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Sustainable Silver Oxide Nanoparticle-Based Electrode for Ultra-Sensitive and Selective Detection of Silver Ions in Aquatic Environment

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ABSTRACT

In this study, a green synthesis approach was employed to prepare nanoparticles using mint leaves as the source material. These nanoparticles were then used to create an ion-selective electrode through a novel method designed to detect and measure silver ions. The process involved preparing a special paste by mixing graphite powder with silver oxide nanoparticles, which had been synthesized from mint leaf extract using an eco-friendly aqueous method. The physical properties of the nanoparticles were analyzed using XRD, SEM, UV-VIS, and FTIR techniques. X-ray diffraction (XRD) revealed an average crystal size of 15.43nm. Scanning electron microscopy (SEM) showed that the particles were spherical or nearly spherical in shape. UV-VIS spectrometry displayed an absorption peak at 422nm, confirming the successful synthesis of silver oxide nanoparticles. Functional groups were identified using FTIR spectroscopy. The resulting electrode demonstrated high selectivity and excellent sensitivity, showing a linear response over the concentration range of 10^{-1} to 10^{-7} M, with a correlation coefficient of 0.9865. It maintained stability for up to 95 days and was performed optimally at temperatures between 15–30°C and pH values of 6–8. The electrode exhibited a slope of 30mV/ decade at 25°C and had a detection limit of 10^{-7} M, with a recovery rate of 100.6%. This method was successfully applied to determine silver ion concentrations in well water and industrial wastewater samples.

INTRODUCTION

In recent years, nanotechnology has gained significant traction in sensor manufacturing. These advancements, along with the use of nanomaterials, have positively influenced sensor performance. Nanomaterials offer unique and diverse physical and chemical properties to devices **(Riaz *et al.*, 2024; Thomas *et al.*, 2024)**.

Nanotechnology is an emerging, dynamic, and rapidly growing field of research explored by scientists globally across universities and laboratories **(Malik *et al.*, 2023)**. It focuses on understanding the chemical, physical, and mechanical properties of nanomaterials. This field is revolutionizing many industries by offering smaller, faster,

and more cost-effective technologies that require fewer raw materials and less energy **(Singh *et al.*, 2023)**.

Silver and silver oxide nanoparticles can be synthesized through chemical, physical, or biological methods **(Kurbanoglu & Ozkan, 2018)**. Two primary approaches exist: the top-down method, which involves physical techniques like grinding or etching materials, and the bottom-up method, where nanoparticles are built from atomic or molecular components to form complex structures **(Singh *et al.*, 2018; Singh *et al.*, 2020)**.

Nanoparticles can also be produced using traditional chemical and physical techniques. However, chemical methods may result in biotoxicity to humans and the environment, while physical methods often require high energy inputs. Additionally, nanoparticles created physically often lack the desired morphology, size, crystallinity, and uniformity **(Baran *et al.*, 2023)**.

Recently, green synthesis using plant-based compounds as natural reducing agents has gained popularity. This includes a wide variety of plant materials, such as leaf extracts, fruits, bark, peels, roots, and seeds **(Hussain *et al.*, 2023)**. Plant extracts contain flavonoids, triterpenoids, and alkaloids, which are rich in antioxidants and serve as both reductants and stabilizers in nanoparticle synthesis **(Hashim *et al.*, 2019)**. The benefits of this method include low cost, environmental friendliness, non-toxic byproducts, and the ability to produce stable nanoparticles quickly. These advantages make green synthesis a preferred approach **(Krishnaveni *et al.*, 2024)**. In this study, silver oxide nanoparticles **(AgO NPs)** were synthesized using mint (*Mentha piperita*) leaves, which offer high efficacy, versatility, and environmental compatibility **(Roy *et al.*, 2019)**.

Various types of sensors are used to detect heavy metals, with carbon paste-based sensors being particularly popular due to their low cost, simple design, ease of fabrication, long lifespan, high conductivity, minimal background current, and wide potential window **(Laghlimi *et al.*, 2021; Aravind *et al.*, 2024)**. Modifying electrodes is often done to create sensors with targeted performance characteristics. Among electrode materials, carbon paste is one of the most suitable choices for creating modified electrodes **(Laghlimi *et al.*, 2021)**.

Modified carbon paste electrodes typically consist of graphite powder blended with other modifying components. These may include one or more substances acting as mediators or carriers—sometimes enzymes—to enhance sensor function. Such designs are especially useful in biosensor applications **(Švancara *et al.*, 2001; Vytřas *et al.*, 2009)**. Research in electrochemical sensors continues to show promise. Selectivity remains a central concern, but electrochemical sensors are valued for their speed, precision, and minimal sample disruption. They allow direct detection in untreated samples **(Lee *et al.*, 2020; Baranwal *et al.*, 2022)**.

Monitoring water quality and detecting contaminants such as heavy metal ions—particularly silver—is vital for environmental and public health protection. Various analytical methods have been developed for this purpose in both freshwater and industrial effluents. Electrochemical techniques like voltammetry, potentiometry, and conductometry are frequently used due to their rapid response and high sensitivity **(Baranwal *et al.*, 2022; Aravind *et al.*, 2024)**. Moreover, electrodes enhanced with nanoparticles demonstrate improved ion detection thanks to their increased surface area and reactivity **(Hwang *et al.*, 2022)**.

Other sensing methods include optical techniques like fluorescence, colorimetric analysis, and UV-Vis spectrophotometry. However, these often require complex equipment and additional reagents **(Lee *et al.*, 2020; Singh *et al.*, 2023)**. Recent advancements in nanomaterial-based sensors, especially those incorporating silver oxide nanoparticles, have shown strong potential due to enhanced selectivity and sensitivity **(Alizadeh & Azizi, 2016)**. These developments highlight the growing importance of sustainable and cost-effective sensors for real-time water quality assessment.

Several recent studies have explored green synthesis techniques for silver nanoparticles, focusing on plant extracts as environmentally friendly reducing agents. **(Haridas *et al.*, 2022)** used *Coffee arabica* leaf extract for nanoparticle synthesis, demonstrating its biosensor potential. **(Okka *et al.*, 2022)** examined *Inula viscosa* extract, emphasizing its efficiency and stability. Green methods are increasingly favored for their sustainability and reduced environmental impact compared to traditional synthesis approaches **(Singh *et al.*, 2018)**. **Ahmed *et al.* (2016)** highlighted the effectiveness of *Azadirachta indica* (neem) aqueous leaf extract as a safe alternative to toxic chemicals. These findings align with earlier research emphasizing the importance of plant-based synthesis in creating stable, functional nanoparticles **(Iravani, 2011)**.

