Analytical & Bioanalytical Electrochemistry

> 2023 by CEE www.abechem.com

Full Paper

Superior Performance Application of TiO₂ Nanocomposites Doped Carbon Dots of Different Sizes as Carbon Paste Electrode Modifiers

Arham Zul,^{1,*} Andi Khaeruni Ramil,² Muhammad Natsir,³ and Muhammad Nurdin^{3,*}

¹Study Program of Agricultural Science, Post Graduate School, Universitas Halu Oleo, Southeast Sulawesi, Indonesia ²Department of Plant Protection, Faculty of Agriculture, Universitas Halu Oleo, Southeast Sulawesi, Indonesia ³Department of Chemistry, Faculty of Mathematics and Natural Sciences, Universitas Halu Oleo, Southeast Sulawesi, Indonesia

*Corresponding Author, Tel.: +6281316551674 E-Mails: <u>mnurdin06@yahoo.com</u> (M. Nurdin), and <u>arhamzul88@yahoo.com</u> (A. Zul)

Received: 5 May 2023 / Received in revised form: 24 September 2023 / Accepted: 25 September 2023 / Published online: 30 September 2023

Abstract- In this study, electrochemical green synthesis, characterization, and application of Carbon dot-doped TiO₂ nanocomposites (TiO₂@CDs) as carbon paste electrode modifiers have been carried out. The preparation of nanocomposites begins with the synthesis of carbon dots (CDs) by varying the value of the oxidation potential. The obtained CDs were incorporated on the surface of TiO₂ through continuous stirring at room temperature followed by heating at a constant temperature of 140°C for 4 hours. To determine the effect of potential variations of CDs on the characteristics of nanocomposites, we used SEM, XRD, and FTIR. Based on SEM characterization, potential variations of CDs didn't affect or change the surface morphology of TiO₂. TiO₂ has a characteristic surface morphology which is composed of spherical particles of uniform size. However, XRD and FTIR characterization showed that the potential variation of CDs caused a 20 angle shift and TiO₂ wavenumber in the fingerprint region. Potential variations of CDs caused the average particle size of TiO₂ to increase from 37.32 nm to 42.89 nm, 45.12 nm, and 49.01 nm for oxidation potentials of 10 V, 15, and 20 V, respectively. The results of the electrochemical characteristics showed superior performance of CPE in the Fe(CN)6³-/Fe(CN)6⁴⁻ solution system after being modified with TiO2@CDs. Superior performance is demonstrated by significantly increased peak currents, both oxidizing and reducing. This phenomenon is strongly influenced by the size of the synthesized CDs particles through potential variations. Based on these results, a potential of 15 V is stated as the best potential in the application of CDs as a modifier.

Keywords- Nanocomposites; Electrochemical green synthesis; TiO₂@CDs; Superior performance; Different sizes of CDs

1. INTRODUCTION

Titanium dioxide (TiO₂) is a photocatalyst material that has attracted the attention of researchers because its particle size can be synthesized and modified to nano size. With nano size, the effectiveness of a material, especially TiO₂ will increase. Based on this, TiO₂ is widely synthesized and applied to various fields of nanotechnology, such as organic pollutant degradation [1–3], water purification [4], COD sensors [5,6], sensors and biosensors [7–9], electrode modifiers [10–12], and many other applications that were currently being studied.

The unique electronic structure of TiO₂ is one of the reasons why this material is used in various applications. As a semiconductor material, TiO₂ has an ideal gap energy level to modify. The TiO₂ gap energy level plays an important role in the process of pollutant degradation [13], conversion of water molecules into hydrogen [14,15], or storage and current transfer in DSSC technology [16,17]. Nevertheless, the role of a very important energy level of TiO₂ is faced with the problem of the recombination rate of the e^-/h^+ pair. Recombination of the e^-/h^+ pair will reduce the performance of TiO₂ [18–20]. In other applications, such as electrode modifiers, TiO₂ is faced with current conductivity and surface area problems. These two problems are reported to affect the interfacial electron transfer and the movement of analyte molecules toward the electrode surface. These two problems are reported to affect the interfacial electron transfer and the electrode surface [21-23].

