AuNPs and graphdiyne nanocomposite as robust electrocatalyst for methyl parathion detection in real samples

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Abstract
The present work describes a simple and rapid synthesis method of gold nanoparticles and graphdiyne (AuNPs@GDY) nanocomposites including porous structure. Moreover, the synthesized AuNPs@GDY material was decorated on the glassy carbon electrode (GCE) with a drop coating method to construct a non-enzymatic electrochemical pesticides sensor. The micro-morphology and elemental composition of the materials were characterized by transmission electron microscopy (TEM) and energy dispersive spectroscopy (EDS). The electrocatalysis and conductivity of the material were studied with cyclic voltammetry (CV) and impedance method, respectively. The properties of the sensor were investigated by CV and differential pulse voltammetry (DPV). The results showed that AuNPs@GDY exhibited excellent electrocatalytic ability for methyl parathion in a wide linear range (from 0.25 ng/mL to 24.43 μg/mL) and low limit of detection value (6.2 pg/mL). Furthermore, the DPV method used in this paper was accurate and sensitive, and could be used for routine quality control of methyl parathion in kiwi fruit and tomato samples.

Keywords Graphdiyne and gold nanocomposite · Electrochemical sensor · Methyl parathion · Kiwi and tomato samples

Introduction
Organophosphate pesticides (OPs) are common pesticides in agriculture. It plays a very important role in agricultural production with its advantages of broad spectrum and high efficiency [1]. However, the use of OPs is a "double-edged sword", which not only protects crops from the threat of pests, but also brings some negative effects to the ecological environment. The toxicity mechanism of OPs to humans and insects is similar, which is inhibiting the hydrolysis activity of acetylcholinesterase to the neurotransmitter acetylcholine, and this process is irreversible [2, 3]. Once the human body has excessive acetylcholine in synapses, it will induce the increase of saliva, causing a series of neurotoxic symptoms such as headache, spasm, respiratory depression, neurological disorder and even death [4, 5]. Methyl parathion (MP, O,O-Dimethyl-O-(4-nitrophenyl)-phosphorothioate) is one type of OPs [6]. As a result of its low cost and high efficiency against many pests in important crops, it has been widely applied in the past few years. However, MP has extremely high toxicity at low doses (oral: 4 mg/kg body weight) and weight inhalation: 0.13 mg/L), and the World Health Organization has classified MP as "extremely dangerous" [7, 8]. The higher the concentration of pesticides and their metabolites in the environment or food, the higher the risk. In other words, MP is highly toxic to organisms and poses a serious threat to health, environment and food safety [9]. Therefore, it is of great significance to analyze the content of MP.

At present, the detection methods of MP can be basically divided into two categories. One is instrumental detection, which refers to chromatography and chromatography-mass spectrometry [10, 11]; the other is rapid detection method, mainly including enzyme inhibition method, immune method, and electrochemical sensor detection method and so on [12–15]. Instrumental analysis is widely used in the detection of OPs residues in food and environmental samples because of its good stability and reproducibility, high
accuracy and fast response [16, 17]. It is the most important quantitative detection method of OPs multi-residues. Although the instrumental detection method has an irreplaceable position in the detection of organic phosphorus, it also has many shortcomings in the actual operation process. For example, the large-scale instruments used in instrument detection method are expensive, need professional guidance or operation. The sample pretreatment is cumbersome and complex, and it cannot realize real-time and rapid detection of samples [18, 19]. In the process of food safety supervision, it is necessary to carry out rapid and accurate on-site detection of samples. Based on these practical needs, rapid detection methods can be continuously established and developed. Among these methods, the electrochemical sensor shows a good application prospect in the field of rapid detection, and has become an important research direction in the field of pesticide residue detection. Because they are miniaturized, cheap, highly sensitive and selective allowing real-time and portable analysis [20, 21]. MP has an electrochemical active nitro group at the para position, which can be reduced to hydroxylamine at a certain potential, and the reaction process is irreversible [22].

