#### **Research Article**

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# Synthesis and characterization of bismuth oxide/commercial activated carbon composite for battery anode

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Abstract: Bismuth oxide has been considered as a promising electrode material due to the high theoretical capacity, low cost, and non-toxic nature. However, its application has been limited by the low electrical conductivity. In this work, bismuth oxide/commercial activated carbon composite were successfully synthesized through hydrothermal method. Bismuth nitrate pentahydrate with concentrations of 8, 24, and 32 mmol were mixed with Na<sub>2</sub>SO<sub>4</sub>, NaOH, and commercial activated carbon. The mixture was then put into a hydrothermal reactor and heated at 110°C for 5 h. These composite materials can have a 10<sup>2</sup>-10<sup>5</sup> higher electrical conductivity, depending on the bismuth oxide ratio, compared to both bismuth oxide and commercial AC separately.

Keywords: bismuth oxide, activated carbon, hydrothermal, battery, anode

## **1** Introduction

The battery is an electrical energy storage technology that is able to convert chemical energy into electrical energy through electrochemical reactions of reduction and oxidation [1]. Battery performance involves the transfer of electrons from the negative electrode (anode) to the

positive electrode (cathode) so as to produce an electric current and a potential difference [2]. The use of materials with high charge storage quality can materialize more durable discharge process and shorter or more efficient charging process, thereby reducing the consumption of electrical energy [3].

The battery consists of an electrode, electrolyte, and separator. The electrode is a battery component that contains active ingredients. The battery electrodes are divided into cathode and anode. The anode is a negative electrode associated with a half-cell oxidation reaction that releases electrons into the external circuit [4]. Materials that can be used as anodes must have good ion/charge conductivity, large energy capacity [5], long cycle life, easy to process, non-toxic, and low in price. One of the kind of materials that can be used as a battery anode is metal oxides because of its high theoretical capacity and low cost, such as bismuth oxide (Bi<sub>2</sub>O<sub>3</sub>), which has good electrical and optical properties [6], has a volumetric capacity value of  $3,765 \text{ mA h cm}^{-1}$ , in the form of  $\text{Bi}_2\text{O}_3$  has a potential difference of 2.8 V, is non-toxic, and relatively cheap [7]. However, the use of bismuth oxide as an anode has a drawback, namely the low conductivity value at 1.56  $\times$  $10^{-7} \,\mathrm{S \,m^{-1}}$  [8], responsible for the slow ion/charge conductivity of the anode, inferring the need for additional materials to produce higher conductivity value, such as activated carbon.

Xia et al. [9] in their research on the synthesis of mesoporous carbon composites with Bi<sub>2</sub>O<sub>3</sub> as an electrode material using a microwave, obtained excellent performance capacitance and specific capacity reaching  $386 \text{ Fg}^{-1}$ . Wang et al. [10] reported on the synthesis of activated carbon composites with bismuth oxide using the vacuum impregnation method as a supercapacitor. The result was that the activated carbon composite with bismuth oxide had a specific capacitance value of 332.6 F  $g^{-1}$  at 1 A  $g^{-1}$ . In addition, a recent study by Astuti et al. [8] regarding the synthesis of Bi/rice husk AC composite by hydrothermal method with variations in the weight ratio of activated carbon and bismuth nitrate of 2:1, 1:1, and 1:2, produced electrical

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conductivities of 0.51  $\times$  10<sup>-5</sup>, 1.24  $\times$  10<sup>-5</sup>, and 0.59  $\times$  $10^{-5}$  S m<sup>-1</sup>, respectively. The electrical conductivity value obtained, based on the said results, did not significantly increase on the account that the composition between activated carbon and bismuth oxide that had been formed might not be precise, emphasizing that the ratio/composition of a composite is very important. Meanwhile, the synthesis of bismuth oxide using the hydrothermal method showed higher electrical conductivity of the product formed in comparison with pure bismuth oxide [11] and composites produced in Astuti et al. [8]. Recently, Astuti et al. [12] reported the production of bismuth oxide/activated carbon composite synthesized using hydrothermal method. The activated carbon was from rice husk. The investigation recommends on paying attention to the factors affecting the formation of composite particularly the composition factor of precursor.

