Silver Nanoparticles Coupled with Graphene Nanoplatelets Modified Screen-Printed Carbon Electrodes for Rhodamine B Detection in Food Products

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ABSTRACT: A rapid, simple, and sensitive voltammetric sensor has been fabricated to determine Rhodamine B (RhB), a textile coloring agent. Silver nanoparticles (AgNPs) were synthesized by the chemical reduction method of silver nitrate and sodium citrate. Graphene nanoplatelets (GPLs) and AgNPs were drop-casted on the surface of a working electrode of a screen-printed carbon electrode (SPCE), forming the SPCE-GPLs/AgNPs samples. Scanning electron microscopy–energy dispersive X-ray and cyclic voltammetry confirmed the altered surface of the SPCE. The square wave voltammetry was used for the electrochemical determination of RhB. The SPCE-GPLs/AgNPs demonstrated electrochemical responses to detect RhB with a linear range of 2–100 μM, and the limit of detection was 1.94 μM. The SPCE-GPLs/AgNPs demonstrated a selective detection of RhB in the presence of common interfering compounds present in the food samples, including sucrose and monosodium glutamate. Furthermore, the sensor presented good reproducibility as well as repeatability in the detection of RhB. When the sensor was used to determine RhB in an actual food sample, similar results were shown as suggested by UV–vis spectroscopy analysis. Hence, the fabricated sensor can be applied for the detection of RhB in food samples.

1. INTRODUCTION

Rhodamine B (RhB) (N-[9-(2-carboxyphenyl)-6-(diethylamino)-3H-xanthen-3-ylidene]-N-ethylethannimium) is a synthetic dye belonging to the xanthene family with strong red characteristics. It is widely used as a colorant in the textile, paper, and printing industries.1 It is also used as an analytical reagent in industries related to the environment, mining, steel, and pharmaceutical.2 In the past, RhB was used as a food additive; however, there is sufficient evidence to suggest that RhB is a carcinogenic and has a toxic effect,3–7 and thus the use of RhB is forbidden. According to the International Agency for Research on Cancer, RhB is classified as a group III carcinogenic agent.8 However, due to inadequate knowledge of the carcinogenic effect of this compound and its economic value (cheap), attractive color, and good stability, some food producers still used this coloring agent. Therefore, inspecting RhB randomly in many food samples is urgent.

Various analytical methods have been used to determine RhB, including high-performance liquid chromatography,8–10 UV–vis spectrometry,11,12 capillary electrophoresis,13 liquid chromatography-tandem mass spectrometry,14 ion-exchange chromatography, and fast ion-pair reversed-phase chromatography.15 Although these methods are powerful, they bear either inconvenience, high cost, complex sample preparation, or being time-consuming. Thus, a developed simple, rapid, and effective method for the detection of RhB is needed.

Considering the nature of RhB as an electroactive compound, the development of an electrochemical sensing system to detect RhB is of interest. Previous studies have reported the potential of electrochemical sensing using glassy carbon electrodes and modified screen-printed carbon electrodes (SPCEs) for detection of RhB in food samples with satisfactory results.16–19 Currently, the SPCE has attracted increasing attention in electrochemical measurements because it offers portability, fast analysis, and low cost and provides analysis in very small quantities (μL). Hence, the SPCE is very prospective in the term of sensor development.20–23 As we all know, the working electrode on the SPCE only consists of carbon, and it is less selective and sensitive. Therefore, modification of the electrode to increase the sensitivity to detect the target analyte is necessary. Although the SPCE has been used for the detection of various electroactive compounds including RhB, however, straight detection of RhB using the SPCE is rarely studied. As far as we know, only one SPCE modification for the detection of RhB has been reported.24

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Graphene is a monolayer material composed of carbon atoms with an sp² bond and π orbital. Graphene has attracted significant attention because it has high electron transferability, high electrocatalytic activity, and high specific surface areas.27

Graphene nanoplatelets (GPLs) are a graphene derivative consisting of a stack of small graphene sheets with a thickness of 5–10 nm and a diameter ranging from 0.5 to 50 µm.28 The thermal and mechanical properties of GPLs are similar to carbon nanotubes (CNTs), but the surface area of GPLs is higher than that of CNTs.29 Furthermore, GPLs have high conductivity, good electron transferability, nanosize,30 and large specific surfaces area.31,32 More importantly, modifying carbon-based working electrodes with GPLs can improve the sensor’s response.

