

Ce-TiO₂/carbon Nanotube Composite Modified Glassy Carbon Electrode for Electrochemical Detection of Caffeic Acid

Xiaoyi Long, Yu Xie, Jinyin Chen^{*}, Ruyi Li, Limin Lu^{*}

Jiangxi Province Key Laboratory for Postharvest Technology and Non-destructive Testing for Fruits & Vegetables, College of Science, Jiangxi agricultural university, Nanchang, China

*E-mail: jinyinchen08@126.com; lulimin816@hotmail.com

Received: 19 March 2019 / Accepted: 17 May 2019 / Published: 30 June 2019

In this paper, cerium doped titanium dioxide/carbon nanotubes (Ce-TiO₂/CNTs) composite was successfully prepared, and the Ce-TiO₂/CNTs modified glassy carbon electrode (Ce-TiO₂/CNTs/GCE) was applied to the electrochemical detection of caffeic acid (CA). Electrochemical methods such as cyclic voltammetry (CV) and differential pulse voltammetry (DPV) were used to characterize the electrochemical behaviors of the Ce-TiO₂/CNTs/GCE. Electrochemical data indicates the Ce-TiO₂/CNTs/GCE possesses a higher peak current for CA oxidation compared with bare GCE, Ce-TiO₂/GCE and CNTs/GCE. Combined with the good catalytic ability of Ce-TiO₂ and the large specific surface area as well as the excellent electrical conductivity of CNTs, the Ce-TiO₂/CNTs exhibited excellent electrochemical sensing of CA. Under the optimum conditions, the oxidation peak current at Ce-TiO₂/CNTs/GCE had a good linear relationship with CA concentration in the range of 1.0 nM to 10.0 μM.

Keywords: Caffeic acid; Cerium-titanium dioxide; Carbon nanotubes; Modified electrode.

1. INTRODUCTION

Caffeic acid (CA, 3, 4-dihydroxycinnamic acid) is a common organic acid and a phenolic monomer compound [1]. It has a wide range of antibacterial [2] and antiviral activity [3], including hepatitis B virus [4], hepatitis C virus [5], human immunodeficiency virus [6], herpes simplex virus [7], influenza virus [8] and so on. In addition, CA has anti-allergic and anti-inflammatory effects, which is of great importance in medicine [9]. However, high concentration of CA has certain cytotoxicity, even carcinogenicity [10]. Therefore, the quantitative analysis of CA is very important. So far, among all the technologies that have been developed to detect caffeic acid [9], electrochemical methods are sensitive, stable and accurate [11, 12], and have been widely used in the electrochemical detection of CA.

TiO₂ has attracted much attention in the field of materials and nano-electrochemistry because of its advantages such as low-cost, non-toxic, stable chemical properties and its efficient catalytic performance. In addition, the electrocatalytic ability of TiO₂ can be further improved by doping the rare earth elements into the system. Among rare earth element, cerium (Ce) is a good dopant, which plays an important role in reducing electron-hole recombination in TiO₂ through electron capture [13]. However, as far as we know, there is no literature reported that Ce-TiO₂-based materials are used as electrochemical detection materials for CA.

Carbon nanotubes (CNTs) are a kind of two-dimensional carbon nanomaterial. They are widely used in analytical chemistry, physics and materials fields because of their excellent electrochemical properties, such as promoting electron transfer, reducing potential, and large specific surface area that especially conducive to the immobilization of organic compounds [14, 15]. Due to their excellent performance, CNTs have been used for electrochemical detection of hydrogen peroxide [16], hydrazine [17], amino acid [18], catechol [19] and other substances. Thus, it is believed the combination Ce-TiO₂ with CNTs could produce good electrocatalytic activity.

In this work, Ce-TiO₂/CNTs composite materials were successfully prepared, and Ce-TiO₂/CNTs modified electrode was prepared by simple dropping method, which was applied to the construction of CA electrochemical sensor. Compared with bare GCE, the CNTs/GCE and the Ce-TiO₂/GCE, the Ce-TiO₂/CNTs/GCE showed higher oxidation peak current to CA, which proved that the composite had good electrocatalytic activity for CA. CV and DPV were applied to investigate the electrochemical behavior of CA on composite modified electrodes. The results showed that the anode current response was linear with the concentration of CA in the range of 1 nM to 10 μM, and the low limit of detection (LOD, S/N=3) was 0.33 nM. Moreover, Ce-TiO₂/CNT/GCE is rapid, highly stable, and sensitive, and has good performance in actual sample analysis.