To improve the sensitivity and selectivity of the electrochemical sensor, the surface modification of the electrode with high conductivity and high specific surface area is a simple and effective method, such as various carbon and metal nano- materials, conductive polymers and their composites [23–27]. Graphdiyne (GDY) is a new allotrope of carbon after graphene, which is composed of sp and sp² carbon atoms of benzene ring and butyne bond, which also makes GDY have a large triangular ring of 18 carbon atoms [28]. To keep the configuration stable, the two-dimensional planar configuration of single-layer GDY will form certain folds as graphene [29]. GDY molecules are stacked through van der Waals force and π–π interaction to form a layered structure, and the large triangular rings of 18 carbon atoms form a three-dimensional pore structure in the layered structure [30]. This porous structure can change the mass transfer mechanism on the electrode surface from linear (planar) diffusion to approximate "thin layer" diffusion, so as to improve the selectivity and sensitivity of the modified electrode [31]. However, compared with graphene, GDY has weaker electrical conductivity and signal amplification ability. Therefore, GDY has been studied more in the fields of electronics, semiconductors and energy storage than in the field of sensors. GDY nanocomposites prepared by introducing nano materials with high conductivity can solve the performance defects of pure GDY electrodes. Gold nanoparticles (AuNPs) have good conductivity and large specific surface area [32]. Without any chemical modification, AuNPs can directly combine with many biomolecules through affinity or covalent interaction, showing good biocompatibility [33].

In summary, the aim of this study is to develop a novel sensor platform for the sensitive electrochemical determination of MP. Thus, we prepared a nanocomposite AuNPs@GDY, and used it to construct an enzyme-free electrochemical sensor for MP. The preparation of nanocomposites of nano gold and graphene has been reported [34–36], but a more rapid and environmentally friendly method under non high temperature is still pursued. Generally, compared with enzyme-based sensors, non-enzyme sensors are more resistant to external conditions such as temperature, pressure and storage. AuNPs@GDY combined the properties of AuNPs and GDY, and exhibited good conductivity, strong adsorption performance and large surface area. The modified electrode provided good electrocatalytic activity and stability, high sensitivity and selectivity.

**Experimental section**

**Chemicals and apparatus**

Graphdiyne (GDY) was purchased from Nanjing XFNANO materials Tech Co. (Nanjing, China). Hydrogen tetrachloroaurate (III) trihydrate (HAuCl₄·3H₂O) was acquired from Aladdin Chemical Reagents Co. Ltd. (Shanghai, China). Methyl parathion (MP) was obtained from Tanmo quality inspection reference material center (TMRM, Beijing, China). All other reagents were analytical grade and purchased from Sinopharm Chemical Reagent Co. (Shanghai, China). The water used in the experiment was ultrapure water.

Electrochemical experiments were carried out on a CHI 660E electrochemical workstation (Chenhua Instruments, Shanghai, China), coupled with a glassy carbon electrode (GCE), a platinum wire and a calomel electrode at 298 K. The surface morphologies and elemental composition were observed by a transmission electron microscopy (TEM, FEI Talos F200S) and energy dispersive spectroscopy (EDS, Super X).

**Synthesis of AuNPs@GDY**

5 mg GDY was ultrasonically dispersed in 1 mL distilled water for 5 min, and then the suspension was stirred in an ice bath for 10 min. In this process, 0.5 mL 1% HAuCl₄ was added dropwise. The mixture was washed by centrifugation to obtain AuCl₄⁻@GDY nanocomposite. Then, the obtained AuCl₄⁻@GDY was dispersed with 1 mL distilled water.
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water. 0.5 mL 10 mg/mL NaBH₄ solution was added drop by drop under ice bath stirring. After 10 min, it was centrifuged and washed to obtain the final product AuNPs@GDY. The preparation process is shown in Scheme 1A.