Silver nanoparticles (AgNPs) have attracted great attention as nanocomposites for surface modification of sensor electrodes. The AgNPs are relatively inexpensive and easy to obtain33 and have high conductivity, large surface area, high stability, and excellent biocompatibility.34,35 More importantly, AgNPs have been reported to have good catalytic activity and improve the current peak response of electrochemical sensing.26,36

A study showed that the SPCE modified with AgNPs indicated an excellent selectivity for detecting dopamine (DA) with a low LOD and high sensitivity.37 Further, Palisoc et al. reported that graphene paste electrodes modified with AgNPs effectively detected heavy metals such as lead, cadmium, and copper.38 For the reasons mentioned earlier, we are interested in incorporating AgNPs with GPLs on an SPCE to detect RhB.

In this work, an SPCE-based sensor that is SPCE-GPLs/AgNPs was fabricated using the drop-casting method to evaluate RhB. A set of parameters including surface morphology on a modified SPCE, electrochemical behavior, and the optimum conditions for measurement of RhB were observed. In addition, we also evaluated the analytical performance SPCE-GPLs/AgNPs in an actual food sample.

2. RESULTS AND DISCUSSION

2.1. Characterizations of the Fabricated SPCE. Prior to the characterization process, the SPCE must be activated. The main purpose of activation on the SPCE was to remove insulating polymers or increase the electron transfer resistance.39 The SPCE was activated with 0.1 M NaOH solution using cyclic voltammetry. A commercial SPCE (Drop Sense 110, Metrohm AG) was used to compare the electrochemical performance of fabricated SPCEs using cyclic voltammetry (CV) for a mixture of K₃Fe(CN)₆/K₄Fe(CN)₆ and NaCl.

As seen in Figure 1, the anodic and cathodic peak potential of the unactivated SPCE (black line) is present at 0.60 and −0.35 V, respectively. After activation, the anodic and cathodic peak potential shifted to 0.25 and −0.035 V, respectively (blue line). Compared with the commercial SPCE (red line), the difference in the anodic peak potential value of the unactivated and activated SPCE was 0.29 and 0.06 V toward commercial SPCE, respectively. Further, the anodic peak current (Iₚa) of the activated SPCE (Iₚa = 358.75 µA) was more significant than that of the unactivated SPCE (Iₚa = 137.06 µA). The increment of current response and negatively shifted peak potential of the activated SPCE was ascribed to the removal of insulating organic binders on the SPCE, thus enhancing electron transfer quality and functionality.40

2.2. Characterizations of the SPCE-GPLs/AgNPs. SEM characterization was applied to study the morphology changes on the surface of the bare SPCE and SPCE-GPLs/AgNPs. The SEM image can be seen in the Supporting Information (Figure S1). As shown in Figure S1a, the bare SPCE showed a rough and uneven surface. Furthermore, the surface morphology of the modified SPCE-GPLs/AgNPs can be seen in Figure S1b,c with different magnification. Indicated by the dash circles in Figure S1b,c, some GPLs were observed on the fracture surface.41 Moreover, the surface of the SPCE modified with GPLs and AgNPs was rougher than that of the bare SPCE. The presence of AgNPs can be observed in Figure S1c. As shown, the AgNPs had white nanostructure (with an average particle size under 100 nm). The observed nanostructure of AgNPs in Figure S1c confirmed a successful preparation of AgNPs. The EDX has evaluated the presence of AgNPs and measured the concentration of AgNPs drop-casted on modified SPCE-GPLs/AgNPs for further confirmation. As shown in Figure S1d, the EDX image showed the elements of carbon, oxygen, and silver on the surface of SPCE-GPLs/AgNPs. Undoubtedly, the C and Ag elements came from carbon and AgNPs. At the same time, the O element may come from water and moisture during storage before EDX evaluation. As also shown in Figure S1d, approximately 0.5 wt % of AgNPs was detected, confirming that AgNPs have been successfully drop-casted on the SPCE.

2.3. Electrochemical Behaviors of RhB on SPCE-GPLs/AgNPs. The electrochemical behaviors of 1 mM RhB on the bare SPCE and SPCE-GPLs/AgNPs were investigated by square wave voltammograms (SWV) in 0.1 M phosphate buffer solution at pH 7 containing 1 mM RhB. The voltammogram and histogram of the evaluated RhB behavior can be seen in Figure 2a,b, respectively.