Efforts to the various problems above, several studies show that the doping of TiO₂ photocatalyst surfaces is reportedly effective in reducing the recombination rate of the e^{-/h^+} pair, increasing electron transfer on the surface of the electrode, and increasing the photocatalyst surface area of TiO₂ [13]. Currently, the doping material that is of interest to researchers is Carbon dots. Carbon dots (CDs) are carbon-derived materials that have been widely applied in various fields since their invention in 2004. Some advantages of using CDs are their unique surface area, where CDs consist of very small spherical nanoparticles (<10 nm). In addition, CDs have strong chemical properties and good biocompatibility. So, the use of doping will produce a nanocomposite that has a good hybrid structure [24].

CDs synthesis methods that have been reported come from many pathways [25–27]. the electrochemical method being one method that shows different characteristics. Among the CDs synthesis methods that have been reported, the electrochemical method is one green method that shows different characteristics. The electrochemical method is a green synthesis method because it is effective in minimizing waste, energy efficient, non-toxic, and has high safety standards [28–30]. This green method is widely applied in the synthesis of organic materials and has been declared an innovative synthesis method. In the synthesis of CDs, the application

of this method will depend on the oxidation potential, current intensity, electrode type, and electrolysis time [31]. This condition has the potential to produce CDs with different characteristics from those previously reported. Based on this, we report the characteristics of the CDs we synthesized through the variation of the oxidation potential. Furthermore, the obtained CDs were applied as a TiO₂ photocatalyst doping material, resulting in the production of TiO₂@CDs nanocomposites whose characteristics of the synthesized CDs through various oxidation potentials. Furthermore, we applied the CDs obtained as a TiO₂ doping material, resulting in a TiO₂@CDs nanocomposite whose characteristics, including morphology, crystal size diameter, and intermolecular vibrations, we report in this study. In addition, another novelty and uniqueness that we report from this study are the electrochemical properties of the TiO₂@CDs nanocomposite when applied as a carbon paste electrode (CPE) modifier. The electrochemical properties were studied using cyclic voltammetry in a $Fe(CN)_6^{3-}/Fe(CN)_6^{4-}$ solution system.

2. EXPERIMENTAL SECTION

2.1. Electrochemical Synthesis of CDs Solution

The CDs solution was synthesized electrochemically by varying the oxidation potential of 10, 15, and 20 Volts, respectively. Graphite rod electrodes are used as an anode and cathode. The two electrodes were inserted in an electrochemical cell in the presence of a mixture of NaOH/Ethanol as an electrolyte solution. The distance between the two electrodes is kept constant at 3 cm. The synthesis process was carried out for 5 hours. Furthermore, the formed CDs solution is separated from the carbon residues through a centrifugation process. The schematic of the electrochemical synthesis of the Carbon dots solution is shown in Figure 1.



Figure 1. Schematic of electrochemical synthesis of CDs solution

2.2. Synthesis of TiO₂@CDs nanocomposites

The electrochemical synthesis process produced three solutions of CDs which were marked as CDs 10 V, CDs 15 V, and CDs 20 V. These three solutions were used in the synthesis of TiO₂@CDs nanocomposites. The synthesis of nanocomposites was carried out by the hydrothermal-impregnation method. A total of 4.0 mL of CDs solution was put into a beaker containing 40 mL of deionized water and 6 mL of ethanol. The solution was homogenized using a magnetic stirrer, then slowly added 1.50 g of TiO₂ nanoparticle. The composite was stirred with a magnetic stirrer at room temperature for 4 hours, followed by separation of the TiO₂@CDs nanocomposites using filter paper and hydrothermally at a constant temperature of 140°C for 4 hours. The success of the synthesis and the effect of potential variations of CDs on the characteristics of TiO₂ nanoparticles were characterized using SEM, XRD, and FTIR.