Pertaining to the above, a Bi/AC composite was synthesized with various concentrations of bismuth nitrate pentahydrate (BNP) using the hydrothermal method to ensure that  $Bi_2O_3$ , as the main constituent of the composite, can be formed optimally and has a high electrical conductivity value. Moreover, the variation in the mole concentration of BNP used was designed to determine the effect of concentration on the formation of bismuth oxide and the characteristics of the composite material produced and would later be used as a battery anode. The combining of activated carbon with bismuth oxide into a composite was carried out to improve the electrical properties of bismuth oxide using the hydrothermal method with varying concentrations of BNP.

## 2 Research methodology

#### 2.1 Materials

The materials used in this study were BNP (Sigma Aldrich), distilled water, sodium sulfate (Merck), sodium hydroxide (Merck), commercial activated carbon (Brataco). All chemicals were of analytical grade without further purification.

#### 2.2 Research methodology

#### 2.2.1 Synthesis of Bi/AC composites

Synthesis of Bi/AC composites were carried out using hydrothermal method with varying concentrations of

BNP (Bi(NO<sub>3</sub>)<sub>3</sub>·5H<sub>2</sub>O) of 8, 24, and 32 mmol. 8 mmol of Bi(NO<sub>3</sub>)<sub>3</sub>·5H<sub>2</sub>O was added with 12 mmol Na<sub>2</sub>SO<sub>4</sub>, dissolved in 40 mL distilled water, then stirred using IKA RH Basic KT/C at 1,500 rpm for 45 min. The solution mixture was then added with 40 mL of 72 mmol of NaOH [13]. Later, 0.5 g of commercial coconut shell AC was added to the solution mixture. The solution mixture was then put into a hydrothermal reactor and heated at 110°C for 5 h. The resulting mixture solution was cooled and then filtered. The filtered precipitate was dried using an oven (Fisher Scientific) at a temperature of 110°C for 60 min. It was then sieved with a size of 100 mesh. The same treatment was applied to the synthesis of composites Bi(NO<sub>3</sub>)<sub>3</sub>·5H<sub>2</sub>O at 24 and 32 mmol.

#### 2.2.2 Characterization of Bi/AC composites

The Bi/AC composites were characterized by Fourier Transform Infra-Red (FTIR) spectrometer Shimadzu IRAffinity-1 to determine the functional groups of the composite material. FTIR analysis was performed at wavenumbers 4,000–400 cm<sup>-1</sup> with a frequency rate of  $0.25 \text{ cm}^{-1}$  at room temperature. The X-Ray Diffraction (XRD) Shimadzu 7000 analysis for the identification of crystalline structures was carried out by measuring at an angle of  $2\theta$  with Cu-K $\alpha$  radiation ( $\lambda$  = 0.15406 nm). Composite conductivity values were determined using Electrochemical Impedance Spectrometry (EIS) (LCR meter HIOKI 3532-50). The samples were analyzed in the form of pellets with a diameter of 1.5 cm and a thickness of 2-5 mm. Scanning Electron Microscopy-Energy Dispersive X-Ray mapping, Jeol JED 6510LA, was used to determine surface morphology and composition of the composite material, while thermal gravimetric analysis-differential thermal analysis (TGA-DTG), Mettler Toledo TGA/DSC 3+, was used to measure changes in mass, thermal decomposition, and thermal stability of the composite material with measurements in the temperature range of 40-800°C. To determine the surface area, the adsorption-desorption isotherms, the pore size, and pore volume of the composite materials, the TriStar II 3020 Gas Sorption Analyzer (GSA) was used.