As depicted in Figure 2a, the peak potentials of the bare SPCE, SPCE-AgNPs, SPCE-GPLs, and SPCE-GPLs/AgNPs are present at 0.69, 0.86, 0.77, and 0.77 V, respectively. The differences in peak potential (ΔE) of SPCE-AgNPs, SPCE-GPLs, and SPCE-GPLs/AgNPs compared with the bare SPCE are 0.17, 0.08, and 0.08 V, respectively. The ΔE of SPCE-GPLs/AgNPs and SPCE GPLs clearly show a smaller value.
than $\Delta E$ of SPCE-AgNPs, indicating a better electron transfer quality.\textsuperscript{30}

It is clearly seen in Figure 2b that the peak current of RhB on the modified SPCE-GPLs/AgNPs (35 $\mu$A) was higher than that of the bare SPCE (15.2 $\mu$A). Further, as also observed, the increased peak current of SPCE-AgNPs and SPCE-GPLs is moderate compared to that of the bare SPCE. A study reported that the increment of surface roughness definitely improves the surface reactivity,\textsuperscript{42} resulting in higher conductivity. No doubt, when the combination of GPLs and AgNPs were applied on the SPCE, the surface roughness was enhanced (See Figure S1b,c), and the area for electron transfer became larger, therefore increasing the current response, showing a synergistic effect between GPLs and AgNPs.\textsuperscript{29,37,43,44}

2.4. Optimization of GPL Concentrations and pH Measurement. The optimization was performed to figure the optimum measurement parameter. In this work, the optimization was carried out using 1 mM RhB because, at this concentration, the RhB exhibited a good current response, as shown in Figure 2. The effects of GPL concentrations at 0.2; 0.4; 0.6; 0.8; and 1 mg·mL$^{-1}$ toward the peak current response of 1 mM RhB in phosphate buffer at pH 7 on a modified SPCE were examined, and the results are presented in Figure 3a. As depicted, the oxidation peak currents of RhB increased gradually when GPLs at 0.2−0.8 mg·mL$^{-1}$ were applied. However, a decrement in peak current response of RhB was recorded when GPLs at a concentration of higher than 0.8 mg·mL$^{-1}$ were applied. It seems that the thickness of coated GPLs on the surface of SPCE plays a role in inhibiting the transfer of electrons on the electrode surface.\textsuperscript{30} Therefore, the concentration of GPLs at 0.8 mg·mL$^{-1}$ was chosen as the optimum concentration.

The influence of pH on the peak current response of 1 mM RhB was also optimized. The experimental data are shown in Figure 3b. As depicted, when the pH of phosphate buffer was increased from 3 to 6, the peak current of RhB tend to increase. However, when the pH value was higher than 6, a decrement in peak current response was recorded. A study reported that RhB, under acidic conditions (pH < 4), is in the form of a cation. Meanwhile, at a pH value higher than 4, the carboxyl group of the RhB cation will be deprotonated, forming a zwitterion.\textsuperscript{45} This phenomenon caused an electrostatic force between the carboxyl ion (−COO$^-$) on RhB and the positively charged electrode surface. With that, RhB at pH 6 is more attracted onto the surface of the electrode. Therefore, the phosphate buffer at pH 6 was selected for further evaluation of RhB using SPCE-GPLs/AgNPs.

2.5. Effect of Scan Rate. Cyclic voltammograms of 1 mM RhB were evaluated at the SPCE-GPLs/AgNPs sensor at different scan rates in the range 25−150 mV·s$^{-1}$. This evaluation is essential to explain the behavior of RhB on the
modified SPCE. According to the Randles–Ševčík equation, a linear relationship between the current and scan rate denotes the adsorption control process. In contrast, a linear relationship between the current and square root of the scan rate indicates the diffusion control process. As seen in Figure 4a, the plot of the peak current ($I_p$) vs the scan rate ($v$) is expressed by the following equation: $I_p = 0.6206v − 1.9371$ ($R^2 = 0.9951$), showing that the anodic peak current is linear to the scan rate in the range 25–150 mV s$^{-1}$. Meanwhile, the plot of the peak current ($I_p$) versus the square root of the scan rate ($v^{1/2}$) is expressed by the following equation: $I_p = 10.6649v^{1/2} − 40.0246$ ($R^2 = 0.9708$) (Figure 4b). Comparing the $R^2$ value in Figure 4a, it is closer to 1, suggesting an adsorption control process.29 Furthermore, if the slope value of $I_p$ versus log $v$ is near 0.5, then it is supposed to be diffusion control. Meanwhile, if the slope value is near 1, then the process is dominantly controlled by adsorption. The plot of log $I_p$ versus log $v$, which is depicted in Figure 4c and is expressed by the following equation: log $I_p$ = 0.9094 log $v$ − 0.0133 ($R^2 = 0.99302$), shows that the slope value is 0.9094, confirming that the adsorption dominantly controls the electro-oxidation process of RhB on SPCE-GPLs/AgNPs.46,47