This study aims to develop a sustainable and efficient method for synthesizing silver oxide nanoparticles (AgO NPs) using *Mentha piperita* extract—an eco-friendly alternative to conventional methods that rely on hazardous chemicals and high energy consumption. The research includes comprehensive characterization of the synthesized nanoparticles using XRD, SEM, UV-VIS, and FTIR to assess their structural and chemical properties. These nanoparticles are then integrated into a modified electrode system to enhance its sensitivity, selectivity, and stability in detecting heavy metal ions, particularly copper, in industrial wastewater—offering a practical and scalable solution for environmental monitoring.

MATERIALS AND METHODS

Chemical substances and solutions

- **Deionized Water** was used throughout all preparations.
- **100 mL Volumetric Flasks** were used for solution preparations.
- **Sodium Hydroxide (NaOH)**: To prepare a 0.1 M NaOH solution, 0.400g of sodium hydroxide was accurately weighed and transferred into a 100mL volumetric flask. A small volume of deionized water was added to dissolve the solid completely. The solution was then diluted to the mark with deionized water and mixed thoroughly.
- **Hydrochloric Acid (HCl)**: A 0.1 M HCl solution was prepared by accurately measuring 0.82 mL of concentrated hydrochloric acid (12.06 M, density 1.19g/ cm^3, 37% purity) using a pipette. The acid was transferred into a 100mL volumetric flask containing a small amount of deionized water. The solution was then diluted to the mark with deionized water and mixed thoroughly.
- **Silver Nitrate ($AgNO_3$)**: A 0.1 M silver nitrate solution was prepared using deionized water.
- Graphite powder and paraffin oil were used for the fabrication of carbon paste electrodes.

Preparation of mint leaf extract

Fresh mint leaves (10g) were weighed and placed in a tea bag. The tea bag was then immersed in 150 mL of deionized water in a large beaker. The mixture was heated to 70–80 °C for 40 minutes. After heating, the extract was allowed to cool to room temperature. It was first filtered through standard filter paper and then through a 0.45µm syringe filter to remove fine particulates. The filtered extract was stored in a refrigerator for later use.

Synthesis of silver oxide nanoparticles (AgO NPs)

A volume of 100mL of the prepared mint leaf extract was transferred into a 500mL beaker. Using a burette, 100mL of the 0.1 M silver nitrate solution was gradually added to the extract under continuous stirring while maintaining the temperature at 60–70°C. During the addition, a visible color change from light greenish-yellow to dark brown was observed, indicating the reduction of silver ions and the formation of silver oxide nanoparticles (AgO NPs).

The mixture was then allowed to cool to room temperature to promote nanoparticle growth. Afterward, the suspension was filtered using filter paper. The collected particles

were dried either at room temperature for 24 hours or in an electric oven at 70°C for 1 hour (Fig. 1)

Fig. 1. Plant extract and silver nanoparticles preparation

Carbon-AgO NPs paste preparation

To prepare the silver oxide-carbon paste, carbon powder was thoroughly ground in an agate mortar to achieve a fine and uniform texture. A small amount of AgO nanoparticles, in a 30:70 weight ratio of silver oxide to carbon, were gradually added to the powdered carbon and mixed thoroughly for 30 minutes to ensure homogeneity. Drops of paraffin oil were then slowly introduced while grinding until the mixture formed a homogeneous sticky paste. The prepared paste was left to rest for 24 hours at room temperature to allow excess paraffin oil to volatilize, resulting in a well-mixed and consistent paste suitable for further applications.

Preparation of modified carbon-silver oxide electrode.

A PVC plastic tube was prepared using a 5cc syringe body. A copper wire was inserted into one end of the tube to serve as the electrical contact. A small amount of the previously prepared paste was packed into the same end of the tube, ensuring direct contact between the copper wire and the paste. This process was repeated until the tip of the tube was completely filled with the paste. The opposite end of the tube was then pressed to secure the contents in place.

The assembled electrode was left undisturbed for 24 hours to allow stabilization. Afterward, it was immersed in a 0.1 M silver nitrate solution for 4 hours. Following this activation step, the electrode was ready for use (Fig. 2) **(Tajik *et al.*, 2020)**.

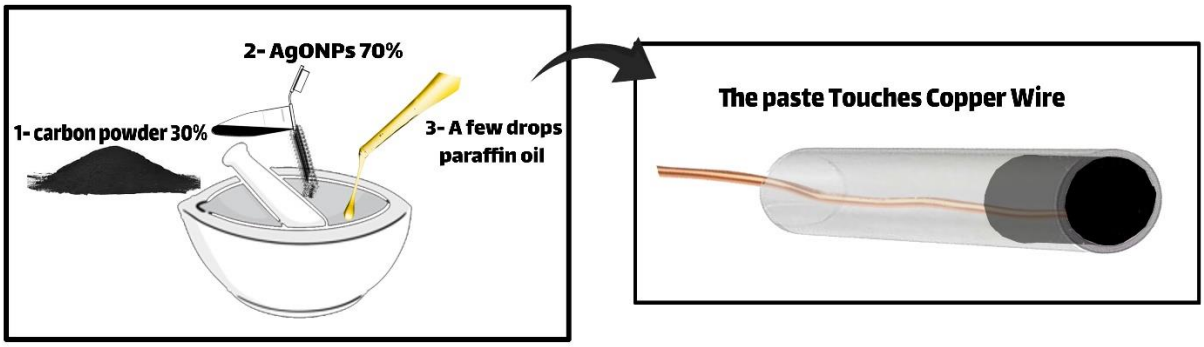

Fig. 2. The electrode preparation

RESULTS and DISCUSSION

Characterization of AgO NPs

UV-Visible Spectroscopy of AgO NPs

The UV-visible spectra of silver nanoparticles (AgO NPs) were examined with a 0.5nm resolution spectrophotometer (SHIMADZU, Japan). A 5mL sample of mint leaf extract solution with silver nanoparticles was made, and UV-Vis was measured. Fig. (3) depicts the UV spectra, which show a peak at 422nm. This peak corresponds to the stable structure of AgO NPs, which typically absorb radiation in the 400-460nm region, consistent with the observations of **Mulvaney (1996)**.