## 3 Results and discussion

#### 3.1 Bi/AC composites

Bi/AC composites were produced by mixing  $Bi(NO_3)_3$ -5H<sub>2</sub>O, sodium sulfate (Na<sub>2</sub>SO<sub>4</sub>), sodium hydroxide (NaOH), and

commercial AC. The mixing of Bi(NO<sub>3</sub>)<sub>3</sub>·5H<sub>2</sub>O and Na<sub>2</sub>SO<sub>4</sub> formed a complex compound, Bi<sub>2</sub>O(OH)<sub>2</sub>SO<sub>4</sub>, as per equation (1), characterized by the presence of a white suspension. When the NaOH solution was added, the OH– ions from the NaOH solution would gradually react with the Bi<sub>2</sub>O(OH)<sub>2</sub>SO<sub>4</sub> complex to form Bi(OH)<sub>3</sub> as presented in equation (2). The Bi(OH)<sub>3</sub> solution along with commercial AC were put into a hydrothermal reactor (autoclave) and then heated. During the heating process, Bi(OH)<sub>3</sub> would hydrate and turn into Bi<sub>2</sub>O<sub>3</sub> [13] as illustrated in equation (3). The overall reaction mechanism that occurred is as follows:

$$2\text{Bi}(\text{NO}_3)_3 \cdot 5\text{H}_2\text{O} + \text{Na}_2\text{SO}_4$$
(1)  
 
$$\rightarrow \text{Bi}_2\text{O}(\text{OH})_2\text{SO}_4 + 2\text{Na}\text{NO}_3 + 4\text{H}\text{NO}_3 + 7\text{H}_2\text{O},$$

$$Bi_2O(OH)_2SO_4 + 2NaOH + H_2O$$
(2)

 $\rightarrow 2Bi(OH)_3 + Na_2SO_4$ ,

$$2\text{Bi}(\text{OH})_3 \to \text{Bi}_2\text{O}_3 + 3\text{H}_2\text{O}.$$
 (3)

The colors of the synthesized Bi/AC vary with the ratio of bismuth oxide in the composite as seen in Figure 1. The 8 mmol Bi/AC composite produced a darker color because the percentages of BNP and commercial AC were almost the same and the color of the activated carbon was still dominated. The 24 mmol Bi/AC composite has light gray in color because the percentage of added BNP was more than the commercial AC, and thus the color of the activated carbon was not too dominant. The 32 mmol Bi/AC composite demonstrated a gray composite with a lumpy texture (agglomerate), as shown in Figure 2, attributed to the percentage of added BNP, which was higher than the commercial AC at 32 mmol. The color generated by the composites originated from the joint color of bismuth oxide, which is pale yellow [14], and commercial AC, which is black. The yellow color of Bi<sub>2</sub>O<sub>3</sub> caused saturation of the black color on the activated carbon so that the resulting composite had appeared blackish gray.

#### 3.2 Material characteristics

#### 3.2.1 Functional group structures

Figure 2 shows that the three composite samples had almost the same absorption peaks, namely the low absorption at wavenumber 826-833 cm<sup>-1</sup>, which identified the presence of the Bi-O-Bi group, and wavenumber 1,384–1,380 cm<sup>-1</sup>, which identified the stretching vibration of Bi-O [15]. The same peaks were also observed in the pure bismuth oxide sample, showcasing absorption at wavenumbers of about 840 cm<sup>-1</sup>, identifying the presence of the Bi–O–Bi group [16], and 1,384 cm<sup>-1</sup>, indicating the presence of the Bi–O group [17]. The results implied that Bi<sub>2</sub>O<sub>3</sub> have been formed in the composite sample. Absorptions at around 1,600 cm<sup>-1</sup> and 1,100 cm<sup>-1</sup> were also observed in the three samples, indicating the presence of the C=C and C–O functional groups [18]. In the spectra of the commercial AC, these vibration modes were also observed at 1540.16 and 1040.90 cm<sup>-1</sup>. The spectra thus suggested that the composite had contained commercial AC. The absorption at wavenumber 3,440 cm<sup>-1</sup> signified the vibrational stretching of the O-H group [19]. Complete FTIR test results on the functional groups of the 8, 24, and 32 mmol Bi/AC composites, pure Bi<sub>2</sub>O<sub>3</sub>, and commercial AC are shown in Table 1.