2. EXPERIMENT

2.1. Reagents

Nano TiO₂ (anatase type, 10-30 nm) was obtained from Shenzhen Jingcai Chemical Co., Ltd (Shenzhen, China). N, N-dimethylformamide (DMF). Cerous sulfate and CNTs were purchased from Vita Chemical Reagent Co., Ltd. (Shanghai, China). Double distilled water was used in the experiment, and the reagents were all analytically pure.

2.2. Apparatus

The CV and DPV were performed at CHI660E electrochemical workstation (Shanghai, China). The conventional three-electrode system was applied in the experiment. It was composed of bare GCE or a modified GCE as the working electrode, platinum electrode as auxiliary electrode and saturated calomel electrode (SCE) as reference electrode.

2.3. Preparation of Ce-TiO₂/CNTs/GCE

1.0 g of TiO₂ was poured into a round bottom flask containing an appropriate amount of distilled water, and ultrasonically dispersed for 10 min. Then, cerous sulfate was added at a molar ratio of Ce to Ti of 1:200. The pH was adjusted to near 6.8, and the reaction was kept at 60 °C for 2~4 h. The precipitate formed after the reaction was filtered, washed three times with water, and dried at 120 °C for 2 h. After calcination at 400 °C for 3 h, Ce-TiO₂ particles were obtained and ground for use.

1.0 mg Ce-TiO₂ was dissolved in 1.0 mL DMF by ultrasound to form 1.0 mg/mL dispersions, and CNTs were also prepared into 1 mg/mL dispersions. Ce-TiO₂/CNTs dispersions were prepared by mixing the 1 mL suspensions of Ce-TiO₂ and CNTs, and then ultrasound for 30 minutes. Subsequently, 5 µL of the suspensions were coated on GCE and dried with infrared lamp to form Ce-TiO₂/CNTs/GCE. Ce-TiO₂/GCE and CNTs/GCE were prepared by the same dropping method.

3. RESULTS AND DISCUSSION

3.1. Electrochemical characterizations

CVs were performed in 0.1 M KCl solution containing 5.0 mM [Fe(CN)₆]^{3-/4-} to investigate the charge transfer ability of different modified electrodes. From Fig. 1A, a pair of well-defined redox peaks was observed on bare GCE (b). The Ce-TiO₂/GCE (a) show decreased peak currents compared to bare GCE (b) owing to the poor conductivity of Ce-TiO₂. While, the CNTs/GCE (d) has a high redox peak current, indicating the good electron transfer capability of CNTs. It also can be seen that the current of Ce-TiO₂/CNTs/GCE (c) increased compared with Ce-TiO₂/GCE (a), which indicates that the introduction of CNTs improves the conductivity.

The electroactive surface areas (*A*) of different modified electrodes were studied by chronocoulometry measurements (Fig. 1B). The *A* can be obtained according to the slope of *Q*-*t*^{1/2} diagram (insert of Fig. 1B) of different modified electrodes, and the following equation:

$$Q(t) = 2nFAcD^{1/2}t^{1/2}/\pi^{1/2} + Q_{dl} + Q_{ads}$$

Where, *n* is the number of electrons. *c* is the substrate concentration, *F* is Faraday constant, *D* is the diffusion coefficient. *Q*_{dl} and *Q*_{ads} refer to the double layer charge and Faradic charge, respectively. Based on the equation, the *A* of bare/GCE (a), Ce-TiO₂/GCE (b), CNTs/GCE (c) and Ce-TiO₂/CNTs/GCE (d) were estimated as 0.061, 0.128, 0.392 and 0.617 cm². These results indicate that the Ce-TiO₂/CNTs have a large specific surface area which is beneficial for adsorbing more CA, thereby improving the electrochemical performance of the sensor.