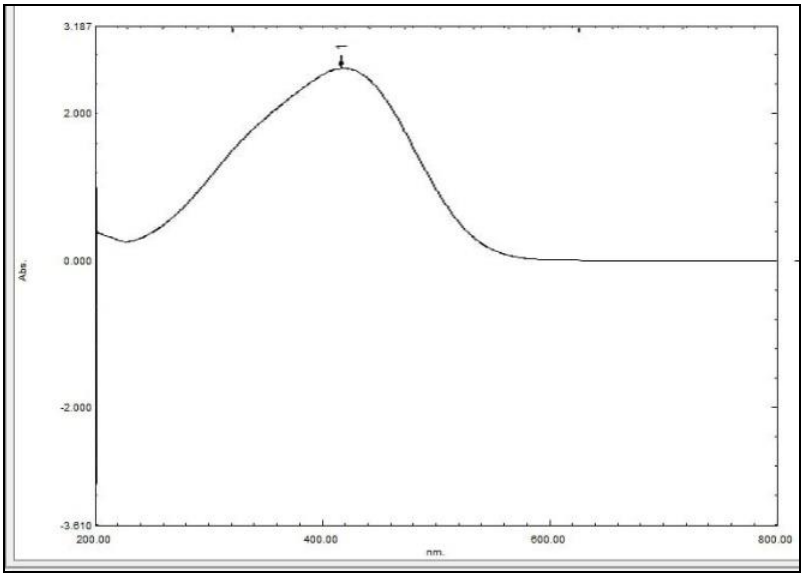

Fig. 3. Wavelength of AgO NPs

SEM Microscopy of AgO NPs

The surface morphology of the synthesized samples was examined using a scanning electron microscope (SEM) (Thermo Scientific Quattro S). Fig. (4) presents SEM images of the produced silver oxide nanoparticles (AgO NPs) at magnifications corresponding to scales of 1μm and 200nm. The AgO NPs exhibited regular semi-spherical shapes with an average particle size of 56.82nm, composed of agglomerated ultra-fine particles.

The SEM analysis confirmed that the use of mint leaf extract effectively reduced the size of the silver oxide nanoparticles, resulting in a distribution of particle sizes. Additionally, the images revealed that variations in the solution's acidity and temperature had a significant influence on the morphology of the synthesized nanoparticles. These findings underscored the critical role of synthesis conditions in determining nanoparticle characteristics.

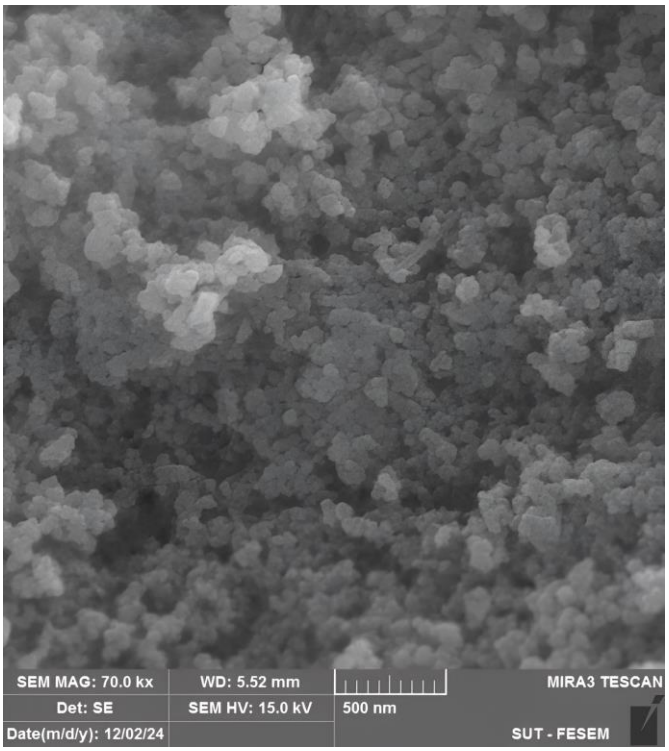

Fig. 4. SEM of AgO NPs

XRD spectrum of AgO NPs

X-ray diffraction (XRD) analysis was performed to determine the crystal structure of the silver oxide nanoparticles (AgO NPs) synthesized via the green synthesis method. Fig. (5) shows the XRD pattern of the prepared AgO NPs, in which several distinct peaks in the characteristics of silver oxide were observed. These peaks appeared at:

- 2θ = 27.89°, corresponding to the (111) plane with a d-spacing of 3.196 Å,
- 2θ = 32.37°, corresponding to the (400) plane with a d-spacing of 2.7636 Å,
- 2θ = 38.28°, corresponding to the (420) plane with a d-spacing of 2.3496 Å,
- 2θ = 44.41°, corresponding to the (040) plane with a d-spacing of 2.0384 Å,
- 2θ = 46.39°, corresponding to the (131) plane with a d-spacing of 1.9557 Å, and
- 2θ = 57.00°, corresponding to the (331) plane with a d-spacing of 1.6156 Å.

These peaks confirmed the successful formation of crystalline AgO nanoparticles. Additional minor diffraction peaks were also detected, which may indicate the presence of impurities or secondary phases within the sample.

The average crystallite size of the synthesized AgO NPs was calculated using the Scherrer equation, and the results are summarized in the table below. This analysis provided insight into the structural properties of the nanoparticles and highlighted the possible presence of contaminants resulting from the synthesis process.

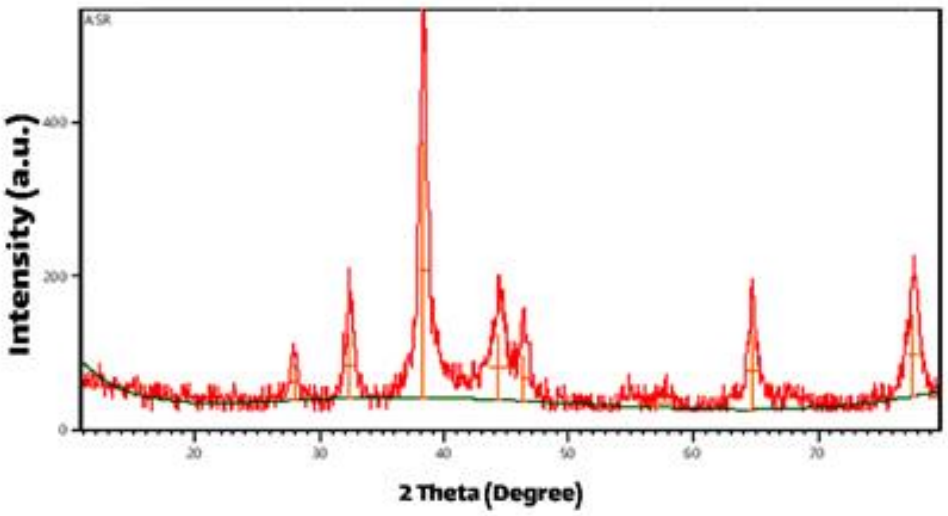

Fig. 5. XRD of AgO NPs

Table 1. X-ray diffraction results of nanoparticles

Pos. [°2Th.]	FWHM Left [°2Th.]	d-spacing [Å]	Height [cts]	Rel. Int. [%]	Tip Width	Average D nm
27.89 (2)	0.60 (7)	3.19670	46 (3)	13.93	0.7165	
32.37 (1)	0.77 (3)	2.76360	84 (3)	25.15	0.9220	
38.276 (6)	0.73 (2)	2.34958	333 (7)	100.00	0.8795	
44.41 (2)	1.51 (6)	2.03842	86 (3)	25.87	1.8073	15.4264
46.39 (2)	0.72 (5)	1.95573	61 (4)	18.28	0.8690	
57.0 (1)	3.1 (3)	1.61564	10 (1)	3.08	3.6750	
64.72 (1)	0.88 (4)	1.43913	98 (5)	29.54	1.0575	
77.63 (1)	0.99 (3)	1.22893	107 (4)	32.30	1.1855	