#### 3.2.2 XRD characterization

Figure 3 shows the diffractograms of composites, bismuth oxide database, commercial activated carbon and BNP. The XRD characterization result of the 8 mmol Bi/AC showed the presence of Bi<sub>2</sub>O<sub>3</sub> with  $\alpha$ -Bi<sub>2</sub>O<sub>3</sub> (monoclinic) crystal structure denoted by peaks at  $2\theta = 27.453^{\circ}$ , 33,316°, 26,992°, 46,372°, 26,992°, 37,667°;  $\beta$ -Bi<sub>2</sub>O<sub>3</sub> (tetragonal) crystal structure demonstrated by peaks at  $2\theta = 30.184^{\circ}$ , 46.372°; and  $\gamma$ -Bi<sub>2</sub>O<sub>3</sub> (cubic) crystal structures at peaks of  $2\theta = 27.453^{\circ}$  and 30.184°. The presence of commercial AC



Figure 1: Bi/AC composites prepared with (a) 8 mmol, (b) 24 mmol, and (c) 32 mmol Bi(NO<sub>3</sub>)<sub>3</sub>·5H<sub>2</sub>O.



Figure 2: FTIR spectra of pure Bi<sub>2</sub>O<sub>3</sub> [20,21], commercial AC [22] and composites.

was indicated by the low intensity peaks at  $2\theta = 23.923^{\circ}$ , 26.992°, 35.463°, while the pure BNP presence was denoted by the peak at  $2\theta$  = 30.184°. The 24 mmol Bi/AC composite showed the presence of  $\alpha$ -Bi<sub>2</sub>O<sub>3</sub> (monoclinic) crystal structure with low intensity peaks at  $2\theta = 46.86^{\circ}$  and  $56.692^{\circ}$ ;  $\beta$ -Bi<sub>2</sub>O<sub>3</sub> (tetragonal) at  $2\theta$  = 30.094°, 32.672°, 46.860°; and y-Bi<sub>2</sub>O<sub>3</sub> (cubic) at  $2\theta$  = 30.094° and 32.672°. The presence of commercial AC was shown at  $2\theta = 23.879^{\circ}$  and  $35.201^{\circ}$ . while the pure BNP were shown by peaks at  $2\theta = 30.094^{\circ}$ , 32.672°, 42.099°, 53.239°. In the 32 mmol Bi/AC composite, the presence of Bi<sub>2</sub>O<sub>3</sub> was indicated by the crystal structures of  $\alpha$ -Bi<sub>2</sub>O<sub>3</sub> (monoclinic) at  $2\theta = 27.485^\circ$ , 33.305° and y-Bi<sub>2</sub>O<sub>3</sub> (cubic) at  $2\theta = 27.485^{\circ}$ , 39.152° at low intensities. The presence of the commercial AC was denoted by peaks at  $2\theta$  = 22.463°, 35.594°, and the pure BNP was signified by peaks at  $2\theta = 21.822^{\circ}$ ,  $28.97^{\circ}$ ,  $31.373^{\circ}$ ,  $35.594^{\circ}$ ,  $40.712^{\circ}$ ,  $53.274^{\circ}$ . The complete data regarding the  $2\theta$  peaks of the composite samples compared with the  $2\theta$  peaks of Bi<sub>2</sub>O<sub>3</sub> (JCPDS), commercial AC, and pure BNP data are shown in Table 2.

#### 3.2.3 Electrical conductivity

Table 3 shows that the conductivity value of pure  $Bi_2O_3$  was smaller than the conductivity value of activated carbon, connoting that the addition of activated carbon could increase the conductivity value of bismuth oxide. The addition of activated carbon functioned as a matrix in the composite prompted the distribution of bismuth oxide to be more even on the surface of the activated carbon [23]. The addition of activated carbon to bismuth oxide to create a composite also showed a higher conductivity value in the product made.