**Construction of the modified electrodes**

Before modification, the GCE with 3 mm diameter was polished with 0.3 μm and 0.05 μm alumina powder. Then, 5 μL AuNPs@GDY suspension was dropped onto the surface of GCE and dried in the natural state. GDY/GCE and AuCl₄⁻@GDY/GCE for comparative study were prepared in the same way. The fabrication progress of the modified electrode is shown in Scheme 1B.

**Real samples**

To evaluate the practicability of the sensor, kiwi fruit and tomato purchased from local supermarkets were used in the recovery experiment. 50 g of the samples were broken up with a food blender, and then centrifuged to take the supernatant. The supernatant was diluted with 0.1 M pH 7.0 PBS in the ratio of 1:4, and then it was used for the detection of MP with the standard addition method.

**Results and discussion**

**Characterization of the modified materials**

Figure 1 illustrates TEM images and EDS of the synthesized AuNPs@GDY nanocomposite. The EDS results (Fig. 1g), combined with the uniform spatial distribution of C and Au atoms observed from the elemental mapping (from Fig. 1a to Fig. 1d), indicate that the AuNPs@GDY have been successfully prepared. TEM images (Fig. 1e) revealed that AuNPs@GDY has a thin sheet shape with occasional folds, in which AuNPs are evenly dispersed. A close-up view (Fig. 1f) confirmed that the diameter of AuNPs is about 3 nm, and the flake structure of GDY can still be maintained in the process of ultrasound and preparation.

**Electrochemical behavior of the modified electrodes**

The electrochemical behavior of the modified electrodes was investigated using CV (Fig. 2A) and electrochemical impedance spectroscopy (EIS) (Fig. 2B) in a 0.1 M KCl solution containing 5 mM [Fe(CN)₆]³⁻/⁴⁻ redox probe, which involved single electron transfer with quasi-reversible
Fig. 1 The elemental mapping analysis of C, Au, and their mix elements of a selected area of AuNPs@GDY (a–d); TEM of AuNPs@GDY with different magnification (e, f); EDS of AuNPs@GDY (g)
kinetic behaviors in the electrode–electrolyte system. It can be seen from the CV that a pair of redox peaks with an anodic and cathodic peak separation of 131.2 mV ($\Delta E_p$) were observed at bare GCE. A $\Delta E_p$ of 232 mV and low peak currents were observed at GDY/GCE, indicating its low electron transfer rate at the interface of GDY/GCE. This decrease in current is mainly due to the semiconductor properties of GDY. However, the block curve of AuNPs@GDY/GCE ($\Delta E_p = 145$ mV) displayed higher electron transfer than the GDY/GCE, which suggested that AuNPs correlated well with GDY and promoted the electron transfer. In EIS, the high-frequency semicircle part and low-frequency linear part represented electron transfer resistance ($R_{ct}$) and finite diffusion process, respectively [37]. The semicircle diameter was equal to $R_{ct}$, which reflected the interfacial electron transfer ability and electron transfer kinetics of redox probe [38]. Figure 2B displayed the Nyquist plots of GCE, GDY/GCE and AuNPs@GDY/GCE. The $R_{ct}$ of GDY/GCE was the largest, indicating that the GDY hindered the electron transfer. After modifying GCE with AuNPs@GDY, the $R_{ct}$ decreased significantly, which is due to the increase of the conductivity of the modified electrode. The consequences of EIS and CV experiment are mutually confirmed.

Figure 2C showed the electrochemical CVs of bare GCE, GDY/GCE, AuNPs/GCE and AuNPs@GDY/GCE in 0.1 M PBS with a scanning rate of 0.1 V/s in the absence and presence of MP (50 ng/mL) (C); CVs of different MP concentrations (from 0.5 to 55 ng/mL) at the AuNPs@GDY/GCE (D).