Optimization of electrode fabrication: Identifying ideal manufacturing conditions

The specifications and properties of the AgO NPs nano-electrochemical sensor were confirmed after it was manufactured to determine the electrode response, linear concentration range, slope value, coefficient of correlation, electrode lifespan, detection limit, accuracy, compatibility, selectivity, applications, pH function, and temperature effect.

Effect of pH

The optimal pH range for the operation of the modified carbon electrodes mixed with silver oxide nanoparticles (AgO NPs) was found to be between pH 6 and 8. Within this range, the electrode potential remained stable and consistent, indicating reliable sensor performance. The pH of the solution was adjusted using diluted sodium hydroxide and hydrochloric acid solutions.

pH values above 8.5 were avoided due to the formation of turbidity, which occurred when excess base led to the precipitation of brown silver hydroxide. Similarly, at lower pH values, the solution became cloudy due to the formation of insoluble silver chloride. These changes negatively affected the electrode's response and measurement accuracy.

Fig. (6) illustrates the effect of pH on the electrode behavior and highlights the importance of maintaining the solution within the optimal range for stable performance.

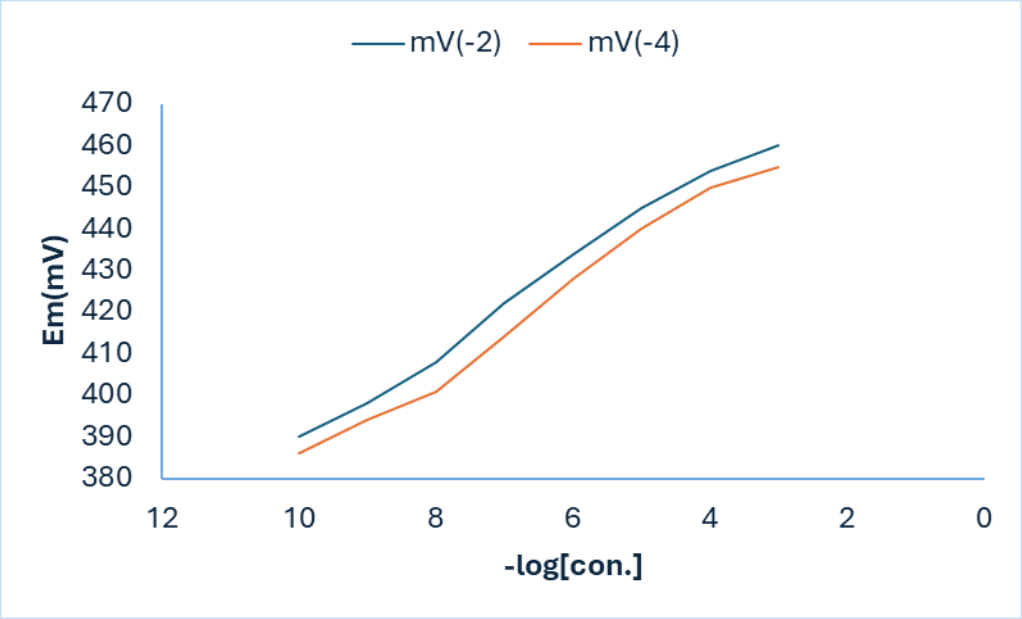

Fig. 6. pH effect on modified carbon paste electrode

Effect of temperature

The influence of temperature on the performance of the modified electrode was examined over a range of 15 to 70°C. The optimal operating temperature range was identified to be between 15 and 30°C, during which the electrode functioned reliably without significant changes in voltage or degradation of the paste.

At temperatures above 30°C, a noticeable decline in voltage response was observed. This reduction was attributed to the thermal sensitivity of the electrode paste, which negatively affected the sensor's ability to detect silver ions accurately. Elevated temperatures likely altered the physical properties of the paste, leading to decreased sensitivity and overall performance.

Fig. (7) illustrates the relationship between temperature and electrode response **(Al-Samarrai *et al.*, 2024)**.

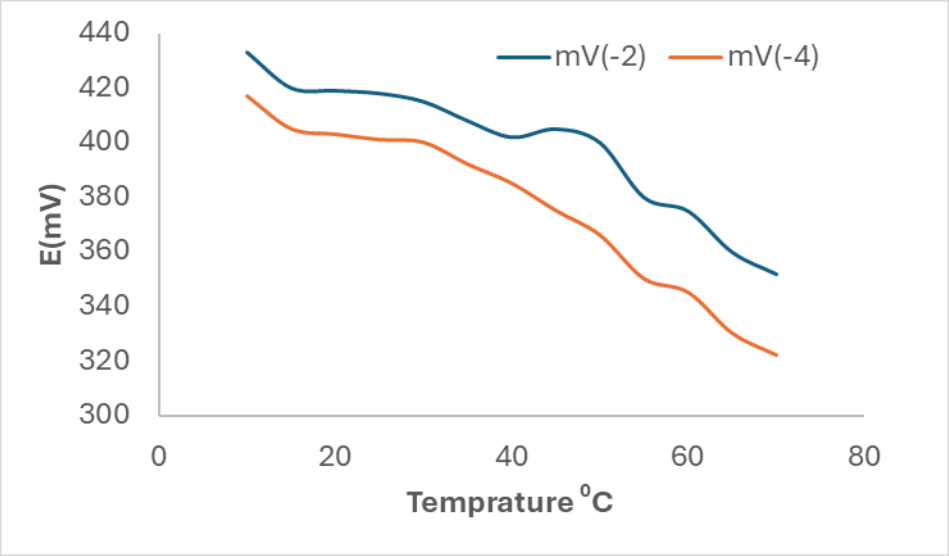

Fig. 7. Temperature on modified carbon paste electrode

Response time

The response time of the modified electrode was evaluated by immersing it alongside a calomel reference electrode (Me-SC900, England) into a series of standard silver nitrate ($AgNO_3$) solutions with decreasing concentrations, ranging from 10^{-1} M to 10^{-8} M. The electrode's response time was observed to vary between 3 and 30 seconds depending on the concentration of silver ions.