2.6. Analytical Performance. 2.6.1. Reproducibility Study. The reproducibility of the SPCE-GPLs/AgNPs was evaluated by recording the peak current response of 1 mM RhB in 0.1 M phosphate buffer at pH 6 using square wave voltammetry. As presented in Figure S2, the data show that the reproducibility of four independently fabricated SPCE-GPLs/AgNPs has an acceptable value of 2.85% (relative standard deviation, RSD), indicating a good reproducibility measurement of RhB.48 These experimental data suggested that SPCE-GPLs/AgNPs has a satisfying reproducibility.

2.6.2. Accuracy Study/Percentage of Recovery. To testify the accuracy of the proposed method, we evaluated the percentage recovery (% R) of RhB. The % R of RhB was expressed as the concentration ratio between the obtained standard solution and the actual standard solution. The % R obtained by the optimized method was 105.40 (Table 1). The results revealed that the proposed method is tolerable and satisfying.29

2.6.3. Linearity Study and Limit of Detection. The linearity was studied to determine the work area and sensitivity of the SPCE-GPLs/AgNPs using square wave voltammetry (SWV). Figure 5a shows the square wave voltammogram profiles of RhB at 2–200 μM, showing an unexpected potential peak shift. The peak potential shifted along with the increase in the RhB concentration, probably due to the reference electrode we used. Conventionally, the potential of the reference electrode Ag/AgCl is directly affected by [Ag$^+$] and [Cl$^-$]. The [Cl$^-$] is maintained by using a supporting electrolyte.50 In this present work, a pseudo- or quasi-reference electrode was employed with the absence of KCl as a supporting electrolyte. The limitation of harnessing a pseudo/quasi-reference electrode is that it is not an ideal non-polarized electrode, possibly resulting in a potential fluctuation during measurement.50,51 In addition, the purity of RhB may also have an effect. For the mentioned reasons, we further recommended modifying the fabricated SPCE-GPLs/AgNPs with a KCl electrolyte.

Figure 5b exhibits the linear behavior for the voltammetric signal of RhB in the concentration range 2–100 μM that showed a correlation of $R^2 = 0.9981$, which corresponds to a regression equation of $I_p = 0.12383\text{[RhB]} + 0.26397$. The limit of detection (LOD) was also calculated from the calibration curve. The LOD was estimated as 3σ/$\lambda$, where $\sigma$ is the standard deviation of intercept and $\lambda$ is the slope of the calibration curve. A previous study has shown that the concentration of RhB resulting in a decrease in cell viability was 25 μg/mL, which is equivalent to ~52 μM.6 Benmassaoud et al. showed a modified SPCE using multi-walled carbon nanotube/TiO$_2$ that performed a greater sensitivity with an LOD of 0.003 μM of RhB.24 however, our fabricated sensor’s electrode is still possible to be applied in detecting the presence of RhB in food samples as well.

2.6.4. Selectivity Study. The selectivity of the SPCE-GPLs/AgNPs was investigated by observing the influence of some interfering compounds on the electrochemical oxidation of RhB. Sucrose and MSG are common additives in food products; therefore, the electrochemical responses of RhB in the mixture of sucrose and MSG on the SPCE-GPLs/AgNPs were studied. In this step, we recorded the response of the modified SPCE toward 1 mM RhB in the presence of 1 mM sucrose and monosodium glutamate (MSG), respectively. Subsequently, the relative standard deviation of the current response was calculated to evaluate the potential of the interferent.