The data shown in Table 3 demonstrate that the 32 mmol Bi/AC composite had the highest electrical conductivity value at  $0.89 \times 10^{-1}$  S m<sup>-1</sup>. This can be attributed to the fact that the 32 mmol composite had a higher percentage of BNP compared to the 8 mmol and 24 mmol composites. Measured through the EIS test, BNP was found to have a very high conductivity value, which

Table 1:	Functional	groups	in the	FTIR	spectra
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Functional group	Wavenumber in the observed sample $(cm^{-1})$					
	8 mmol Bi/AC	24 mmol Bi/AC	32 mmol Bi/AC	Commercial AC	Bismuth oxide (Bi <sub>2</sub> O <sub>3</sub> )	
Bi-O	1384.09	1383.77	1380.52	_	1384.67	
Bi-O-Bi	826.25	833.75	826.25	_	839	
C=C	1635.57	1640.70	1636.60	1540.16	_	
C-0	1107.09	1116.28	1107.2	1040.90	_	
0-Н	3434.38	3448.04	343.72	_	_	



**Figure 3:** Diffractograms of 8, 24, and 32 mmol Bi/AC composites along with  $Bi_2O_3$  (JCPDS database under the numbers 41-1449 for  $\alpha$ - $Bi_2O_3$ , 27-0050 for  $\beta$ - $Bi_2O_3$ , and 45-1344 for  $\gamma$ - $Bi_2O_3$ ), commercial AC, and pure BNP.

was 1.70  $\times$  10<sup>-1</sup> S m<sup>-1</sup>. The 24 and 8 mmol Bi/AC composites had electrical conductivity values of 0.15  $\times$  10<sup>-2</sup> and 0.69  $\times$  10<sup>-3</sup> S m<sup>-1</sup>, respectively.

## 3.2.4 Distribution of elements containing in the composites

The SEM images of the 8, 24, and 32 mmol Bi/AC composites are shown in Figure 4, depicting long needle-like Table 3: The conductivity values measured from the EIS test

Sample	Conductivity (S $m^{-1}$ )		
8 mmol Bi/AC	$0.69  imes 10^{-3}$		
24 mmol Bi/AC	$0.15 \times 10^{-2}$		
32 mmol Bi/AC	$0.89 imes10^{-1}$		
Pure Bi <sub>2</sub> O <sub>3</sub>	$0.15 \times 10^{-6}$ [11]		
BNP	$1.70  imes 10^{-1}$ [12]		
Commercial AC	$0.74  imes 10^{-5}$ [22]		

shape in the 8 mmol composite as the embodiment of the monoclinic  $Bi_2O_3$  crystals [24]. Meanwhile, the 24 and 32 mmol Bi/AC composites were both irregular in shapes. The low content of  $Bi_2O_3$  in the 24 and 32 mmol Bi/AC, as illustrated in the XRD data, brought the non-needle-like structure of the two composites.

SEM mappings of 8, 24, and 32 mmol composites are shown in Figure 5. The 8, 24, and 32 mmol Bi/AC composites all had evenly distributed Bi element on the composite surface.

#### 3.2.5 Transition phase

The TGA–DTG curves of the Bi/AC composites are shown in Figure 6, presenting the changes in mass of the 8, 24, and 32 mmol Bi/AC composites entailing the mass transformation phases from precursor to Bi<sub>2</sub>O<sub>3</sub> and removal of the amorphous residue in the form of SO<sub>4</sub><sup>2–</sup>, HNO<sub>3</sub>, and NO<sup>3–</sup> in regions I and II at temperatures around 220–380°C [20]. In region III, the formations of  $\alpha$ -Bi<sub>2</sub>O<sub>3</sub> at temperatures around 400–500°C [25] and  $\beta$ -Bi<sub>2</sub>O<sub>3</sub> at