A clear inverse relationship was found between ion concentration and response time. At higher concentrations, the electrode responded more rapidly, requiring only a few seconds to stabilize. In contrast, as the ion concentration decreased, the electrode required a longer time to reach equilibrium, resulting in increased response times.

Fig. (8) illustrates the response time across different concentrations, while Table (2) summarizes the optimal working conditions for the AgO NP-modified electrode.

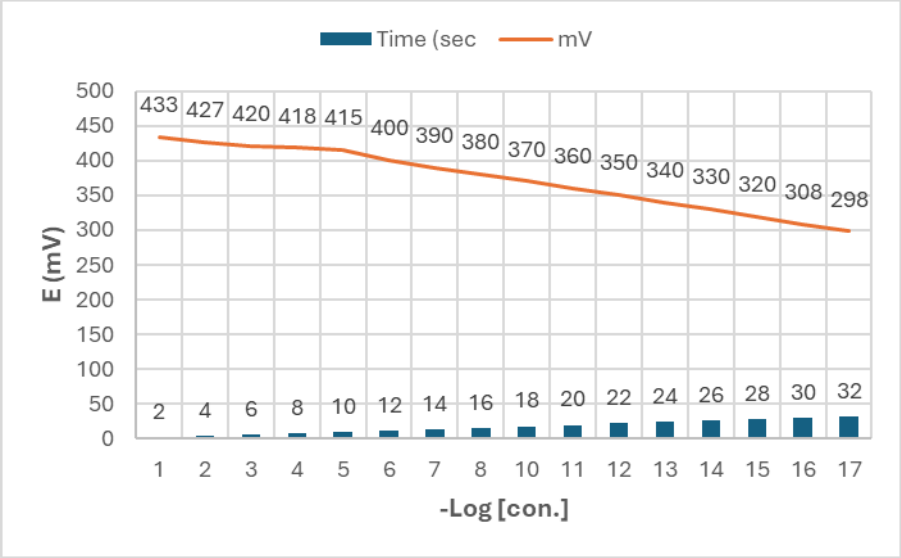

Fig. 8. Response time modified carbon paste electrode

Table 2. The optimal conditions for AgO NPs electrode

Parameter	Modified carbon paste electrode
pH Effect	6 - 8
Temperature (˚C)	15 - 30
Response Time (sec.)	3 - 30
Lifetime (day)	95

Calibration curve

After establishing the optimal operating conditions—temperature at 25°C and pH at 7—the modified carbon electrode was immersed alongside a calomel reference electrode into a series of standard silver nitrate ($AgNO_3$) solutions of descending concentrations, ranging from 10^{-1} M to 10^{-7} M. All measurements were conducted in 50mL beakers under controlled conditions.

For each concentration, the potential difference was recorded five times at 25°C to ensure consistency and reliability. These values were used to construct a calibration curve based on the linear relationship described by the Nernst equation.

Fig. (9) illustrates the calibration curve, and Table (3) presents the corresponding data. The results confirmed that the electrode exhibited a linear Nernstian response within the range of 10^{-1} to 10^{-7} M, with a correlation coefficient (R^2) of 0.9865. The slope of the

electrode response was calculated to be 30 mV/decade, closely approximating the theoretical value of 29 mV/decade **(Verlicchi, 2019; Abdullad & Al-Samarrai, 2021)**.

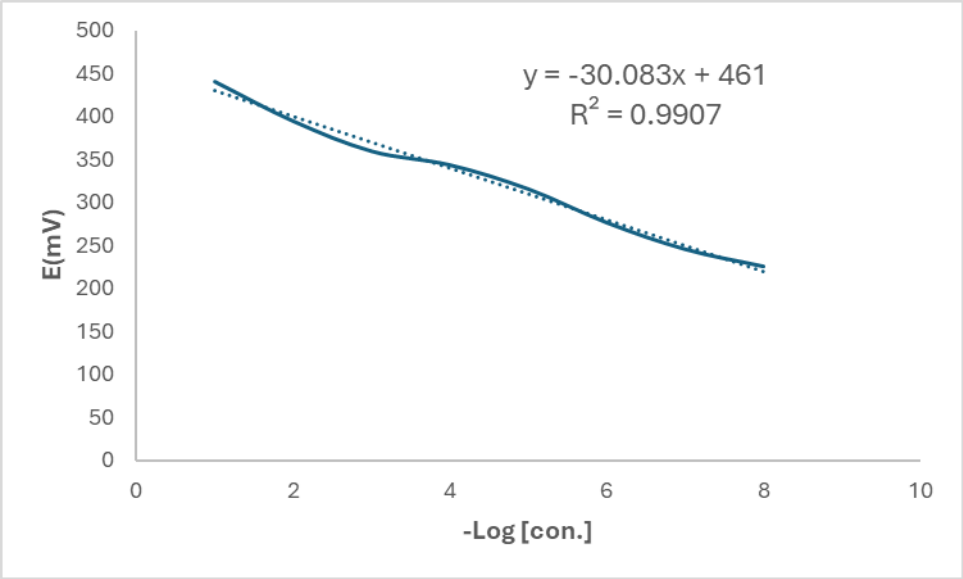

Fig. 9. Calibration curve of modified carbon paste electrode

Table 3. The potentiometric properties for modified carbon paste electrode

Properties	Modified carbon paste electrode values
Linear range	10^{-1} – 10^{-7} molar
Slope	30 mV/decade
Intercept	461 mV
Detection limit	7×10^{-7} molar
Correlation coefficient	0. 9865

Accuracy and precision

Drawing the electrode's calibration curve was a crucial step in evaluating the optimal working conditions of the modified electrode. To assess accuracy and precision, several concentrations within the established calibration range were tested. After stabilizing the ideal conditions—temperature at 25°C and pH at 6—the voltage for each concentration was measured individually and sequentially.

The results demonstrated that the method was effective in estimating silver ion concentrations. The electrode exhibited low standard deviation values and high

repeatability, indicating strong accuracy and precision. These findings confirm the reliability of the method under the specified conditions.

The detailed accuracy and precision results are presented in Table (4) **(Ganash *et al.*, 2022; Buniya *et al.*, 2023)**.