2.3. Electrochemical performance of TiO₂@CDs nanocomposites

The electrochemical performance of the CPE-TiO₂@CDs nanocomposites was studied using cyclic voltammetry. Fabrication of electrodes is done through mechanical homogenization. A total of 0.70 g of pristine graphite is mixed simultaneously with 0.10 g of TiO₂@CDs into paraffin oil at 80°C. The composite was then homogenized and inserted into the electrode body with a diameter of ± 4.0 mm. As a result, three electrodes were obtained, namely CPE-TiO₂@CDs 10 V, CPE-TiO₂@CDs 15 V, and CPE-TiO₂@CDs 20 V. The tests were carried out alternately by inserting these electrodes into a voltammetric cell containing Fe(CN)₆³⁻/Fe(CN)₆⁴⁻ 0.01 mol L⁻¹. The performance test of the three electrodes was carried out at a potential range of -1.0 to +0.8 V. The scan rate values were varied to determine whether the electrochemical reaction in the Fe(CN)₆³⁻/Fe(CN)₆⁴⁻ solution system was controlled by the diffusion rate. In addition, scan rate variations are performed to calculate the EASA value. The design of the electrode body and the stages of the cyclic voltammetry test are shown in Figure 2.



Figure 2. Design of electrode body and the stages of the cyclic voltammetry test

3. RESULTS AND DISCUSSION

3.1. Characteristics of CDs solution

The characteristics of the electrochemically synthesized CDs solution are shown in Figure 3. The CDs solution visually produces a brick-red color. This specific color is shown in Figure 3a. The fundamental difference from the variation of the oxidation potential to the visual color of the CDs solution is the intensity of the color produced. The large oxidation potential (20 V) shows a dark brick red color compared to the use potential of 10 and 15 V. This is correlated with the number of carbon particles produced. Based on previous studies it was explained that certain oxidation potentials will affect the formation and characteristics of CDs [32].



Figure 3. Characteristics of the CDs solution: (a) the color of the synthesized CDs solution; (b) Maximum wavelength; and (c) Specific IR absorption

Figure 3b is the result of a characteristic test using UV-Vis spectroscopy. The results show that the active CDs solution absorbs UV light with wavelengths of 242 and 352 nm. This wavelength is the specific wavelength of the CDs solution we synthesized. The variation of the oxidation potential shows the effect on the absorbance intensity of the CDs molecules. The

absorbance bands at 242 and 352 nm result from the $\pi \rightarrow \pi^*$ and $n \rightarrow \pi^*$ transitions originating from the C=C and C=O double bonds. The C=C double bond is a bond originating from the carbon core, while C=O is a carboxylate group found on the surface of CDs. Based on the comparison results with previous studies, it is known that the specific wavelength of the CDs molecule is also influenced by the nature of the electrolyte solution and the electrodes (anode and cathode) used [14,15]. In addition, different synthesis methods and carbon sources will provide unique characteristics of CDs. This characteristic is seen in the visual color and the resulting wavelength [34].

Figure 3c shows the IR absorption characteristics of CDs. Although there are differences, these characteristics have similar functional groups to CDs which were synthesized hydrothermally using lemon juice as a carbon source [35]. Based on the results of the literature comparison of the specific IR peaks of the ethanol molecule, we believe that the specific IR peaks of the CDs we synthesized were indicated by the presence of a peak at 3417.86 cm⁻¹ (O-H stretching); 1641.42 cm⁻¹ and 1635.63 cm⁻¹ (C=C stretching); 1381.03 cm⁻¹ (C-H bending); 1305.81 cm⁻¹ and 1274.95 cm⁻¹ (C-O stretching); and 435.91 cm⁻¹ which is a specific peak for carbon in the fingerprint region.