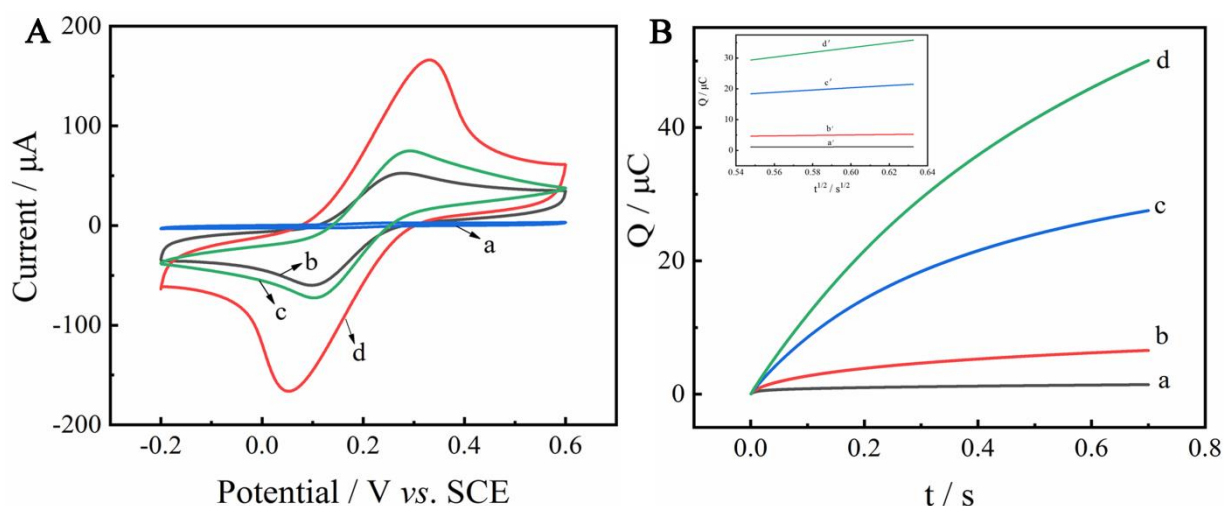


Figure 1. CV voltammograms of Ce-TiO₂/GCE (a), bare GCE (b), Ce-TiO₂/CNTs/GCE (c) and CNTs/GCE (d) in 0.1 M KCl containing 5.0 mM [Fe(CN)₆]^{3-/4-}. (B) Q-t curves of bare/GCE (a), Ce-TiO₂/GCE (b), CNTs/GCE (c) and Ce-TiO₂/CNTs/GCE (d). Inset: Plots of Q-t^{1/2} curves.

3.2. Electrochemical behaviors of CA at modified electrodes

The electrochemical behaviors of 4.5 μM CA in 0.1 M PBS (pH 6.0) at modified electrodes were studied by CV. As depicted in Fig. 2, no redox peak of CA was observed on the bare GCE (b). After modified with Ce-TiO₂ (a), a weak redox peak can be observed, which is probably due to the semiconducting properties of Ce-TiO₂ and its catalytic ability to CA. For CNTs/GCE (c), a pair of well-defined redox peaks appeared owing to the good conductivity of CNT. In addition, the peak current increased significantly at the Ce-TiO₂/CNTs/GCE (d) compared to Ce-TiO₂/GCE (a) and CNTs/GCE (c). The good catalytic performance of Ce-TiO₂/CNTs was resulted from the large surface area and good conductivity of CNTs and the excellent catalytic activity of Ce-TiO₂.

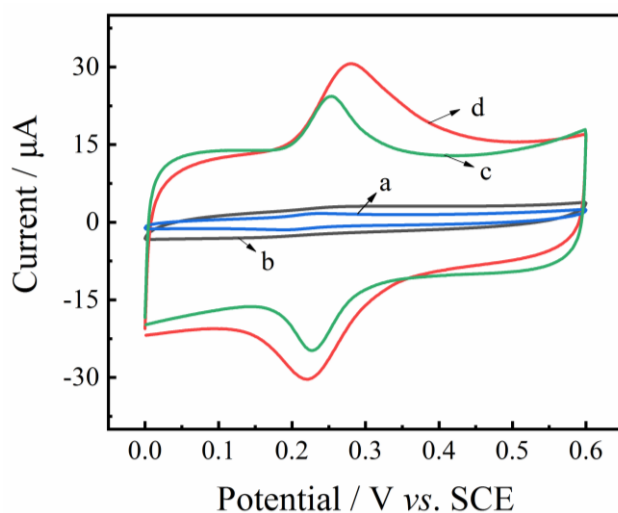


Figure 2. CV voltammograms of Ce-TiO₂/GCE (a), bare GCE (b), CNTs/GCE (c) and Ce-TiO₂/CNTs/GCE (d) in 0.1 M PBS (pH 6.0) containing 4.5 μM CA. Scan rate: 100 mV s⁻¹.