**Table 2:** XRD  $2\theta$  data comparison of the composite samples with Bi<sub>2</sub>O<sub>3</sub> (JCPDS), commercial AC, and pure BNP

Bi/Commercial AC Composite	20					
	α-Bi <sub>2</sub> O <sub>3</sub>	$\beta$ -Bi <sub>2</sub> O <sub>3</sub>	γ-Bi <sub>2</sub> O <sub>3</sub>	Commercial AC	Pure BNP	
8 mmol	27.453°	30.184°	27.453°	23.923°	30.184°	
	33.316°					
	26.992°					
	46.372°	46.372°	30.184°	26.992° 35.463		
	26.992°					
	37.667°					
24 mmol	46.860°	30.094°	30.094°	23.879°	30.094°	
					32.672°	
	56.692°	32.672°	32.672°	35.201°	42.099°	
		46.860°			53.239°	
32 mmol	27.485°	-	27.485°	22.463°	21.822°	
					28.974°	
					31.373°	
	33.305°		39.152°	35.594°	35.594°	
					40,712°	
					53,274°	



Figure 4: SEM images of Bi/AC composites prepared with (a) 8 mmol, (b) 24 mmol, and (c) 32 mmol BNP.

temperatures around 500–650°C [26] were shown. Additionally, at temperatures around 650–700°C, the conversion of  $\beta$ -Bi<sub>2</sub>O<sub>3</sub> to  $\gamma$ -Bi<sub>2</sub>O<sub>3</sub> and further to  $\alpha$ -Bi<sub>2</sub>O<sub>3</sub> [25] was depicted. The pattern of the formation and phase

transformation of bismuth oxide in bismuth oxide/ commercial activated carbon composites is similar to that of bismuth oxide composites/rice husk-activated carbon composite as reported by Astuti et al. [12].



Figure 5: SEM mappings of Bi/AC composites prepared with (a) 8 mmol, (b) 24 mmol, and (c) 32 mmol BNP.



Figure 6: TGA-DTG curves of Bi/AC composites prepared with (a) 8 mmol, (b) 24 mmol, and (c) 32 mmol BNP.



Figure 7: N<sub>2</sub> adsorption-desorption isotherms of Bi/CA composites prepared with (a) 8 mmol, (b) 24 mmol, and (c) 32 mmol BNP.

Parameter	Composite sample					
	8 mmol Bi/CA	24 mmol Bi/CA	32 mmol Bi/CA	Commercial AC		
Surface area (m <sup>2</sup> g <sup>-1</sup> )	2.131	8.329	3.514	39.733		
Pore volume (cm <sup>3</sup> g <sup>-1</sup> )	0.007	0.022	0.0124	0.032		
Pore size (nm)	13.655	11.044	14.167	3.267		

Table 4: GSA analysis results of 8, 24, and 32 mmol Bi/commercial AC composite

#### 3.2.6 Pore and surface properties

Figure 7 shows that the 8, 24, and 32 mmol Bi/AC composite had similar patterns, whereby the adsorption process ensued from low pressure to the relative pressure of 1 ( $p/p^{\circ}$ ). At  $p/p^{\circ} = 1$ , the adsorption process had reached its saturation point or maximum adsorption capacity, which would then be replaced by the desorption process. The 8, 24, and 32 mmol Bi/AC composites all had type IV adsorption isotherms characterized by the presence of loop hysteresis expressive of the porous nature of the materials as they were able to adsorb N<sub>2</sub>.

Based on the data presented in Table 4, the 8, 24, and 32 mmol Bi/AC composites were all classified as mesoporous materials (2–50 nm pore size) [27]. Table 4 also marks that the 8 mmol Bi/AC composite had a small surface area and pore volume with a fairly large pore size, which can be assumed that the 8 mmol composite had smaller number of pores. The 24 mmol Bi/AC composite had a large surface area and pore volume, as well as small pore size implying a higher number of pores. Meanwhile, the 32 mmol composite had smaller surface area and pore volume than the 24 mmol composite but larger than the 8 mmol composite, with its pore size largest out of all three composites produced. Based on this, it can be concluded that the 32 mmol composite had fewer pores than the 24 mmol composite but had more pores than the 8 mmol composite but had more pores than the 8 mmol composite but had more pores than the 8 mmol composite but had more pores than the 8 mmol composite but had more pores than the 8 mmol composite.