Table 4. Accuracy and precision value

Conc. Taken (mole\L)	Conc. Found (mole\L)	Rec%	RSD%
1×10^{-2}	0.9855×10^{-2}	99.05	0.6268
1×10^{-4}	1.006×10^{-4}	98814	0.9540
1×10^{-6}	0.9862×10^{-6}	99.322	0.59846

Selectivity

The ability of the fabricated electrode to selectively detect silver ions in the presence of other ions was evaluated using the selectivity coefficient **(Tesfaye *et al.*, 2022; Al-Khafaji & Al-Hayawi, 2024)**. The effect of potential interfering species on the electrode's response was assessed using the mixed solutions method. In this approach, various concentrations of different salts were added to a 10^{-2} M silver nitrate solution. The changes in potential were monitored to determine how the presence of other ions influenced the electrode's performance. This analysis provided insight into the electrode's specificity for silver ions and its potential application in complex matrices. The selectivity coefficient was measured using the equation (1) provided:

$$\log K_{A,B}^{pot} = \frac{E_2 - E_1}{S} \dots\dots\dots\dots (1)$$

Table 5. Selectivity coefficient values

$\log K_{A,B}^{pot}$ Selectivity Coefficient	Interference Ion Concentration	Type of interference ion
0.051476882	10^{-2} M	$CO3^{-2}$
0.202354685	10^{-4} M	
0.408649563	10^{-2} M	Na+
0.052117294	10^{-4} M	

0.196198109	10^{-2} M	Ni^{+2}
0.095651236	10^{-4} M	
0.122455829	10^{-2} M	Cr^{+3}
0.047527114	10^{-4} M	
0.08412264	10^{-2} M	$SO4^{-2}$
0.025712382	10^{-4} M	

The lifespan of the electrode

The lifespan of the electrode was discovered by measuring the potential difference within 95 days using a standard $AgNO_3$ solution at a concentration of 1×10^{-2} molar. The results proved that the measured voltage remained constant and stable throughout this duration. Consequently, the age of the electrode was estimated to be 95 days. However, it was noted that after this period, the measured voltages started dropping, potentially due to damage to the electrode paste (Fig. 10) **(Alizadeh & Azizi, 2016)**.

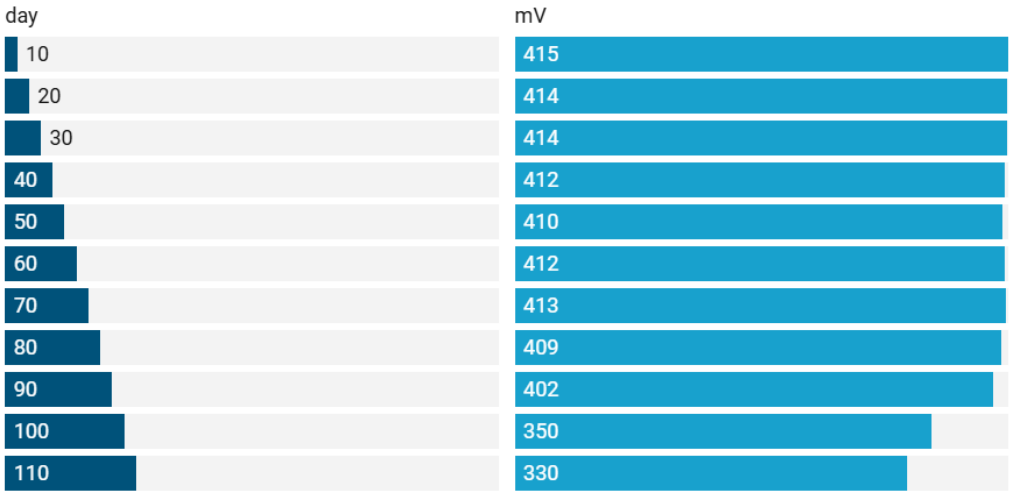

Fig. 10. Lifetime of modified carbon paste electrode

Comparison of modified carbon electrode fabrication methods

After completing the fabrication and testing of the modified carbon electrode incorporating silver oxide nanoparticles, its performance was compared with previously reported methods in the literature. The results demonstrated that this method offered several advantages over earlier approaches.

One of the most notable improvements was the extended lifespan of the electrode, which exceeded 95 days under proper storage and usage conditions. The electrode performed optimally at temperatures between 20–25°C and within a pH range of 6–8. Additionally, the response time ranged from 3 to 30 seconds, representing a rapid and reliable detection capability for silver ions.

A comparative summary of this method with selected previous studies is presented in Table (6) **(Hwang *et al.*, 2022)**.

Table 6. Selectivity coefficient values

Reference	pH	Temperature	Electrode lifespan	Response time	Detection limit (ion)
This study	6 - 8	20 – 30 °C	95 days	3-30 sec.	10^{-7} M for Ag
Alizadeh & Azizi, 2016	10	25 °C	8 months	25 min.	10^{-7} M for fluoxetine
Hwang *et al.*, 2022	7	25 °C	Unconfirmed	5 sec.	2 mM
Sanjaya *et al.*, 2021	7	4 °C	7 days	70 sec.	3-5 mM of glucose
Koirala *et al.*, 2016	1 - 5	25 °C	60 days	5-80 sec.	0.25-12.5 µg mL^{-1} for lead
Souza *et al.*, 2020	6.5	25 °C	40 cycles	10 sec.	1.78×10^{-7} M for riboflavin

Applications

Silver ion concentrations were estimated in water samples collected from various sources, including well water from different locations in the Kirkuk Governorate, industrial wastewater from the North Oil Company, and industrial wastewater from the North Gas Company. Measurements were conducted immediately after stabilizing the optimal electrode conditions at pH 6 and a temperature of 25°C.

Voltage readings were recorded using the silver-selective electrode, and the concentrations of silver ions in each sample were determined using the calibration curve's linear equation. The corresponding results are summarized in Table (7).

Table 7. Direct method result

Sample area	Taken Conc.	Found Conc.	Rec %	RSD %
Well water from Kirkuk **C**ity	1×10^{-4}	1.004×10^{-4}	99.6	0.44
Industrial water from North Oil Company	1×10^{-4}	1.006×10^{-4}	99.4	0.32
Industrial water from North Gas Company	1×10^{-4}	1.003×10^{-4}	99.7	0.49

The accuracy and tuning results obtained indicate that the method used is highly retrievable, low in standard deviation, and successful in estimating silver ions in industrial wells and waters. It is also simple, inexpensive, and environmentally friendly.

CONCLUSION

This study successfully synthesized silver oxide nanoparticles (AgO NPs) using *Mentha piperita* (mint) leaf extract through a green chemistry method that avoided toxic chemicals. Incorporating the AgO NPs into modified carbon paste electrodes enhanced the electrode's conductivity, selectivity, and electrochemical performance. SEM analysis revealed semi-spherical nanoparticles with an average size of 15.43nm, and results indicated that variations in temperature and medium composition significantly influenced nanoparticle morphology. XRD analysis confirmed the crystalline nature of the synthesized silver oxide, validating the effectiveness of the plant-based reduction process.