Table 1. Percent Recovery of 40 μM RhB in a 0.1 M Phosphate Buffer (pH = 6) Using SPCE-GPLs/AgNPs

| Concentration of RhB (μM) | Δ$I_p$ (μA) | concentration of RhB found (μM) | average concentration (μM) | percent recovery (%R) |
|--------------------------|-------------|---------------------------------|----------------------------|------------------------|
| 40                       | 5.8         | 44.24                           | 42.19                      | 105.40                 |
| 5.6                      | 41.95       |                                 |                            |                        |
| 5.4                      | 40.36       |                                 |                            |                        |

Figure 6 exhibits the oxidation peak of RhB on SPCE-GPLs/AgNPs at 0.788 V and two separated oxidation peaks at 0.05 V.
and 0.737 V from the mixture of MSG and RhB. The mixture of sucrose and RhB that produced only one oxidation peak was observed at 0.728 V. Hence, the signature oxidation peak of RhB on SPCE-GPLs/AgNPs at 0.737−0.728 V was still observed. The results showed that the SPCE-GPLs/AgNPs based on the voltammetric sensor is selective for the detection of 1 mM RhB. Considering the prominent separation oxidation peak, the experimental method is acceptable and does not interfere with the detection of 1 mM RhB. In Table 2, the tabulated data also showed that sucrose and MSG did not cause significant interference (signal change ≤ 8%), which corroborates the results from Figure 6.

Table 2. Influence of Interfering Compound at 1 mM RhB

| Interferent | Concentration (mM) | Concentration ratio of Interferent/RhB | % RSD |
|------------|--------------------|--------------------------------------|-------|
| Sucrose    | 1                  | 1                                    | 7 28  |
| MSG        | 1                  | 1                                    | 4 83  |

2.7. Analysis of Real Samples. The SPCE-GPLs/AgNPs were applied using a SWV to measure the RhB concentration in traditional crackers as a real sample for practical application. The crackers were bought from a local supermarket. In order to verify the accuracy of the sensing performance, the content of RhB was also analyzed by UV−vis spectrophotometry. The results determined by UV−vis spectrophotometry and by the SPCE-GPLs/AgNPs are in good agreement (Table 3).

Table 3. Result of RhB Determination on SPCE-GPLs/AgNPs Using SWV and UV−vis Spectrophotometric Methods

| Method | Sample | This Method (μM) | UV−vis (μM) | t-test* |
|--------|--------|-----------------|-------------|---------|
|        | crackers | 2.61 ± 0.12     | 2.66 ± 0.02 | 0.21    |

*N The t-table value at the 95% confidence level (n = 3) is 4.3.

Noviandri and Raminas previously reported the potency of voltammetry using a CPE/MIP-based sensor to detect RhB in crackers and sekoteng with satisfactory results. In comparison with their work, our results similarly detected the RhB content in crackers with an insignificant difference compared with the UV−vis evaluation. Thus, either the CPE/MIP-based sensor or SPCE-GPLs/AgNPs can be used to detect RhB electrochemically in food products. Considering the design of our modified SPCE, we offer portability and faster evaluation.

The result of the t-test shows that the experimental t-value is smaller than the t-table value (t-table = 4.3). There was no significant difference between the measurement results using the voltammetry method and the UV−vis spectrophotometric method at the 95% confidence level. Hence, the SPCE-GPLs/AgNPs can be applied for the determination of RhB in a food sample.

3. CONCLUSIONS

In conclusion, an electrochemical sensing platform for RhB was developed based SPCE-GPLs/AgNPs. Due to the high conductivity and synergistic effects of GPLs and AgNPs, the current response of RhB is significantly improved. The linear response range of RhB at the SPCE-GPLs/AgNPs is 2−100 μM with a detection limit of 1.94 μM. Additionally, the developed SPCE-GPLs/AgNPs and proposed method in this work have promising applications for detecting RhB in food samples.
4. EXPERIMENTAL SECTION

4.1. Reagents and Solutions. The chemicals used in this study were alumina substrates obtained from PT. Pridhana Eka (Bandung, Indonesia), carbon paste was obtained from Dynamo (Stockholm, Sweden), silver paste (Ag) and dielectric paste were purchased from SHOEI Chemical Co Ltd. (Osaka, Japan), and graphene nanoplatelets were purchased from Johnson Matthey PLC (London, England). Silver nitrate/AgNO₃ (≥99.0%) was purchased from Sigma-Aldrich (Germany). Trisodium citrate/Na₃C₆H₅O₇, potassium hexacyanoferrate (III)/K₃[Fe(CN)₆], potassium hexacyanoferrate (III)/K₃[Fe(CN)₆] (≥99%), potassium hydrogen phosphate/K₂HPO₄ (≥99.9%), potassium dihydrogen phosphate/KH₂PO₄ (≥99.5%), sodium hydroxide/NaOH, Rhodamine B/C₁₂H₁₇ClN₂O₂, sucrose/C₁₂H₂₂O₁₁ (≥99.5%), monosodium glutamate/C₃H₅NO₂Na, and sodium benzoate/C₇H₅NaO₂ were obtained from Merck (Germany). All reagents used in this work were of analytical grade and were used without further purification. All solutions were prepared using DI water with a resistivity of >18 MΩ. Traditional crackers were purchased from a local market.