Subhan [4] explained that a material with high porosity would give rise to a large resistance, thereby reducing the conductivity value of the material. However, it should be borne in mind that Bi/AC prepared with 32 mmol BNP contains high concentration of BNP as precursor which may results in the highest electrical conductivity compared to other composites [12].

## **4** Conclusion

Bi/AC composites were successfully synthesized with 8, 24, and 32 mmol variations in the amount of BNP,

confirmed by FTIR and XRD analyses. The 8 mmol Bi/ AC composite showed the presence of monoclinic Bi<sub>2</sub>O<sub>3</sub> crystals and had an electrical conductivity value of  $0.69 \times 10^{-3}$  S m<sup>-1</sup>. The 24 and 32 mmol Bi/commercial AC composites showed a low Bi<sub>2</sub>O<sub>3</sub> content based on the XRD characterization, and accordingly portrayed by Bi<sub>2</sub>O<sub>3</sub> lack of appearance in the SEM characterization. The two composites had electrical conductivity values of  $0.15 \times 10^{-2}$ and  $0.89 \times 10^{-1} \, \text{Sm}^{-1}$ , respectively. The three composites produced were all porous materials as they were able to adsorb N<sub>2</sub> gas. The electrical conductivity of composites prepared with 24 and 32 mmol BNP could be due to the high content of impurities resulting from precursor BNP. This study is expected to provide a scientific contribution related to the utilization of activated carbon and bismuth oxide in the form of a composite as an alternative material for lithium-ion battery anode. Factors affecting composite properties such as the right composition during the synthesis process need special attention to gain composite with the desired properties.

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## References

- [1] Linden D, Reddy T. Handbook of batteries. USA: McGraw-Hill Companies Inc.; 2002.
- [2] Aflahannisa A, Astuti A. Sintesis nanokomposit karbon-TiO<sub>2</sub> Sebagai Anoda baterai lithium. J Fisika Unand. 2016;5(4):357-63.
- [3] Prihandoko B. Pemanfaatan soda lime silica dalam pembuatan komposit elektrolit baterai lithium = Application of soda lime silica for the composite synthesis of lithium battery electrolyte. PhD Thesis, Universitas Indonesia: Depok; 2008.
- [4] Subhan A. Fabrikasi dan karakterisasi Li<sub>4</sub>Ti<sub>5</sub>O<sub>12</sub> untuk bahan anoda Baterai Lithium Keramik = Sinthesis and characterization of Li<sub>4</sub>Ti<sub>5</sub>O<sub>12</sub> as anode material for lithium ceramic battery. PhD Thesis, Universitas Indonesia: Depok; 2011.
- [5] Goriparti S, Miele E, De Angelis F, Di Fabrizio E, Zaccaria RP, Capiglia C. Review on recent progress of nanostructured anode materials for Li-ion batteries. J Power Sources. 2014;257:421–43.
- [6] Bedoya Hincapie CM, Pinzon Cardenas MJ, Alfonso Orjuela JE, Restrepo Parra E, Olaya Florez JJ. Physical-chemical properties of bismuth and bismuth oxides: synthesis, characterization and applications. Dyna (Medellin). 2012;79(176):139–48.
- [7] Li Y, Trujillo MA, Fu E, Patterson B, Fei L, Xu Y, et al. Bismuth oxide: a new lithium-ion battery anode. J Mater Chem A Mater Energy Sustain. 2013 Oct;1(39):12123–7.
- [8] Astuti Y, Aprialdi F, Haryanto I. Synthesis of activated carbon/ bismuth oxide composite and its characterization for battery electrode. IOP Conference Series: Materials Science and Engineering. IOP Publishing; 2019.
- [9] Xia N, Yuan D, Zhou T, Chen J, Mo S, Liu Y. Microwave synthesis and electrochemical characterization of mesoporous carbon@ Bi<sub>2</sub>O<sub>3</sub> composites. Mater Res Bull. 2011;46(5):687–91.
- [10] Wang S, Jin C, Qian W. Bi<sub>2</sub>O<sub>3</sub> with activated carbon composite as a supercapacitor electrode. J Alloy Compd. 2014;615:12–7.
- [11] Astuti Y, Musthafa F, Arnelli A, Nurhasanah I. French fries-like bismuth oxide: physicochemical properties, electrical conductivity and photocatalytic activity. Bull Chem React Eng Catal. 2022;17(1):146–56.
- [12] Astuti Y, Mei R, Darmawan A, Arnelli A, Widiyandari H. Enhancement of electrical conductivity of bismuth oxide/ activated carbon composite. Scientia Iranica In Press. 2022.
- [13] Wu C, Shen L, Huang Q, Zhang YC. Hydrothermal synthesis and characterization of Bi<sub>2</sub>O<sub>3</sub> nanowires. Mater Lett. 2011;65(7):1134–6.
- [14] Astuti Y, Andianingrum R, Wulansari AD, Haris A. The influence of precipitating agents on the morphological and photocatalytic properties of bismuth oxide. Adv Sci Lett. 2017;23(7):6521–3.
- Bartonickova E, Cihlar J, Castkova K. Microwave-assisted synthesis of bismuth oxide. Process Appl Ceram. 2007;1(1-2):29-33.