**Fig. 2** CV curves (A) and EIS curves (B) of bare GCE, GDY/GCE and AuNPs@GDY/GCE in a ferricyanide solution (0.1 M KCl; 5 mM) at the scan rate of 0.1 V/s; the electrochemical CVs of bare GCE, GDY/GCE, AuNPs/GCE and AuNPs@GDY/GCE in 0.1 M PBS with a scanning rate of 0.1 V/s in the absence and presence of MP (50 ng/mL) (C); CVs of different MP concentrations (from 0.5 to 55 ng/mL) at the AuNPs@GDY/GCE (D)
−22.5 μA at −0.52 V, and the ΔE\textsubscript{p} at about 0 V was 0.03 V. When introducing the GDY into the bare GCE, the response reduction peak current increased from −28.1 μA to −31.1 μA, but the reduction peak potential shifted to the right by −0.04 V to −0.67 V. Moreover, after introducing AuNPs@GDY into the surface of GCE, the reduction peak current of MP increased up to −32.8 μA, and the reduction peak potential was −0.61 V, and the ΔE\textsubscript{p} of the redox peak was 0.05 V. Compared with GCE and GDY/GCE, the reduction peaks of AuNPs@GDY/GCE shifted toward lower potential, and the ΔE\textsubscript{p} for the redox process decreased. It can be concluded that the co-contribution of AuNPs and GDY made the synthesized nanocomposites have synergistic effects and excellent properties, such as excellent conductivity, high surface area and more electroactive interaction sites, which could improve electron and mass transport, thus improving the response performance of the sensor.

The CV response of AuNPs@GDY/GCE to different concentrations of MP was shown in Fig. 2D. The peak current response of direct reduction at −0.63 V increased linearly with the increasing of MP concentration. The linear correlation coefficient was shown in the inset of Fig. 2D. In contrast, the reversible reduction process did not have such a large and sharp response, which indicated that the modified electrode was more advantageous in the direct reduction process.

Figure 3A represented that the CV curves of the AuNPs@GDY/GCE in 0.1 M KCl solution containing 5 mM [Fe(CN)\textsubscript{6}]\textsuperscript{3−/4−} at different scan rates. The redox peak currents increased with the increasing of scanning rate. Furthermore, the peak currents had a good linear relationship with the square root of the scanning rate (R\textsuperscript{2} = 0.998, Fig. 3B). The electrochemically surface area of the modified electrode was calculated by using the Randles–Sevcik equation [39, 40]:

\[
I_p = 2.69 \times 10^5 AD^{1/2} n^{3/2} v^{1/2} c
\]

I\textsubscript{p} is the peak current density (A), A is the effective surface area (cm\textsuperscript{2}), D (7.6 × 10\textsuperscript{−6} cm\textsuperscript{2}/s) is the diffusion coefficient.

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Fig. 3 CV curves of the AuNPs@GDY/GCE in ferricyanide solution at different scan rates (0.01 to 0.2 V/s) (A); the linear calibration plot of peak currents vs. \( \sqrt{v} \) for AuNPs@GDY/GCE (B); CV responses of the AuNPs@GDY/GCE at different scan rate (0.01 to 0.2 V/s) in the fixed concentration of MP (50 ng/mL) at (C, inset: the relationship between reduction peak current and the scan rate); CV response of MP (50 ng/mL) in PBS with different pH value (D, inset: the relationship between pH value and reduction peak current and potential).
of \(K_{3}[\text{Fe(CN)}_6]\), \(n\) is the number of electron transfer (\(n = 1\)), \(\nu\) is the scan rate (V/s) and \(c\) is the bulk concentration of \(K_{3}[\text{Fe(CN)}_6]\) (mol/cm\(^3\), 5 mM). The effective surface area is 0.2704 cm\(^2\), which is larger than that of bare GCE (0.2423 cm\(^2\)) (the CV curves of GCE in 0.1 M KCl solution containing 5 mM \([\text{Fe(CN)}_6]\)\(^3−/4−\) at different scan rates are shown in Fig. 1S). It illustrated that AuNPs@GDY can provide a wide surface area and improve the electron surface transfer rate. Furthermore, the kinetic analysis of the surface of AuNPs@GDY/GCE was also investigated in the presence of 50 ng/mL MP by CV (Fig. 3C). The reduction peak current is proportional to the square root of scanning rate (\(R^2 = 0.98\)) (inset of Fig. 3C), which suggested that the reduction of MP was a typical diffusion-controlled process [41].

