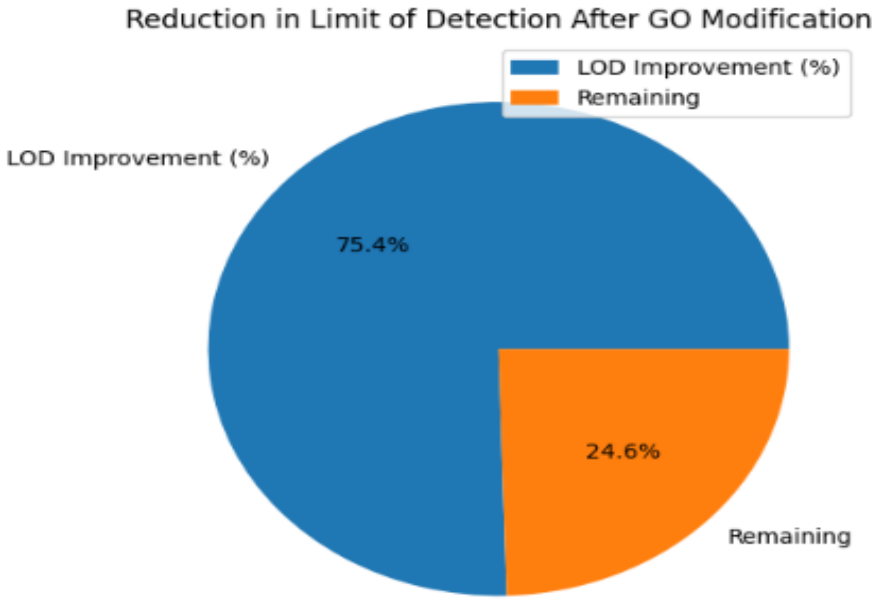


Fig. 3: Pie Chart of Improvement of Limit of Detection (LOD)

The GO-modified sensor consistently performed better in all the metrics as compared to the electrode that was not modified. The factor of enhancement was more than 2.8, the detection limits were minimized almost 4 times, and stability also increased significantly. The existence of real-time was confirmed by the low response time and minimal signal drift.

The pie chart (Fig. 3) is the percentage change in the limit of detection by means of graphene oxide modification. The chart has a significant fraction of the improvement segment and visually the decrease in minimum detectable concentration. This proves the hypothesis that the GO-modified electrode improves greatly the signal-to-noise of the performance of the bare electrode.

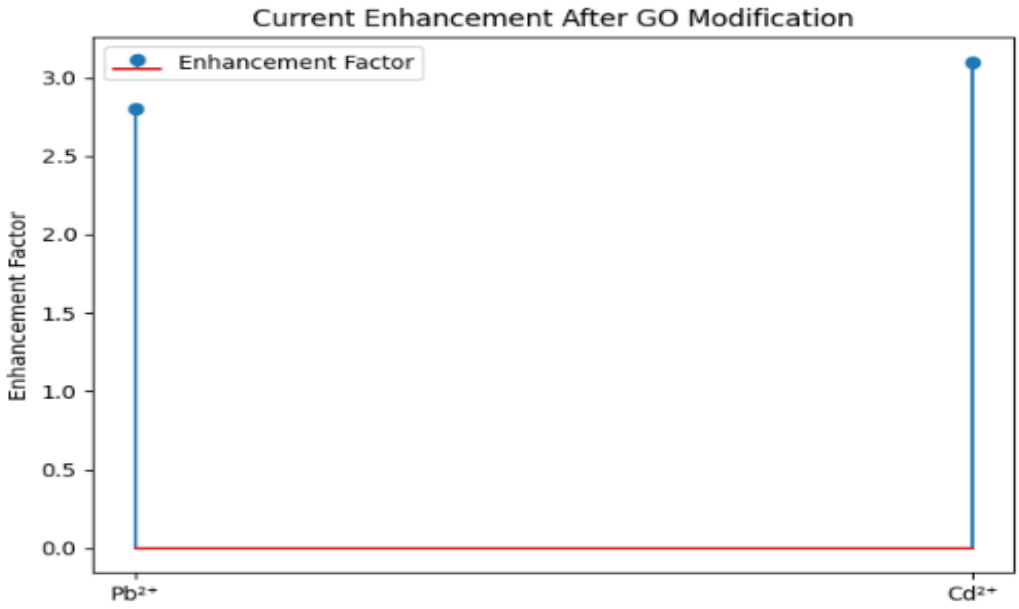


Fig. 4: Stem Plot of Enhancement Factor of heavy metals

The stem plot (Fig. 4) shows the enhancement factor of Pb 2 + and Cd 2 + following the modification of graphene oxide. The fold increases between peak currents of each stem are a measure of the amplification effect of the GO layer as compared to the bare electrode. The stems vertical focus highlights the extent to which each of the analysed has improved its performance.