3.3. Optimization of pH and accumulation time

As depicted in Fig. 3A, the effect of different pH values on anodic peak current of 4.5 μM CA at Ce-TiO₂/CNTs/GCE was investigated by CV. When the pH varying from 3.0 to 6.0, the response current of CA increased continuously, and reached the maximum at 6.0. While, the response current decreased with the further increase of pH value. So 6.0 was chosen as the optimal pH for subsequent experiments.

Moreover, as can be seen from Fig. 3B, anode peak potential (E_{pa}) has a linear relationship with pH. The linear equation is $E_{\text{pa}} = 0.632 - 0.064 \text{ pH}$ ($R^2 = 0.999$), and the slope is -0.064 V pH^{-1} , which close to the theoretical value -0.059 V pH^{-1} [20]. Therefore, it can be inferred that the number of protons and electrons involved in the electrochemical oxidation of CA is the same [21]. The electrochemical oxidation process of CA at Ce-TiO₂/CNTs/GCE is shown in scheme 1 [22].

The effect of enrichment time on 4.5 μM CA was investigated by DPV. As depicted in Fig. 3C, when the accumulation time increased from 10 s to 180 s, the DPV response current increased significantly. When the accumulation time increased from 180 s to 300 s, the peak current tends to be stable. This was due to the saturated adsorption of CA on the surface of the electrode. Therefore, 180 s was chosen as the optimal accumulation time.

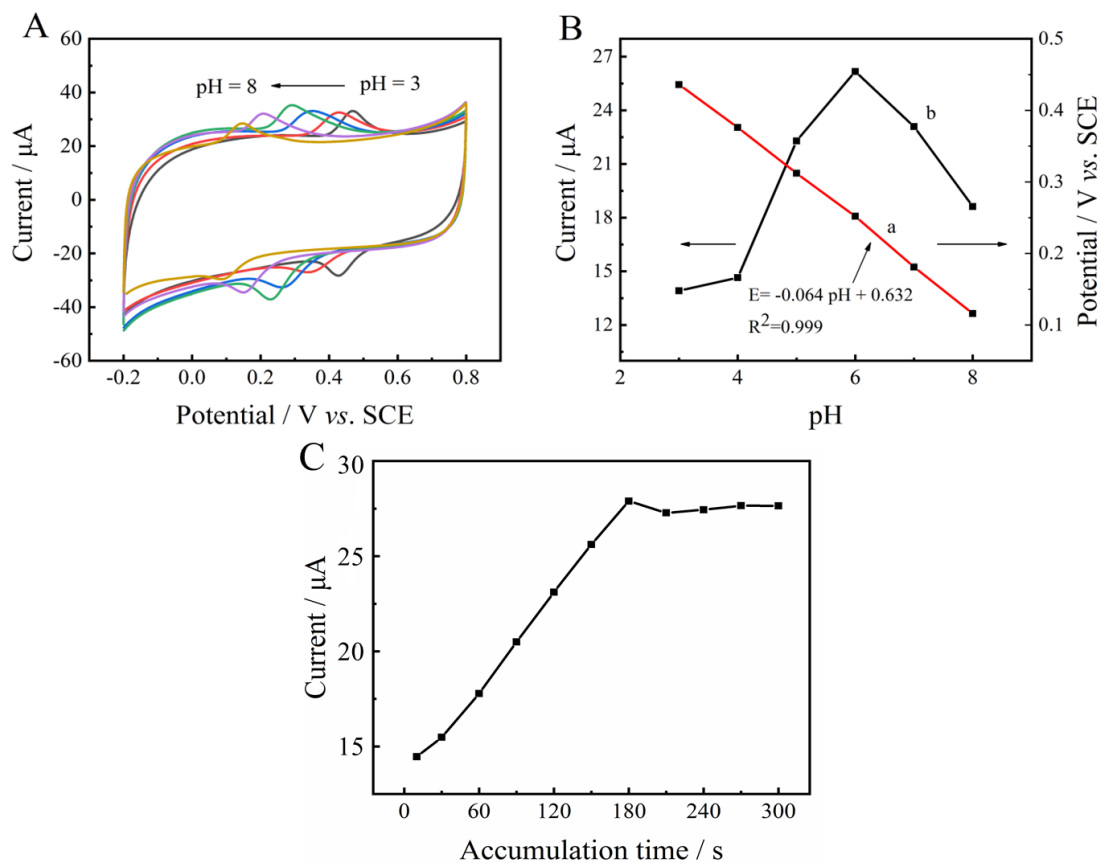
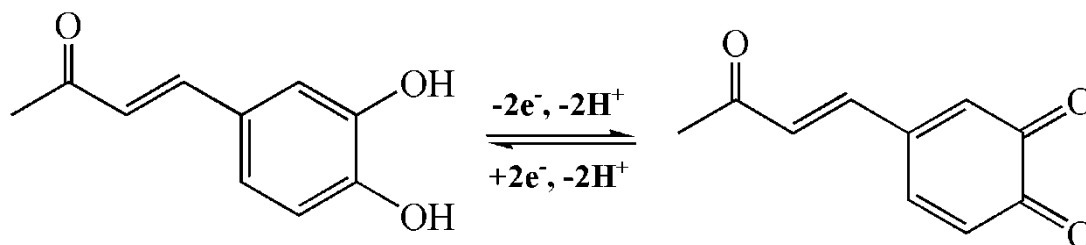