Based on previous reports and the redox mechanism of MP (Fig. 4), protons participated in electrochemical redox action [1, 22]. The concentration of H\(^+\) has a significant effect on the determination of MP on the modified electrode. Thus, the pH value of the solution was optimized by CV. As shown in Fig. 3D, when 50 ng/mL of MP was in the solution, the peak potentials shifted negatively with the increase of pH value. The linear relationship between peak potential and pH value was as follows: \(E = -0.058pH - 0.246\) \((R^2 = 0.99)\). The slope was very close to the standard theoretical value \(-0.059\) V/pH for Nernst equation [1]. This revealed that the number of electrons (4e\(^-\)) and protons (4H\(^+\)) involved in the reaction of MP on the modified electrode was equal, and this was consistent with the electrochemical mechanism of MP shown in Fig. 4. When the value was in the range of 3.0 to 7.0, the response peak current of MP increased gradually and reached its maximum at 7.0. After that, the peak current decreased significantly (inset of Fig. 3D). Thus, PBS with a pH of 7.0 was chosen as the best test solution for all subsequent experiments in this work.

**DPV determination of MP on AuNPs@GDY/GCE**

In order to evaluate the analytical performance of the constructed AuNPs@GDY/GCE, the method of DPV was used to determine the detection limit, linear range and sensitivity of the working electrode by introducing MP step by step in the selected \(-0.8–0.4\) V potential window. The results were shown in Fig. 5A,B. As can be seen from Fig. 5A, the peak current increased sharply with the increasing of concentration of MP, and the peak potential moved to negative potential, which may be due to the adsorption of MP with higher concentration. Figure 5B showed that the reaction of MP on the AuNPs@GDY/GCE involved two linear ranges of 0.25 ng/mL \(- 384.25\) ng/mL \((R^2 = 0.989)\) and 1.38 \(\mu\)g/mL \(- 24.43\) \(\mu\)g/mL \((R^2 = 0.996)\). Furthermore, the slope of low concentration was larger than that of high concentration, indicating that the electrode was more sensitive to low concentration MP. The reasons for the two-stage linearity may be as follows: when the concentration of the target is low, even a small change in the concentration will lead to a significant change in the electrode response due to the diffusion effect on the electrode surface. The adsorption of thiophosphate groups in MP with AuNPs and the \(\pi–\pi\) adsorption between MP and GDY can make MP rapidly gather on the electrode surface. In addition, at low matrix levels, the target can be quickly transformed into a product, resulting in a high sensitivity response of the electrode. When the concentration of the target substance is high, AuNPs@GDY should supply the substrate for a long time, and the reaction should be carried out in a larger time window [42]. This, together with the possibility that the reaction product contaminates the electrode surface, leads to a reduction in sensitivity [43]. Finally, the target can reach saturation level at higher concentration. According to the formula LOD = 3 N/S \((N\) is the standard deviation of the blank reagent, \(S\) is the slope) [44],

![Fig. 4 The electrochemical reduction mechanism of MP](image)
the LOD was calculated as 6.2 pg/mL. Compared with previously reported method (Table 1), under the same technical conditions, this work has advantages in both linear range and detection limit. This is mainly due to the good conductivity, larger surface area and rich active sites of the AuNPs@GDY.