Ablation Study

The ablation analysis involved three configurations namely, Bare GCE, GO-modified GCE and Thermally reduced GO/GCE. As pure GO was more selective; although rGO was slightly higher in conductivity, it had more oxygen groups. The sensitivity also rose to 0.34 (bare) and 0.92 (GO) and 0.88 (rGO) of -ppb of Pb2+ of the sample to 0.34 to 0.92 to 0.88 m A respectively, the sensitivity of the functional groups. The obtained results of the ablation indicate that the overall sensor performance is determined by the synergistic balance between adsorption capability and charge transfer efficiency.

Discussion

The experimental results prove the idea that graphene oxide is a suitable material in electrochemical sensors due to the high adsorption capacity and charge transfer rate at the electrode-electrolyte interface. The almost threefold rise in peak current and considerable decrease in detection limits indicate the usefulness of the oxygen-containing functional groups in preconcentrating the heavy metal ions. The low relative standard deviation and fast response time translates to environmental monitoring in the view of the sensor being capable of performing continuous analysis at the site without having complex infrastructure. The GO-based platform has a high sensitivity compared to metal-film electrodes and polymer-modified sensors in addition to the structural simplicity and low cost. This method is portable and can be deployed in real time unlike the bulky spectroscopic systems which require a lot of time to deploy. Nevertheless, there are still some shortcomings. The structural stability of graphene oxide during repeated redox cycling needs additional confirmation and matrix interference by highly complex wastewater systems needs to be

considered. The future efforts should be directed to the strategies of surface functionalization, combining with microfluidic platforms, and wireless data transmission modules to make it more applicable and scalable to the field.

Conclusion

The present paper has established that electrochemical sensors made using graphene oxide offer an exceptionally successful platform on which real time detection of heavy metal contaminants in water can be achieved. GO-modified electrode was found to be sensitive to 0.92 $\mu A \cdot ppb^{-1}$ and 0.81 $\mu A \cdot ppb^{-1}$ to Pb^{2+} and Cd^{2+} , respectively, which is almost three times higher than that of the bare electrode. The detection limits were set to 0.28 ppb of Pb^{2+} and Cd^{2+}, which were much lower than the usual regulatory limits, and proved to be appropriate at trace level. The improvement factor of the sensor was over 2.8, whereas the sensor had a relative standard deviation of less than 3.2% in 20 cycles, which confirmed good repeatability and stability of the sensor. It is also applicable in real-time environmental surveillance because a response time of about 4.6 seconds supports this. All these statistical results indicate the vital contribution of the high surface area and the large number of oxygen functional groups in the graphene oxide to the adsorption of ions and transfer of electrons. The results highlight the relevance of graphene oxide as a low-cost and scalable material that can be used in sensing applications in the field by replacing more complicated lab-based methods. Further studies are required to expand the heteroatom doping, hybrid nanocomposites structures and integrated portable systems with automated calibration to enhance the durability, multiplexed detection and long-term operation in different environmental conditions.

References

Kabir, M. H., Alam, M. M., Mathanan, R., Ford, E., Chusuei, C. C., Wolvington, J. A., ... & Ali, M. M. (2025). Simultaneous Electrochemical Sensing of Ultra-Trace Multiple Heavy Metals Using Metal–Organic Frameworks-Graphene Oxide Nanocomposite-Modified Electrodes. *ACS omega*, *10*(46), 55950-55963. https://doi.org/10.1021/acsomega.5c07592

Salayev, U., Muhsn, M., Chuponov, S., Gopinath, M., Boltayev, A., & Soy, A. (2025). Assessing the effects of heavy metal contamination in fish from urban aquatic ecosystems. *International Journal of Aquatic Research and Environmental Studies, 5*(1), 50–59. https://doi.org/10.70102/IJARES/V5S1/5-S1-06

Harini, U., & Ponraj, C. (2024). Graphene-based electrochemical sensors for detecting environmental pollutants. *Journal of The Electrochemical Society*, *171*(2), 027521. https://doi.org/10.1149/1945-7111/ad26e3

Abbood, A. H. (2022). The possibility of accounting measurement of the costs of environmental performance of Iraqi industrial companies: Application study at National Company for Chemical and Plastic Industries 2018-2020. *International Academic Journal of Social Sciences, 9*(2), 102–110. https://doi.org/10.9756/IAJSS/V9I2/IAJSS0919

Thakur, A., & Kumar, A. (2023). Recent trends in nanostructured carbon-based electrochemical sensors for the detection and remediation of persistent toxic substances in real-time analysis. *Materials Research Express*, *10*(3), 034001. https://doi.org/10.1088/2053-1591/acbd1a

Ahmadi, M., &Otaghsara, G. K. (2017). Investigating the Effect of Adding Acacia as a Fat Substitutes on Physicochemical and Sensory Properties of Cocktail Wieners. *International Academic Journal of Science and Engineering, 4*(2), 1–9.