Figure 3. (A) CVs of Ce-TiO₂/CNTs/GCE in 0.1 M PBS with different pH containing 4.5 μM CA. (B) The relationship of pH value vs E_{pa} and I_{pa} . (C) Effect of accumulation time.



Scheme 1. The electrochemical oxidation process of CA.

3.4. The influence of scan rate

The effects of different scan rates on the peak current of 4.5 μM CA at Ce-TiO₂/CNTs/GCE were investigated by CV. As can be seen in Fig. 4A, when the scan rates (ν) increased from 10 to 300 mV/s, the peak currents (I) gradually increased. It can be seen from Fig. 4B that I is proportional to the ν . The equations are as follows: I (μA) = $-0.316 \nu - 6.251$ ($R^2=0.992$) and I (μA) = $0.278 \nu + 6.819$ ($R^2=0.992$), respectively. These demonstrate that the electrochemical behavior of CA on Ce-TiO₂/CNTs/GCE is the adsorption control process [23].

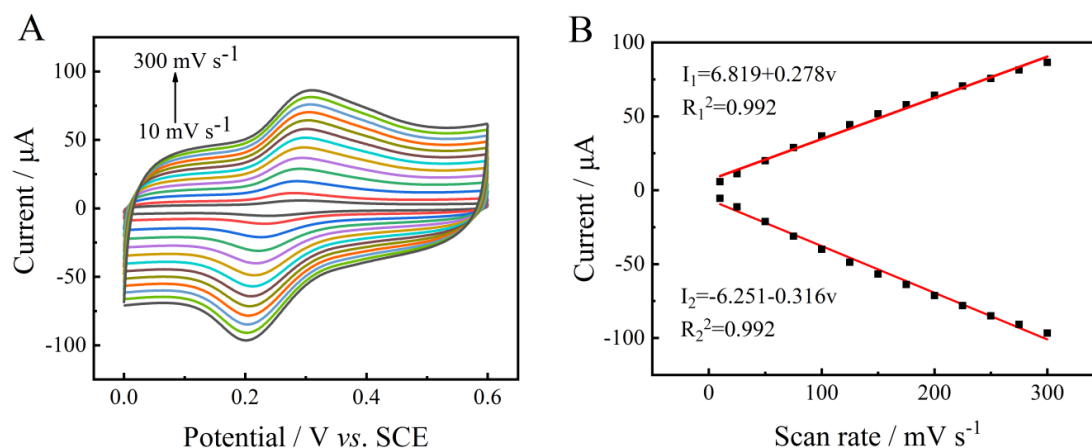


Figure 4. (A) CVs of 4.5 μM CA in 0.1 M PBS (pH 6.0) on Ce-TiO₂/CNTs/GCE at different ν in the range of 10~300 mV/s. (B) the plot of I and ν .

3.5. The electrochemical detection of CA

Under optimized experimental conditions, the relationship between anode peak current and concentration of CA at Ce-TiO₂/CNTs/GCE was studied by DPV. As depicted Fig. 5, the DPV response increases with the increase of CA concentration from 1 nM to 10 μM . The regression equation is $I = 5.688 c + 2.744$ ($R^2=0.997$). The LOD was calculated as 0.33 nM ($S/N=3$). Compared with the detection performance of previously reported sensors in Table 1, the Ce-TiO₂/CNTs/GCE exhibited wider linear range and lower LOD. Good electrochemical performance of the sensor was attributed to the catalytic properties of Ce-TiO₂ and the large effective surface area and good electrical

conductivity of CNTs. Therefore, the Ce-TiO₂/CNTs can be served as a suitable electrode modified material for sensitive electrochemical detection of CA.