3.2. Morphological Characteristics of TiO₂@CDs

In the synthesis of TiO₂@CDs nanocomposites, we used three solutions of CDs (shown in Figure 1a) as doping agents. The effect of these three solutions in the formation of nanocomposites was observed based on the results of morphological characterization, crystallinity properties, and functional groups. Physically, the synthesized TiO₂@CDs are white and are composed of fine particles. Based on the morphological characterization (Figure 4), it is known that the hydrothermal-impregnated doping process of three CDs solutions does not affect the surface of TiO₂ nanoparticles. TiO₂ nanoparticles have a specific morphology which is composed of spherical particles [33,34]. These particles have a uniform size.



Figure 4. Morphological characterization of TiO2@CDs

Advanced morphological mapping of the doping effect of three CDs solutions on the TiO_2 surface is shown in Figure 5. These results clearly show that the CDs molecules are evenly distributed on the TiO_2 surface. In addition, the mapping results also provide an overview of the effect of variations in oxidation potential on the number of CDs produced.



Figure 5. Advanced morphological mapping of TiO₂@CDs

3.3. Crystal size characteristics and Functional groups of TiO₂@CDs

In addition to looking at the diffractogram peaks and IR absorption, the characteristics of crystalline properties and functional groups were used to observe how variations in the oxidation potential of CDs affected the characteristics of TiO₂. Figure 6 is the peak of the TiO₂@CDs diffractogram which we specifically observed in the $2\theta = 60-80^{\circ}$ region. The selection of this region is based on our previous study which found the specific diffractogram peak for TiO₂@CDs was in the $2\theta = 50-80^{\circ}$ region [24].



Figure 6. Diffractogram peaks of pristine TiO₂ and TiO₂@CDs synthesized by impregnationhydrothermal

The diffractogram comparison between pristine TiO₂ (black line) and TiO₂@CDs (red, blue, and green lines) shows the same diffractogram pattern. Pristine TiO₂ has a diffractogram peak at 2θ =62.32°, 68.43°, 69.99°, 74.72°, and 75.76°. The presence of CDs causes these specific peaks to shift towards a larger 2 θ . This was shown for all synthesized nanocomposites, both TiO₂@CDs 10 V, TiO₂@CDs 15 V, and TiO₂@CDs 20 V.

In addition to the 2θ shift, based on the calculation of the average particle size using the Scherrer equation, data were obtained that the CDs doping on the TiO₂ surface caused a change in the average particle size. Where this change is shown for all variations of the oxidation potential. The greater the value of the oxidation potential used in the synthesis of CDs, the greater the change in the average particle size of TiO₂. The average particle size values of pristine TiO₂ and TiO₂@CDs are shown in Table 1.

Table 1. Average particle size values of prestige TiO₂ and TiO₂@CDs



Figure 7. IR spectra of pristine TiO₂ and TiO₂@CDs in the fingerprint region

Figure 7 shows the IR absorption characteristics of pristine TiO₂ (black line), TiO₂@CDs 10 V (red line), TiO₂@CDs 15 V (blue line), and TiO₂@CDs 20 V (green line). This characteristic is observed in the fingerprint region. The observed phenomenon of the variation of CDs oxidation potential is the shift of the specific IR peak of pristine TiO₂. In the fingerprint

area, pristine TiO₂ has specific IR peaks at several wave numbers, including 410 cm⁻¹, 417 cm⁻¹, 426 cm⁻¹, 433 cm⁻¹, and 482 cm⁻¹. The doping process causes the wave numbers to experience irregular vibrations so that the peak shift pattern becomes different between 10 V CDs, 15 V CDs, and 20 V CDs.