Selectivity, reproducibility and stability

Anti-interference ability (Selectivity) is one of the most important factors to evaluate performance of electrochemical sensors. To determine the selectivity of the AuNPs@GDY/GCE toward MP, DPV was employed and executed in 0.1 M PBS (pH = 7.0) containing 5 ng/mL MP and other organic and inorganic interfering species that may coexist with MP in fruits and vegetables, such as dimethoate, ascorbic acid, phorate, Na⁺, K⁺, Cl⁻, NO₃⁻, etc. As shown in Fig. 6A, the presence of these compounds had no significant effect on the peak current and peak potential of MP, which indicated that the AuNPs@GDY/GCE had good anti-interference capability for MP detection, and could be a potential candidate in the field of food analysis. The reproducibility of the AuNPs@GDY/GCE was tested with five independent electrodes in 0.1 M PBS containing 5 ng mL⁻¹ MP (Fig. 6B). The relative standard deviation (RSD) is about 3.26%, which is acceptable as this may be due to unavoidable errors in the measurement process. The stability of the modified electrode has been studied in two ways. One is to directly electro-reduce MP for 100 consecutive times by cyclic voltammetry (Fig. 6C). The results showed that the peak current of MP still maintains 75.7% of the original current. The other is to use the same modified electrode to detect the same concentration of MP every 3 days (Fig. 6D), and the peak current has no obvious change. According to the data obtained above, the AuNPs@GDY/GCE has good selectivity, reproducibility and stability for the determination of MP.

Table 1 Comparison of the analytical performance of the proposed method with other previously reports

| Electrode            | Linear range (ng/mL) | LOD (ng/mL) | pH  | Technique | References |
|----------------------|----------------------|-------------|-----|-----------|------------|
| CuO-TiO₂/GCE         | 0–2000               | 1.21        | 6.0 | DPV       | [5]        |
| CS@TiO₂/rGO/GCE      | 9.47–5944            | 7.63        | 7.4 | DPV       | [37]       |
| GO@Ce-TiO₂/GCE       | 0.53–12,710          | 0.42        | 7.0 | DPV       | [40]       |
| NPG/Au               | 5–50                 | 0.6         | 7.0 | DPV       | [45]       |
| Biochar/CPE          | 0–18000              | 10.3        | 4.0 | DPV       | [46]       |
| BCL@MOF/GCE          | 2.63–9994            | 17.62       | 7.0 | DPV       | [47]       |
| GdHCF/GNS/GCE        | 2100–2,632,000       | 263.2       | 6.0 | DPV       | [48]       |
| Au-ZrO₂-GNs/GCE      | 1–2400               | 1.0         | 5.6 | SWV       | [22]       |
| ZrO₂rGO              | 0.01–10,000          | 0.01        | 5.0 | GECT      | [49]       |
| AuNPs@GDY/GCE        | 0.25–24,430          | 0.0062      | 7.0 | DPV       | This work |

NPG nanoporous gold, CPE carbon paste modified electrode, CS@TiO₂/rGO chitosan-TiO₂ sol–gel-reduced graphene oxide, BCL@MOF Burkholderia cepacia lipase@ metal–organic framework, GdHCF/GNS gadolinium hexacyanoferrate/ graphene nanosheets
Recovery test

The applicability of the modified electrode to real samples was also investigated with the DPV method and standard addition calibration. As shown in Table 2, the recovery for MP was in the range of 96.9–104.2%, which indicated that the prepared electrochemical sensor had good applicability in real samples.

Conclusions

In this work, a simple, fast, sensitive and stable electrochemical sensor was constructed and used to detect MP in real samples. The sensor overcomes many disadvantages of enzymatic sensors, such as high cost, low stability, difficult storage, and short service life. The preparation processes of AuNPs@GDY nanocomposites and modified electrodes are simple. The strong adsorption of GDY, the high conductivity of AuNPs and their synergistic effect together resulted in the high catalysis, high sensitivity and high selectivity of the sensor towards MP.

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Declarations

Conflict of interest The authors declare that they have no competing financial interest.