4.2. Apparatus. All fabrication equipment includes a screen mask, de haat screen printing, 300 TT Richmond screen maker, furnace RTC, oven, hotplate, and diamond cutter. All electrochemical experiments were performed using a PGSTAT302N potentiostat-galvanostat equipped with Nova 1.11.2 software (Metrohm) for data processing. Commercial screen-printed electrodes (Dropens, DS-110) were obtained from Metrohm Autolab. A particle size analyzer (Horiba Scientific SZ-100) at the Research Center for Nanoscience and Nanotechnology (Bandung, Indonesia) was used to determine the particle size of AgNPs. The surface and cross-sectional morphology of the SPCE was examined by scanning electron microscopy (JEOL JSM IT300). The matrix composition was examined by an energy dispersive X-ray (Oxford X-Max 20) at the Advanced Characterization Laboratories (Research Unit for Clean Technology, Indonesian Institute of Sciences, Bandung, Indonesia). The absorbance of RhB was observed by a Spectrophotometer Agilent 8453, sonication of the composite material used an ultrasonic cleaner delta 318H, electrolysis used an Escort DC power supply EPS-3030S, and optimization of pH measurement used a Mettler Toledo pH meter.

4.3. Fabrication of SPCEs. The SPCEs were fabricated on an alumina substrate by using a screen printing machine. The printing process consists of three steps. First, the reference electrode was made by printing silver paste onto an alumina substrate and then heated in an oven at 120 °C for 30 min and continued with a firing process for 1 h at 750 °C. After that, the working and auxiliary electrodes were printed using carbon paste and heating at 120 °C for 30 min to cure the patterned paste. The last step was the printing and curing process of the dielectric layer. After the SPCE printing process, imprinted silver paste was electrolyzed with 0.1 M KCl solution at 2 V for 3 min until the Ag/AgCl layer color changed from brownish to black, indicating a successful electroplating process.

4.4. SPCE Modification with GPLs-AgNPs. The electrodes were electrochemically activated in 0.1 M NaOH before modification by repeating the potential scan five times from 0 to 1.2 V at 100 mV·s⁻¹. Silver nanoparticles (AgNPs) were synthesized with a chemical reduction method using sodium citrate as a reducer and stabilizer. The stepwise construction of the modification process is illustrated in Figure S3. First, 6 mg of graphene was dissolved in 3 mL of DMF and sonicated for 1 h until homogeneous. The graphene solution was then mixed with silver nanoparticles (at a ratio of 3:2) and then sonicated for 30 min. Subsequently, 0.5 μL of AgNPs-GPLs suspension was drop-casted onto the working electrode and dried at 70 °C for 10 min.

4.5. Electrochemical Measurements. Characterization of activated electrodes was carried out in 0.1 M K₃[Fe(CN)₆]/K₄[Fe(CN)₆] solution containing 0.1 M NaCl as a supporting electrolyte. Cyclic voltammetry (CV) responses were measured in a potential range from −1 to 1 V at a scan rate of 100 mV·s⁻¹. SWV was used for electrochemical determination of RhB in 0.1 M phosphate buffer solution at pH 6. SWV responses were measured by applying a potential scan from −0.2 to 1.8 V and 20 Hz.

■ AUTHORS CONTRIBUTION

A.E.K. contributed in data collection, data analysis, and manuscript writing. H.S. and V.S. contributed in the design, concept, data collection, data analysis and interpretation, and manuscript writing. R.V.M. contributed in manuscript writing, design layout of the figure, data collection, data analysis and interpretation, and fabrication of modified SPCE. S.N.A.J. contributed in manuscript proofreading and data verification.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomga.1c03414.

SEM image of bare SPCE, SPCE-GPLs (at 10,000× magnification), and SPCE-GPLs/AgNPs (at 50,000× magnification) and EDX analysis of SPCE-GPLs/AgNPs (Figure S1); plot of the current peak of 1 mM RhB on four different SPCE-GPLs/AgNPs (Figure S2); and schematic representation of the SPCE-GPLs/AgNPs electrode preparation and electrochemical oxidation of RhB (Figure S3) (PDF)

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Notes
The authors declare no competing financial interest.

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