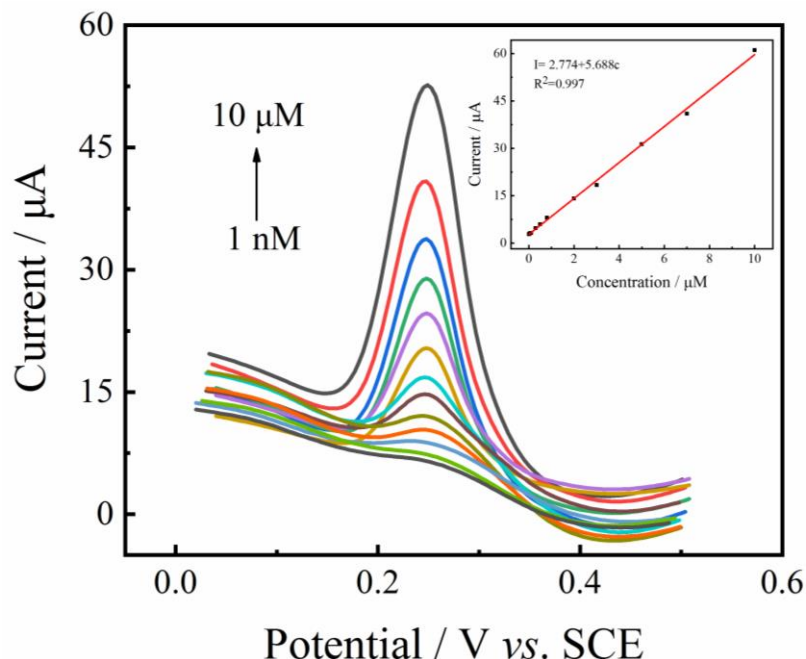


Figure 5. DPV of 0.001, 0.03, 0.05, 0.09, 0.3, 0.5, 0.7, 1.0, 2.0, 3.0, 5.0, 7.0 and 10.0 µM CA on Ce-TiO₂/CNTs/GCE. Insert: the linear plot of DPV response and CA concentration.

Table 1. Comparison of the different modified electrodes for CA determination.

Modified electrodes	Liner range	LOD (µM)	Reference
ERGO/Nafion	0.1-1.0 µM	0.09	[24]
Nafion/Tyre/Sonogel-Carbon	0.04-2 µM	0.06	[25]
GPC ^a	0.965 to 11 µM	0.29	[26]
Ag/PTh/GCE ^b	0.01 to 4.83 µM	0.0053	[27]
ZrO ₂ /Co ₃ O ₄ /rGO/FTO ^c	0.0024 to 0.0524 µM	0.0006	[28]
GCE/PG ^d	4.0 to 30 µM	1.25	[29]
PDA/Au NPs/GCE	100 to 2000 µM	0.79	[30]
Ce-TiO ₂ /CNTs/GCE	0.001 -10 µM	0.0003	This work

^aelectroactive poly(caffeic acid) thin film containing quinone moiety on a preactivated glassy polymeric carbon electrode.

^bsilver nanoparticle decorated poly(thiophene) modified glassy carbon electrode.

^cZrO₂/Co₃O₄/reduced graphene oxide nanocomposite catalyst/fluorine doped tin oxide.

^dGlassy carbon electrodes were coated with films of poly(glutamic acid).

3.6. Reproducibility, stability and selectivity

In order to investigate the repeatability of Ce-TiO₂/CNTs/GCE, the modified electrode was used for 20 consecutive detection of 4.5 µM of CA. As can be seen from Fig. 6, the oxidation peak

currents after the 20 successive CVs were 94.2 % of its initial value, indicating that the satisfactory repeatability of the electrode.

Ce-TiO₂/CNTs/GCE was used to detect 4.5 μM CA for 30 days to study the stability of the modified electrode. The results show that after 30 days, the detection current of the modified electrode to the 4.5 μM CA can still maintain 96.15% of the initial current value, which indicates that the modified electrode has good stability.

In addition, the selectivity of Ce-TiO₂/CNTs/GCE was also studied for 4.5 μM CA detection. During the experiment, some organic and inorganic substances were added to the solution containing 4.5 μM CA to investigate the effect of the interference on the oxidation current intensity of CA. The results showed that 50-fold concentration of potential interfering ions such as Cl⁻, Br⁻, SO₄²⁻, NO₃⁻, H₂PO₄⁻, Na⁺, K⁺, Mg²⁺ and Al³⁺ had no effect on the detection of CA. Common organic interfering substances such as 10-fold concentration of glucose, L-serine, uric acid, urea, oxalic acid, glycine, alanine, L-cysteine, L-tyrosine, L-glutamic acid and guanidine acid, had almost no effect on the detection of CA. This shows that the proposed sensor has good selectivity. This proved the good selectivity of the sensor.