The fabricated electrode exhibited strong performance for silver ion detection, with a low detection limit of 10^{-7} M, a rapid response time ranging from 3 to 30 seconds, a broad linear range from 10^{-1} to 10^{-7} M, and a lifespan exceeding 95 days. These features mark a clear improvement over conventional, electrochemical sensors. Moreover, the sensor proved effective in real-world applications by accurately detecting silver ions in industrial wastewater and well water samples, demonstrating its practicality for environmental monitoring.

Future research should explore extending this sensor's application to detect other heavy metals and environmental contaminants. Further optimization of the nanoparticle synthesis process could enhance long-term stability, while the miniaturization and integration of the sensor into portable devices would support on-site monitoring. Additionally, investigating other plant extracts may yield nanoparticles with improved properties and increase the sustainability of the approach. These directions will advance the development of green-synthesized nanomaterials as viable tools for environmental monitoring and electrochemical sensing.

REFERENCES

Abdullad, Z. K. and Al-Samarrai, S. Y. (2021). Modified solid ion-selective electrode for potentiometric determination of sulfide in oil refineries water. *Sci. Rev. Eng. Environ. Sci.*, *30*(1): 98–105. https://doi.org/10.22630/PNIKS.2021.30.1.9.

Al Samarrai, S. Y.; AlZubaidi, R. and Al-Ansari, N. (2024). Charge transfer complex-based spectrophotometric analysis of famotidine in pure and pharmaceutical dosage forms. *Sci. Rep.*, *14*(1): 3661. https://doi.org/10.1038/s41598-024-54402-4.

Alizadeh, T. and Azizi, S. (2016). Graphene/graphite paste electrode incorporated with molecularly imprinted polymer nanoparticles as a novel sensor for differential pulse voltammetry determination of fluoxetine. *Biosens. Bioelectron.*, 81: 198–206. https://linkinghub.elsevier.com/retrieve/pii/S0956566316301579.

Al-Khafaji, S. M. M. and Al-Hayawi, A. Y. (2024). Deciphering the impact of miR-92a-3p on controlling BCL11A gene expression and its implication in easing thalassemia symptoms. *Med. J. Babylon.*, *21*(Suppl 2): S250–S257. https://doi.org/10.4103/MJBL.MJBL_1337_23.

Hwang, J. J.; Bibi, A.; Chen, Y. C.; Luo, K. H.; Huang, H. Y. and Yeh, J. M. (2022). Comparative studies on carbon paste electrode modified with electroactive polyamic acid and corresponding polyimide without/with attached sulfonated group for electrochemical sensing of ascorbic acid. *Polymers*, *14*(17): 3487. https://www.mdpi.com/2073-4360/14/17/3487.

Koirala, K.; Santos, J. H.; Tan, A. L.; Ali, M. A.; Mirza, A. H. (2016). Chemically modified carbon paste electrode for the detection of lead, cadmium, and zinc ions. *Sens. Rev.*, *36*(4): 339–346. https://www.emerald.com/insight/content/doi/10.1108/SR-03-2016-0054/full/html.

Krishnaveni, P.; Karunakaran, M.; Usha, S.; Prabakaran, S. and Ganeshwari, N. (2024). Green synthesis of nanoparticles. In: Ganeshkar, M.; Gangaraju, G.; Biswas, H. S.; Wani, M. A.; Elangovan, S.; Srivastava, M. K. (Eds.), *Futuristic Trends in Chemical Material Sciences & Nano Technology 3*(23):282–288. Iterative International Publishers, Selfypage Developers Pvt Ltd. https://www.iipseries.org/viewpaper.php?pid=4640& pt=green-synthesis-of-nanoparticles.

Kurbanoglu, S. and Ozkan, S. A. (2018). Electrochemical carbon-based nanosensors: A promising tool in pharmaceutical and biomedical analysis. *J. Pharm. Biomed. Anal.*, *147*: 439–457. https://linkinghub.elsevier.com/retrieve/pii/S0731708517313729.

Laghlimi, C.; Ziat, Y.; Moutcine, A.; Hammi, M.; Zarhri, Z.; Ifguis, O., *et al.* (2021). A new sensor based on graphite carbon paste modified by an organic molecule for

efficient determination of heavy metals in drinking water. *Chem. Data Collect.*, *31*: 100595. https://linkinghub.elsevier.com/retrieve/pii/S2405830020303001.

Lee, K. X.; Shameli, K.; Yew, Y. P.; Teow, S. Y.; Jahangirian, H.; Rafiee-Moghaddam, R., *et al.* (2020). Recent developments in the facile bio-synthesis of gold nanoparticles (AuNPs) and their biomedical applications. *Int. J. Nanomed.*, *15*: 275–300. https://www.dovepress.com/recent-developments-in-the-facile-bio-synthesis-of-gold-nanoparticles--peer-reviewed-article-IJN.

Malik, S.; Muhammad, K.; Waheed, Y. (2023). Nanotechnology: A revolution in modern industry. *Molecules*, 28(2): 661. https://www.mdpi.com/1420-3049/28/2/661.

Mulvaney, P. (1996). Surface plasmon spectroscopy of nanosized metal particles. *Langmuir*, *12*(3): 788–800. https://pubs.acs.org/doi/10.1021/la9502711.

Riaz, A.; Din, S. U.; Rakha, A.; Shad, N. A. and Munawar, A. (2024). Nanotechnology-based sensors' design and fabrication. In: Tonelli, F. M. P.; Roy, A.; Ozturk, M.; Murthy, H. C. A. (Eds.), *Nanotechnology-based Sensors for Detection of Environmental Pollution* (pp. 175–198). Elsevier. https://www.sciencedirect.com/science/article/pii/B9780443141188000103.

Roy, A.; Bulut, O.; Some, S.; Mandal, A. K. and Yilmaz, M. D. (2019). Green synthesis of silver nanoparticles: Biomolecule-nanoparticle organizations targeting antimicrobial activity. *RSC Adv.*, *9*(5): 2673–2702. http://dx.doi.org/10.1039/C8RA08982E.

Sanjaya, R. K.; Sukmawati, D. A. N.; Ismillayli, N. and Hermanto, D. (2021). Determination of glucose with cellulose acetate/glucose oxidase modified carbon paste electrodes. *Molekul*, *16*(3): 178. https://ojs.jmolekul.com/ojs/index.php/jm/article/view/679.

Singh, A.; Gautam, P. K.; Verma, A.; Singh, V.; Shivapriya, P. M. and Shivalkar, S., *et al.* (2020). Green synthesis of metallic nanoparticles as effective alternatives to treat antibiotic-resistant bacterial infections: A review. *Biotechnol. Rep.*, 25: e00427. https://linkinghub.elsevier.com/retrieve/pii/S2215017X19305934.