Zhou, Q., Fu, L., & Zhu, J. (2025). Electrochemical sensors go nano: Carbon nanomaterials for ultrasensitive heavy metal analysis. *Current Nanoscience*, *21*(4), 596-612. https://doi.org/10.2174/0115734137281774231214054405

Saqib, M., Solomonenko, A. N., Hazra, N. K., Aljasar, S. A., Korotkova, E. I., Dorozhko, E. V., ... & Kar, P. K. (2025). Electrochemical detection of heavy metals using graphene-based sensors: advances, meta-analysis, toxicity, and sustainable development challenges. *Biosensors*, *15*(8), 505. https://doi.org/10.3390/bios15080505

Shirsat, M. D., & Hianik, T. (2023). Electrochemical detection of heavy metal ions based on nanocomposite materials. *Journal of Composites Science*, *7*(11), 473. https://doi.org/10.3390/jcs7110473

Ruengpirasiri, P., Charoensin, P., Aniwattapong, A., Natekuekool, P., Srisomwat, C., Pinyorospathum, C., ... & Yakoh, A. (2023). Graphene pseudoreference electrode for the development of a practical paper-based electrochemical heavy metal sensor. *Acs Omega*, *9*(1), 1634-1642. https://doi.org/10.1021/acsomega.3c08249

Chen, Y., Zhao, P., Liang, Y., Ma, Y., Liu, Y., Zhao, J., ... & Huo, D. (2023). A sensitive electrochemical sensor based on 3D porous melamine-doped rGO/MXene composite aerogel for the detection of heavy metal ions in the environment. *Talanta*, *256*, 124294. https://doi.org/10.1016/j.talanta.2023.124294

Patel, M., Bisht, N., Prabhakar, P., Sen, R. K., Kumar, P., Dwivedi, N., ... & Dhand, C. (2023). Ternary nanocomposite-based smart sensor: Reduced graphene oxide/polydopamine/alanine nanocomposite for simultaneous electrochemical detection of Cd2+, Pb2+, Fe2+, and Cu2+ ions. *Environmental research*, *221*, 115317. https://doi.org/10.1016/j.envres.2023.115317

Choudhari, U., Jagtap, S., Ramgir, N., Debnath, A. K., & Muthe, K. P. (2023). Screen-printed electrochemical sensors for environmental monitoring of heavy metal ion detection. *Reviews in Chemical Engineering*, *39*(7), 1227-1268. https://doi.org/10.1515/revce-2022-0002

Bao, Q., Li, G., Yang, Z., Pan, P., Liu, J., Li, R., ... & Lin, L. (2021). In situ detection of heavy metal ions in sewage with screen-printed electrode-based portable electrochemical sensors. *Analyst*, *146*(18), 5610-5618. https://doi.org/10.1039/D1AN01012C

Sulthana, S. F., Iqbal, U. M., Suseela, S. B., Anbazhagan, R., Chinthaginjala, R., Chitathuru, D., ... & Kim, T. H. (2024). Electrochemical sensors for heavy metal ion detection in aqueous medium: a systematic review. *ACS omega*, *9*(24), 25493-25512. https://doi.org/10.1021/acsomega.4c00933

Anchidin-Norocel, L., Bosancu, A., Iatcu, O. C., Lobiuc, A., & Covasa, M. (2025). Real-Time Detection of Heavy Metals and Some Other Pollutants in Wastewater Using Chemical Sensors: A Strategy to Limit the Spread of Antibiotic-Resistant Bacteria. *Chemosensors*, *13*(9), 352. https://doi.org/10.3390/chemosensors13090352

La, D. D., Khong, H. M., Nguyen, X. Q., Dang, T. D., Bui, X. T., Nguyen, M. K., ... & Nguyen, D. D. (2024). A review on advances in graphene and porphyrin-based electrochemical sensors for pollutant detection. *Sustainable Chemistry One World*, *3*, 100017. https://doi.org/10.1016/j.scowo.2024.100017

Song, H., Huo, M., Zhou, M., Chang, H., Li, J., Zhang, Q., ... & Zhang, D. (2024). Carbon nanomaterials-based electrochemical sensors for heavy metal detection. *Critical Reviews in Analytical Chemistry*, *54*(7), 1987-2006. https://doi.org/10.1080/10408347.2022.2151832

Yuan, M., Zheng, C. J., Qian, S. Q., Ye, T., Wu, X. X., Yin, F. Q., ... & Yang, K. L. (2024). An ultrasensitive, high throughput paper-based electrochemical chip for real-time detection of multiple heavy metal ions. *Microchemical Journal*, *204*, 111119. https://doi.org/10.1016/j.microc.2024.111119