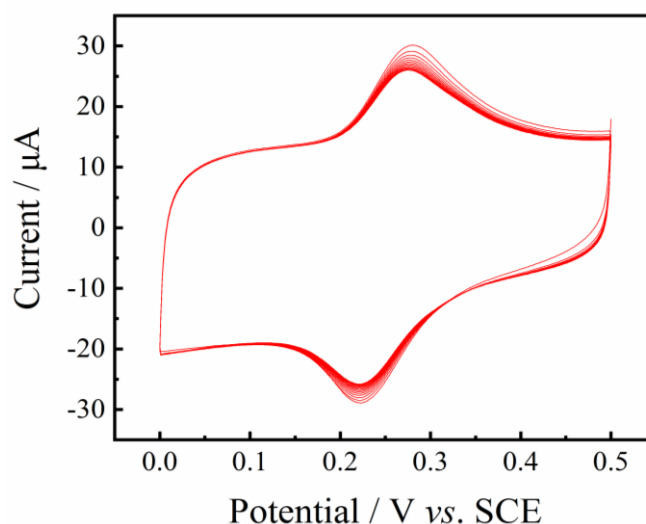


Figure 6. The CV curves of 4.5 μM CA for 20 successive assays in 0.1 M PBS at pH 6.0 at Ce-TiO₂/CNTs/GCE.

3.7. Practical Application

This Ce-TiO₂/CNTs/GCE was applied to detect CA in the real samples by standard addition method to investigate the applicability of the sensor. CA tablets purchased from pharmacies of Jiangxi Agricultural University were ground into powder, and then added with pH 6.0 PBS to prepare solution. After CA samples with different concentrations were prepared, DPV was used to determine the samples successively. The results were showed in Table 2. The recoveries range from 98.33% to

105.00%, indicating that Ce-TiO₂/CNTs/GCE can be successfully applied to the detection of CA in real samples.

Table 2. Recovery measurements of CA in the caffeic acid tablets samples (n = 5).

Sample	Added (μM)	Found (μM)	Recovery (%)	RSD (%)
1	0.004	0.0042	105.00	2.11
2	0.060	0.0590	98.33	4.10
3	0.500	0.4920	98.40	1.28
4	2.000	1.9890	99.45	3.76
5	10.00	10.020	100.2	1.50

4. CONCLUSION

In the paper, Ce-TiO₂/CNTs/GCE was successfully prepared and utilized to the electrochemical detection of CA. Ce-TiO₂/CNTs composites combine large specific surface area and good electrical conductivity of CNTs and good electrocatalytic activity of Ce-TiO₂. After optimization of several experimental conditions, DPV was used for electrochemical detection, showing high sensitivity and good linear range (1 nM~10 μM .). In addition, Ce-TiO₂/CNTs/GCE has good reproducibility, stability and anti-interference. The adequate results in real sample analysis indicated that the composite is suitable for the electrochemical detection of CA.

ACKNOWLEDGEMENTS

We are grateful to the National Natural Science Foundation of China (21665010, 51862014, 31741103, 51302117), The Natural Science Foundation of Jiangxi Province (20142BBF60002), Key Scientific Research Projects of Jiangxi Education Department (GJJ150377), Natural Science Foundation of Nanchang City (No. 2018CXTD014) for their financial support of this work.