Singh, H.; Desimone, M. F.; Pandya, S.; Jasani, S.; George, N. and Adnan, M., *et al.* (2023). Revisiting the green synthesis of nanoparticles: Uncovering influences of plant extracts as reducing agents for enhanced synthesis efficiency and its biomedical applications. *Int. J. Nanomed.*, *18*: 4727–4750. https://www.dovepress.com/revisiting-the-green-synthesis-of-nanoparticles-uncovering-influences--peer-reviewed-fulltext-article-IJN.

Singh, J.; Dutta, T.; Kim, K. H.; Rawat, M.; Samddar, P. and Kumar, P. (2018). 'Green' synthesis of metals and their oxide nanoparticles: Applications for environmental remediation. *J. Nanobiotechnol.*, *16*(1): 84. https://jnanobiotechnology.biomedcentral. com/articles/10.1186/s12951-018-0408-4.

Souza, E. S. D.; Manjunatha, J. G.; Raril, C.; Tigari, G. and Pushpanjali, P. A. (2020). Polymer-modified carbon paste electrode as a sensitive sensor for the electrochemical determination of riboflavin and its application in pharmaceutical and biological samples. *Anal. Bioanal. Chem. Res.*, *7*(4). https://doi.org/10.22036/abcr.2020.214882.1445.

Ahmed, S.; Ahmad, M.; Swami, B. L. and Ikram, S. (2016). Green synthesis of silver nanoparticles using *Azadirachta indica* aqueous leaf extract. *J. Radiat. Res. Appl. Sci.*, *9*(1), 1–7. https://doi.org/10.1016/j.jrras.2015.06.006.

Aravind, S. P.; Anandhu, T. P.; Jayakumar, K.; Appukuttan, A.; Rahul Krishna, B.; Amala, J., *et al.* (2024). Activated carbon-based paste electrodes for the simultaneous and effective detection of divalent cadmium and lead ions in wastewater. *Environ. Technol.*, *45*(15): 3062–3075. https://www.tandfonline.com/doi/full/10.1080/09593330.2023.2206528.

Baran, M. F.; Keskin, C.; Baran, A.; Hatipoğlu, A.; Yildiztekin, M.; Küçükaydin, S., *et al.* (2023). Green synthesis of silver nanoparticles from *Allium cepa* L. peel extract, their antioxidant, antipathogenic, and anticholinesterase activity. *Molecules*, *28*(5): 2310. https://www.mdpi.com/1420-3049/28/5/2310.

Baranwal, J.; Barse, B.; Gatto, G.; Broncova, G.; Kumar, A. (2022). Electrochemical sensors and their applications: A review. *Chemosensors*, *10*(9): 363. https://www.mdpi.com/2227-9040/10/9/363.

Buniya, H. K.; Hameed, A. K.; Al-Hayawi, A. Y. (2023). Cloning and expression of staphylokinase-streptokinase recombinant protein in *E. coli* BL21(DE3). *Biologia*, *78*(7): 1113–1117. https://doi.org/10.1007/s11756-023-01311-y.

Ganash, A.; Alshammari, S.; Ganash, E. (2022). Development of a novel electrochemical sensor based on gold nanoparticle-modified carbon-paste electrode for the detection of Congo red dye. *Molecules*, *28*(1): 19. https://www.mdpi.com/1420-3049/28/1/19.

Haridas, E. S. H.; Bhattacharya, S.; Varma, M. K. R.; Chandra, G. K. (2022). Green synthesis of eco-friendly silver nanoparticles using *Coffee arabica* leaf extract and development of a cost-effective biosensor for cysteine. *arXiv preprint arXiv:2209.03823*. https://doi.org/10.48550/arXiv.2209.03823.

Hashim, N.; Bashi, A. M.; Jasim, A. (2019). Biosynthesis of silver nanoparticles by *Mentha spicata* ethanolic leaves extract and investigation of their antibacterial activity. In *Karbala City, Iraq* (p. 040009). https://pubs.aip.org/aip/acp/article/600124.

Hussain, Z.; Jahangeer, M.; Sarwar, A.; Ullah, N.; Aziz, T.; Alharbi, M., *et al.* (2023). Synthesis and characterization of silver nanoparticles mediated by the *Mentha piperita* leaves extract and exploration of its antimicrobial activities. *J. Chil. Chem. Soc.*, *68*(2): 5865–5870. http://www.scielo.cl/scielo.php?script=sci_arttext&pid=S0717-

Iravani, S. (2011). Green synthesis of metal nanoparticles using plants. *Green Chem.*, *13*(10), 2638–2650. https://doi.org/10.1039/C1GC15386B.

Okka, E. Z.; Tongur, T.; Aytas, T. T.; Yilmaz, M.; Topel, Ö. and Sahin, R. (2022). Green synthesis and the formation kinetics of silver nanoparticles in aqueous *Inula viscosa* extract. *arXiv preprint arXiv:2209.03022*. https://doi.org/10.1016/j.ijleo.2023.171487.

Singh, P.; Pandit, S.; Mokkapati, V. R. S. S.; Garg, A.; Ravikumar, V. and Mijakovic, I. (2018). Green synthesis of nanoparticles: Current developments and limitations. *Appl. Microbiol. Biotechnol.*, *102*(15), 6165–6183. https://doi.org/10.1007/s00253-018-9078-7.

Tajik, S.; Beitollahi, H.; Nejad, F. G.; Safaei, M.; Zhang, K. and Van Le, Q., *et al.* (2020). Developments and applications of nanomaterial-based carbon paste electrodes. *RSC Adv.*, *10*(36), 21561–21581. https://xlink.rsc.org/?DOI=D0RA03672B.

Tesfaye, E.; Singh Chandravanshi, B.; Negash, N. and Tessema, M. (2022). A novel carbon paste electrode modified with N1-hydroxy-N1, N2-diphenylbenzamidine for the electrochemical determination of cadmium (II) in environmental samples. *J. Anal. Methods Chem.*, 2022, 1–12. https://www.hindawi.com/journals/jamc/2022/3426575/.

Thomas, N. B.; Kumar, L. P.; James, J. and George, N. A. (2024). Trends, progress and future directions of nanomaterial-based sensors: A bibliometric overview. *Sens. Rev.*, *44*(3), 231–248. https://doi.org/10.1108/SR-09-2023-0466.

Verlicchi, P. (2019). Silvio Vaz Jr.: Analytical chemistry applied to emerging pollutants. *Anal. Bioanal. Chem.*, 411(2), 289–290. http://link.springer.com/10.1007/s00216-018-1458-z.

Vytřas, K.; Švancara, I. and Metelka, R. (2009). Carbon paste electrodes in electroanalytical chemistry. *J. Serb. Chem. Soc.*, 74(10), 1021–1033. https://doiserbia.nb.rs/Article. aspx?ID=0352-51390910021V.