3.4. Effect of TiO₂@CDs on the electrochemical performance of CPE

This section examines the role of TiO₂@CDs on the electrochemical performance of CPE. In this case, the observed electrochemical performance is the value of the redox potential and peak current of the Fe(CN)₆³⁻/Fe(CN)₆⁴⁻ aqueous system. In addition, this observation specifically aims to study the role of CDs synthesized with varying potential on the performance of the TiO₂@CDs composite. Figure 8 shows the superior performance of CPE after the addition of TiO₂@CDs. The addition of TiO₂@CDs succeeded in increasing the conductivity and electron transfer rate of CPE. In the Fe(CN)₆³⁻/Fe(CN)₆⁴⁻ aqueous system, pristine CPE (inset) shows a cyclic voltammogram with small and wide current peaks, both oxidation and reduction peaks. But interestingly, the addition of TiO₂@CDs makes CPE electrochemical performance very good. This performance is shown in all observed modifiers. The high and narrow current peak indicators and small potential values are the basis for our belief that the TiO₂@CDs modifier has a significant effect on increasing the electrochemical performance of CPE.



Figure 8. Cyclic voltammogram of the electrochemical performance of TiO₂@CDs as a CPE modifier in the $Fe(CN)_6^{3-}/Fe(CN)_6^{4-}$ 0.01 mol L⁻¹ aqueous system (supporting electrolyte: NaCl 0.1 mol L⁻¹)

Table 2 shows the redox current potential and peak values of TiO₂@CDs modified CPE. Based on Figure 8 and Table 2, the electrochemical performance of CPE modified by TiO₂@CDs 15 V as a modifier showed much better performance than the other two modifiers, namely TiO₂@CDs 10 V and TiO₂@CDs 20 V. Homogenization of CPE with TiO₂@CDs 15 V effectively changed the electrochemical characteristics of CPE in the Fe(CN)₆³⁻/Fe(CN)₆⁴⁻ aqueous system. Previously, CPE was quasi-reversible and turned into reversible. The peak current value (Ip) generated from CPE-TiO₂@CDs 15 V is Ip (I_{pa}/I_{pc}) = 1. These results also show how the effect of potential bias CDs against performance modifiers. CDs synthesized using a potential of 15 V showed the best performance compared to using a potential bias of 10 V and 20 V. The difference in bias potential will result in different sizes of CDs particles, so their use as a dopant will give different characteristics. This condition is corroborated by the average particle size data from TiO₂@CDs as shown in Table 1. The use of a large potential bias will result in a large CDs particle size that correlates with a larger average particle size of the modifier. Based on this, it was found that CDs suitable for application as dopants in the synthesis of electrode modifiers were 15 V CDs.

Electrodes	E _{pa}	I _{pa}	Epc	I _{pc}
	(V)	(A/cm^2)	(V)	(A/cm ²)
CPE-TiO ₂ /CDs 10 V	-0.03	1.74×10 ⁻⁵	-0.39	-2.01×10 ⁻⁵
CPE-TiO ₂ /CDs 15 V	-0.06	2.20×10 ⁻⁵	-0.33	-2.45×10 ⁻⁵
CPE-TiO ₂ /CDs 20 V	-0.02	1.66×10 ⁻⁵	-0.39	-2.01×10 ⁻⁵