References

1. T. Rahmani, A. Hajian, A. Afkhami, H. Bagheri, New J. Chem. 42, 7213–7222 (2018)
2. C. Lamberth, S. Jeannart, T. Luksch, A. Plant, Science 341(6147), 742–746 (2013)
3. S. Garcia, A. Abu-Qare, W. Meeker-O’Connell, A. Burton, M. Abou-Donia, J. Toxicol. Env. Healt B. 6(2), 185–210 (2003)
4. R. Thota, V. Ganesh, Sens. Actuators B Chem. 227, 169–177 (2016)
5. X.K. Tian, L. Liu, Y. Li, C. Yang, Z.X. Zhou, Y.L. Nie, Y.X. Wang, Sens. Actuators B Chem. 256, 135–142 (2018)
6. F.L. Edwards, P.B. Tchounwou, Int J Env Res Pub He. 4990 (2007)
7. X.K. Tian, L. Liu, Y. Li, C. Yang, Z.X. Zhou, Y.L. Nie, Y.X. Wang, Sens. Actuators B Chem. 227, 169–177 (2016)
8. W. H. Organization, 2004.
9. J. Wu, L. Lin, T. Luan, Y.S.C. Gilbert, C. Lan, Food Chem Toxi. (1), 15–32 (2019)
10. L. Chen, X. Dang, Y. Ai, H. Chen, J. Sep. Sci. 41(18), 3508–3514 (2018)
11. V.A. Muckoya, P.N. Nomnngo, J.C. Ngila, Int. J. Environ. Sci. Te. 17(4), 2325–2336 (2020)
12. K.G. Reddy, G. Madhavi, B.K. Swamy, S. Reddy, A.V.B. Reddy, V. Madhavi, J. Mol. Liq. 180, 26–30 (2013)
13. P. Raghu, T.M. Reddy, B.K. Swamy, B.N. Chandrashekar, K. Reddiah, M. Kreedhar, J. Electroanal. Chem. 665, 76–82 (2012)
14. L. Hu, N. Wu, J. Zheng, J. Xu, M. Zhang, P. He, Anal. Sci. 30(6), 663–668 (2014)
15. A.H. Hassan, S.L. Moura, F.H. Ali, W.A. Moselhy, M.D.P.T. Sotomayor, M.I. Pividori, Biosens. Bioelectron. 118, 181–187 (2018)
16. M. Nousiaainen, K. Peräkorpi, M. Sillanpää, Talanta 72(3), 984–990 (2007)
17. X.P. Tan, Y. Liu, T.Y. Zhang, S.S. Luo, X. Liu, H.X. Tian, Y. Yang, C.L. Chen, RSC Adv. 9(1), 345–353 (2019)
18. S. Tanwar, D. Mathur, J. Solid State Electr. 25(8), 2145–2159 (2021)
19. H. Parham, N. Rahbar, J. Hazard. Mater. 177, 1077–1084 (2010)
20. R. Kaur, S. Rana, K. Lalit, P. Singh, K. Kaur, Biosens. Bioelectron. 167, 112486 (2020)
21. M.H. Facure, L.A. Mercante, L.H. Mattoso, D.S. Correa, Talanta 167, 59–66 (2017)
22. N. Gao, C. He, M. Ma, Z. Cai, Y. Zhou, G. Chang, Y. He, Anal. Chim. Acta 1072, 25–34 (2019)
23. J. Wang, Electroanal. 17(1), 7–14 (2005)
24. A.T. Lawal, Talanta 131, 424–443 (2015)
25. S. Chen, R. Yuan, Y. Chai, F. Hu, Microchem. Acta 180(1), 15–32 (2013)
26. A. Ramanavičius, A. Ramanavičienė, A. Malinauskas, Electrochim Acta 51(27), 6025–6037 (2006)
27. Y. Li, Y. Ma, E. Lichtfouse, J. Song, R. Gong, J. Zhang, L. Xiao, J. Hazard. Mater. 421, 126718 (2022)