References

1. Y. Shi, H. Xu, J. Wang, S. Li, Z. Xiong, B. Yan, C. Wang, Y. Du, *Sens. Actuators B Chem.*, 272 (2018) 135.
2. J. H. Kim, D. Yu, S. H. Eom, S. H. Kim, J. Oh, W. K. Jung, Y. M. Kim, *Mar Drugs*, 15 (2017) 167.
3. H. K. Erdemli, S. Akyol, F. Armutcu, O. Akyol, *J Intercult Ethnopharmacol*, 4 (2015) 344.
4. G.-F. Wang, L.-P. Shi, Y.-D. Ren, Q.-F. Liu, H.-F. Liu, R.-J. Zhang, Z. Li, F.-H. Zhu, P.-L. He, W. Tang, P.-Z. Tao, C. Li, W.-M. Zhao, J.-P. Zuo, *Antiviral Research*, 83 (2009) 186.
5. H. Shen, A. Yamashita, M. Nakakoshi, H. Yokoe, M. Sudo, H. Kasai, T. Tanaka, Y. Fujimoto, M. Ikeda, N. Kato, *PLoS one*, 8 (2013) 82299.
6. X. Zhang, N. Neamati, Y. K. Lee, A. Orr, R. D. Brown, N. Whitaker, Y. Pommier, T. R. Burke Jr, *Bioorgan. Med. Chem.*, 9 (2001) 1649.
7. H. Yamasaki, *Int J Mol Med.*, 28 (2011) 595.
8. H. Utsunomiya, M. Ichinose, K. Ikeda, M. Uozaki, J. Morishita, T. Kuwahara, A. H. Koyama, H. Yamasaki, *Int J Mol Med*, 34 (2014) 1020.
9. Y. Shi, H. Xu, Z. Gu, C. Wang, Y. Du, *Colloids and Surf., A*, 567 (2019) 27.

10. M. Sakthivel, S. Ramaraj, S. M. Chen, B. Dinesh, H. V. Ramasamy, Y. S. Lee, *Anal. Chim. Acta*, 1006 (2018) 22.
11. Y. Qian, C. Wang, F. Gao, *Biosens. Bioelectron.*, 63 (2015) 425.
12. Y. Qian, D. Tang, L. Du, Y. Zhang, L. Zhang, F. Gao, *Biosens. Bioelectron.*, 64 (2015) 177.
13. Y. Poo-arporn, S. Kityakarn, A. Niltharach, M. F. Smith, S. Seraphin, M. Wörner, A. Worayingyong, *Mat. Sci. Semicon. Proc.*, 93 (2019) 21.
14. L. Jiang, R. Wang, X. Li, L. Jiang, G. Lu, *Electrochem. Commun.*, 7 (2005) 597.
15. P. Santhosh, K. Manesh, A. Gopalan, K.-P. Lee, *Anal. Chim. Acta*, 575 (2006) 32.
16. J. Li, Z. J. Yang, Y. Tang, D. W. Diao, *Adv. Mater. Res.*, 391 (2012) 1383.
17. J. Zhang, H. Liu, M. Dou, F. Wang, J. Liu, Z. Li, J. Ji, *Electroanalysis*, 27 (2015) 1188.
18. S. Mallakpour, A. Zadehnazari, *Carbon*, 56 (2013) 27.
19. H. Qi, C. Zhang, *Electroanalysis*, 17 (2005) 832.
20. J. Zhang, X. Xu, L. Chen, *Sens. Actuators B Chem.*, 261 (2018) 425.
21. G. Bharath, E. Alhseinat, R. Madhu, S. M. Mugo, S. Alwasel, A. H. Harrath, *J Alloy Compd.*, 750 (2018) 819.
22. K. Thangavelu, N. Raja, S. M. Chen, W. C. Liao, *J Colloid Interface Sci.*, 501 (2017) 77.
23. Y. Dong, L. Yang, L. Zhang, *J Agric Food Chem*, 65 (2017) 727.
24. H. Filik, G. Çetintaş, A. A. Avan, S. Aydar, S. N. Koç, İ. Boz, *Talanta*, 116 (2013) 245.
25. M. ElKaoutit, I. Naranjo-Rodriguez, K. R. Temsamani, M. P. Hernández-Artiga, D. Bellido-Milla, J. L. H.-H. de Cisneros, *Food Chem.*, 110 (2008) 1019.
26. L. F. da Silva, N. Stradiotto, H. P. Oliveira, *Electroanalysis*, 20 (2008) 1252.
27. Ş. U. Karabiberoglu, E. M. Ayan, Z. Dursun, *Electroanalysis*, 25 (2013) 1933.
28. A. Puangjan, S. Chaiyasith, *Electrochim. Acta*, 211 (2016) 273.
29. D. P. Santos, M. F. Bergamini, A. G. Fogg, M. Zanoni, *Microchim. Acta*, 151 (2005) 127.
30. G. Zhang, H. Fu, D. Zou, R. Xiao, J. Liu, S. Li, *Int. J. Electrochem. Sci.*, 12 (2017) 11465.

© 2019 The Authors. Published by ESG (www.electrochemsci.org). This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution license (<http://creativecommons.org/licenses/by/4.0/>).