Table 2. Redox current potential and peak values of CPE-TiO2@CDs

The superior electrochemical performance of TiO₂@CDs in the Fe(CN) $_{6}^{3-}$ /Fe(CN) $_{6}^{4-}$ the aqueous system was also studied by varying the scan rate in the range of 0.02 to 0.50 Vs⁻¹. Variation of scan rate is important in obtaining information regarding whether an electrochemical reaction is driven by a diffusion process. The current is directly related to the concentration of the analyte in the body of the solution. So that the value of the scan rate has a linear relationship to the peak current, both anodic and cathodic. Figure 9 shows how the performance of the three electrodes, namely CPE-TiO₂@CDs 10 V, CPE-TiO₂@CDs 15 V, and CPE-TiO2@CDs 20 V when the scan rate values are varied. In general, the three electrodes show a linear relationship between the value of the scan rate and the peak current. This is indicated by the increase in the peak current value along with the increase in the scan rate value. So it can be assumed that the electrochemical reactions produced by the three electrodes in the $Fe(CN)_{6}^{3}/Fe(CN)_{6}^{4}$ solution system are controlled by a diffusion process. Nonetheless, CPE-TiO₂@Ds 15 V exhibits the property that most interests us. This electrode shows the stability of the potential value, both oxidation and reduction of solutions containing $Fe(CN)6^{3-1}$ $/Fe(CN)_{6}^{4-}$ analytes. The resulting oxidation and reduction potential values for each scan rate variation are 0.1 V and 0.3 V respectively. The stability of the potential values, when the scan rate varies, illustrates that the electrochemical reactions that occur on the surface of the

electrode are reversible. These results corroborate the previous information shown in Figure 8 and Table 1.



Figure 9. Cyclic voltammogram of scan rate variation in Fe(CN)₆³⁻/Fe(CN)₆⁴⁻ solution system: (a) CPE-TiO₂@CDs 10 V; (b) CPE-TiO₂@CDs 15 V; and (c) CPE-TiO₂@CDs 20 V

Figure 10 shows the results of plotting the roots of the scan rate vs. the peak anodic current. We use the slope values from these plotting results to estimate the electroactive surface area (EASA) of the three electrodes that we synthesize.



Figure 10. Plotting of root scan rate vs. peak anodic current

The estimated value of EASA is calculated according to the Randles-Sevcik equation [21,22,38]. For the Fe(CN)6³⁻/Fe(CN)6⁴⁻ aqueous system, we use the equation Ip = 269 n^{3/2} AD^{1/2} Cv^{1/2}, where n = 1, D = 7.6×10⁻⁶ cm²/s, and C = 0.01 M. The Ip is the slope value as shown in Figure 10. The estimated EASA value is then shown in Table 3. Overall, the results illustrate that the CPE-TiO₂@CDs electrode composite has a different surface area. These differences affect the electrochemical characteristics, especially the transfer of electrons on the surface of the electrode.

Table 3. Estimation of the EASA value of CPE-TiO₂@CDs in the $Fe(CN)_6^{3-}/Fe(CN)_6^{4-}$ aqueous system

Electrodes	Slope	EASA Values
		(cm)
CPE-TiO ₂ /CDs 10 V	$8 \times 10^{-5} (R^2 = 0.9984)$	0.01
CPE-TiO ₂ /CDs 15 V	$7 \times 10^{-5} (R^2 = 0.9974)$	0.009
CPE-TiO ₂ /CDs 20 V	$7 \times 10^{-5} (R^2 = 0.9999)$	0.009

4. CONCLUSION

The effect of electrochemically synthesized CDs using various oxidation potentials on the characteristics of nanocomposite based on TiO₂ has been successfully studied in this study. The variation of the oxidation potential resulted in a brick red CDs solution that actively absorbs UV light at a wavelength (λ max) of 242 nm and 352 nm. The CDs solution also showed

specific IR peaks at wave numbers $(1/\lambda)$ of 3417.86 cm⁻¹, 1641.42 cm⁻¹, 1635.63 cm⁻¹, 1381.03 cm⁻¹, 1305.81 cm⁻¹, 1274.95 cm⁻¹ and 435.91 cm⁻¹. The doping process carried out by hydrothermal impregnation succeeded in obtaining TiO₂@CDs nanocomposites with morphological characteristics composed of spherical particles of uniform size. Another characteristic produced is the increased average particle size which has a specific IR absorption in the fingerprint region. These characteristics are influenced by the variation of the oxidation potential used during the synthesis of CDs. The results of electrochemical tests in the Fe(CN)₆³⁻ /Fe(CN)₆⁴⁻ solution system illustrate that TiO₂ doped with CDs 15 V (TiO₂@CDs 15 V) is the best modifier for CPE. However, the application is closely related to its performance as an electrode modifier for voltammetry-based chemical pollutant detection. Based on preliminary observations, we found the superior performance of CPE after the addition of TiO₂@CDs make the rate of electron transfer at the electrode surface increase significantly.