28. C. Huang, N. Wang, Graphdiyne: Fundamentals and Applications in Renewable Energy and Electronics, 2022, 125–163.
29. Y. Zhao, L. Chai, X. Yan, W. Huang, T. Fan, O.A. Al-Hartomy, H. Zhang, Mater. Chem. Front. (2022). https://doi.org/10.1039/DIQM01342D
30. Y. Zhao, Q. Pan, H. Liu, Graphdiyne: Fundamentals and Applications in Renewable Energy and Electronics, 2022, 79–123.
31. Y. Zhang, Q. Xie, Z. Xia, G. Gui, F. Deng, J. Electrochem. Soc. 166(14), B1293 (2019)
32. G.H. Yang, L.L. Li, R.K. Rana, J.J. Zhu, Carbon 61, 357–366 (2013)
33. I.H. Cho, D.H. Kim, S. Park, Biomater. Res. 24(1), 1–12 (2020)
34. X. Chen, F. He, W. Fang, J. Shen, X. Liu, Y. Xue, C. Fan, ACS Cent. Sci. 6(5), 779–786 (2020)
35. T. Yao, R. Wang, Y. Meng, X. Hun, ACS Appl. Mater. Interfaces. 13(22), 26515–26521 (2021)
36. Y. Gao, C. Li, W. Yi, J. Fei, L. Yi, P. Yu, L. Mao, Analyst 146(2), 444–449 (2021)
37. H.F. Cui, W.W. Wu, M.M. Li, X. Song, Y. Lv, T.T. Zhang, Biosens. Bioelectron. 99, 223–229 (2018)
38. H. Bagheri, A. Afkhami, H. Khoshasafer, A. Hajian, A. Shahriyari, Biosens. Bioelectron. 89, 829–836 (2017)
39. P.T. Kissinger, W.R. Heineman, Cyclic voltammetry. J. Chem. Educ 60(9), 702 (1983)
40. R. Nehru, Y.F. Hsu, S.F. Wang, C.D. Dong, M. Govindasamy, M.A. Habila, N. AlMasoud, Microchim. Acta 188(6), 1–11 (2021)
41. G.J.S. Junior, J.S.G. Selva, A. Sukeri, J.M. González, M. Regiart, M. Bertotti, Talanta 226, 121230 (2021)
42. X.X. Dong, M.Y. Li, N.N. Feng, Y.M. Sun, C. Yang, Z.L. Xu, RSC. Adv. 5(105), 86485–86489 (2015)
43. A. Gholizadeh, S. Shahrokhian, A. Iraji zad, S. Mohajerzadeh, M. Vosoughi, S. Darbari, J. Kooohsorkhi, M. Mehran, Anal. Chem. 84(14), 5932–5938 (2012)
44. Y.V.M. Reddy, S. Bathinapatla, T. Luczak, M. Osiińska, H. Maseed, P. Ragavendra, G. Madhavi, New J. Chem. 42(4), 3137–3146 (2018)
45. X. Gao, Y. Gao, C.C. Bian, H.Y. Ma, H.Y. Ma, H.L. Liu, Electrochim. Acta 310, 78–85 (2019)
46. P.R. de Oliveira, C. Kalinke, J.L. Gogola, A.S. Mangrich, L.H.M. Junior, M.F. Bergamini, J. Electroanal. Chem. 799, 602–608 (2017)
47. Z. Wang, B.K. Ma, C. Shen, L.Z. Cheong, Talanta 197, 356–362 (2019)
48. Y. Lu, M. Xu, P. Li, J. Dong, S. Ai, Anal. Methods 7, 2157–2162 (2014)
49. T. Tao, Y. Zhou, M. Ma, H. He, N. Gao, Z. Cai, Y. He, Sens. Actuators, B Chem. 328, 128936 (2021)

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