Acknowledgments

We acknowledge the financial support from the Ministry of Education, Culture, Research and Technology of the Republic of Indonesia under the Doctoral Dissertation Research award grant no 44/UN29.20/PG/2022 and SP-DIPA-023.17.1.690523/2022.

Declarations of interest

The authors declare no conflict of interest in this reported work.

REFERENCES

- [1] Z. Arham, M. Nurdin, and B. Buchari, Int. J. ChemTech Res. 9 (2016).
- [2] M. Nurdin, M.Z. Muzakkar, M. Maulidiyah, T. Trisna, Z. Arham, O.A. La Salim, I. Irwan, and A.A. Umar, Electrocatalysis (2022) 1–10.
- [3] M. Nurdin, D. Wibowo, T. Azis, R.A. Safitri, M. Maulidiyah, A. Mahmud, F. Mustapa,R. Ruslan, A. Salim, and L. Ode, Surf. Eng. Appl. Electrochem. 58 (2022) 125.
- [4] M. Zhang, S. Jiang, F. Han, H. Chen, N. Wang, L. Liu, and L. Liu, Cellulose 29 (2022) 3529.
- [5] M. Zu, TiO₂-based Photoelectrocatalysis Technology for Degradation and Detection of Organics in Wastewater, PhD thesis (2021) https://doi.org/10.25904/1912/4285.
- [6] M. Zu, X. Zhou, S. Zhang, S. Qian, D.-S. Li, X. Liu, and S. Zhang, J. Mater. Sci. Technol. 78 (2021) 202.
- [7] Z. Yang, W. Xu, B. Yan, B. Wu, J. Ma, X. Wang, B. Qiao, J. Tu, H. Pei, and D. Chen,

ACS Omega 7 (2022) 2474.

- [8] V. Mazzaracchio, R. Marrone, M. Forchetta, F. Sabuzi, P. Galloni, M. Wang, A. Nazligul, K.-L. Choy, F. Arduini, and D. Moscone, Electrochim. Acta 426 (2022) 140766.
- [9] J. Ma, M. Zhang, W. Su, B. Wu, Z. Yang, X. Wang, B. Qiao, H. Pei, J. Tu, and D. Chen, Langmuir 38 (2022) 751.
- [10] N. Dali, M. Maulidiyah, S. Samsiah, I. Irwan, L.O.A. Salim, Z. Arham, and M. Nurdin, Journal of Physics Conference Series 1763 (2021) 012067.
- [11] M. Nurdin, M. Maulidiyah, A.H. Watoni, A. Armawansa, L.O.A. Salim, Z. Arham, D. Wibowo, I. Irwan, and A.A. Umar, Korean J. Chem. Eng. 39 (2022) 209.
- [12] M. Nurdin, Z. Arham, W.O. Irna, M. Maulidiyah, K. Kurniawan, I. Irwan, and A.A. Umar, Mater. Sci. Semicond. Process. 151 (2022) 106994.
- [13] Z. Arham, K. Kurniawan, I. Ismaun, Biointerface Research in Applied Chem. (2021).
- [14] A. Naldoni, M. Altomare, G. Zoppellaro, N. Liu, S. Kment, R. Zboril, and P. Schmuki, ACS Catal. 9 (2018) 345.
- [15] J. Cai, J. Shen, X. Zhang, Y.H. Ng, J. Huang, W. Guo, C. Lin, and Y. Lai, Small Methods. 3 (2019) 1800184.
- [16] C. Zhou, Z. Xi, D.J. Stacchiola, and M. Liu, Energy Sci. Eng. 10 (2022) 1614.
- [17] M. Ismail, M.M. Chebaane, L. Bousselmi, O. Zahraa, C. Olivier, and T. Toupance, Surfaces and Interfaces. 27 (2021) 101543.
- [18] L. Yuan, X. Xu, X. Song, L. Hong, Z. Zhang, J. Ma, and X. Wang, Biomater. Adv. 137 (2022) 212853.
- [19] W. Choi, J. Yeo, J. Ryu, T. Tachikawa, and T. Majima, Environ. Sci. Technol. 44 (2010) 9099.
- [20] S. Amiri-Hosseini, and Y. Hashempour, Environ. Heal. Eng. Manag. J. 8 (2021) 295.
- [21] M. Nurdin, O.A. Prabowo, Z. Arham, D. Wibowo, M. Maulidiyah, and S.K.M. Saad, Surfaces and Interfaces. 16 (2019) 108.
- [22] M. Nurdin, L. Agusu, A.A.M. Putra, M. Maulidiyah, Z. Arham, D. Wibowo, M.Z. Muzakkar, and A.A. Umar, J. Phys. Chem. Solids. 131 (2019) 104.
- [23] M. Nurdin, N. Dali, I. Irwan, M. Maulidiyah, Z. Arham, R. Ruslan, B. Hamzah, S. Sarjuna, and D. Wibowo, Anal. Bioanal. Electrochem. 10 (2018) 1538.
- [24] Z. Arham, and K. Kurniawan, Korean J. Chem. Eng. 39 (2022) 1333.
- [25] T. Zhao, N. Oh, D. Jishkariani, M. Zhang, H. Wang, N. Li, J.D. Lee, C. Zeng, M. Muduli, and H.-J. Choi, J. Am. Chem. Soc. 141 (2019) 15145.
- [26] B. Shao, Z. Liu, G. Zeng, H. Wang, Q. Liang, Q. He, M. Cheng, C. Zhou, L. Jiang, and B. Song, J. Mater. Chem. A. 8 (2020) 7508.
- [27] Q. Ma, and X. Su, Analyst 135 (2010) 1867.
- [28] C. Schotten, T.P. Nicholls, R.A. Bourne, N. Kapur, B.N. Nguyen, and C.E. Willans,

Green Chem. 22 (2020) 3358.

- [29] N. Sbei, T. Hardwick, and N. Ahmed, ACS Sustain. Chem. Eng. 9 (2021) 6148.
- [30] Y.H. Budnikova, E.L. Dolengovski, M.V. Tarasov, and T.V. Gryaznova, J. Solid State Electrochem. (2023) 1.
- [31] B. Bin Chen, R.S. Li, M.L. Liu, H.Z. Zhang, and C.Z. Huang, Chem. Commun. 53 (2017) 4958.
- [32] T.C. Canevari, M. Nakamura, F.H. Cincotto, F.M. de Melo, and H.E. Toma, Electrochim. Acta 209 (2016) 464.
- [33] P. Miao, K. Han, Y. Tang, B. Wang, T. Lin, and W. Cheng, Nanoscale 7 (2015) 1586.
- [34] W.A. Amer, A.F. Rehab, M.E. Abdelghafar, N.L. Torad, A.S. Atlam, and M.M. Ayad, Carbon N.Y. 179 (2021) 159.
- [35] M. He, J. Zhang, H. Wang, Y. Kong, Y. Xiao, and W. Xu, Nanoscale Res. Lett. 13 (2018) 1.
- [36] J.F. Li, Z.L. Xu, H. Yang, L.Y. Yu, and M. Liu, Appl. Surf. Sci. 255 (2009) 4725.
- [37] S. Jamil, and M. Fasehullah, Mater. Innovations. 1 (2021) 22.
- [38] Z. Arham, F.B. Awad, T. Nakai, I. Ismaun, and L. Anhusadar, Mater. Chem. Phys. (2023) 128419.