- [16] Das TR, Patra S, Madhuri R, Sharma PK. Bismuth oxide decorated graphene oxide nanocomposites synthesized via sonochemical assisted hydrothermal method for adsorption of cationic organic dyes. J Colloid Interface Sci. 2018 Jan;509:82–93.
- [17] Bandyopadhyay S, Dutta A. Thermal, optical and dielectric properties of phase stabilized  $\delta$ -Dy-Bi<sub>2</sub>O<sub>3</sub> ionic conductors. J Phys Chem Solids. 2017;102:12–20.
- [18] Sastrohamidjojo H. Dasar-dasar spektroskopi. UGM Press: Yogyakarta; 2018.
- [19] Zhang Y, Shao Q, Chen C, Jiang H, Su F, Hu Q, et al. Microwave-hydrothermal synthesis of beta-bismuth (III) oxide nanopowders and their enhanced photocatalytic properties. Powder Technol. 2020;370:226–36.
- [20] Astuti Y, Elesta PP, Widodo D S, Widiyandari H, Balgis R. Hydrazine and urea fueled-solution combustion method for Bi2O3 synthesis: characterization of physicochemical properties and photocatalytic activity. Bull Chem React Eng Catal. 2020;15(1):104–11.
- [21] Astuti Y, Amri D, Widodo DS, Widiyandari H, Balgis R, Ogi T. Effect of fuels on the physicochemical properties and photocatalytic activity of bismuth oxide, synthesized using solution combustion method. Int J Technol. 2020;11(1):26–36.
- [22] Astuti Y, Widiyandari H, Zaqia FA, Annisa L, Fajarwati RM, Hartinah S. Physicochemical characteristics and electrical conductivity of bismuth oxide/activated carbon composite. IOP Conference Series: Materials Science and Engineering. Vol. 1053. Issue 1. IOP Publishing; 2021. p. 012014.
- [23] Arsita Y, Astuti A. Sintesis Komposit TiO<sub>2</sub>/Karbon Aktif Berbasis Bambu Betung (*Dendrocalamus asper*) dengan menggunakan metode solid state reaction. J Fisika Unand. 2016;5(3):268–72.
- [24] Irmawati R, Nasriah MN, Taufiq-Yap Y, Hamid SA. Characterization of bismuth oxide catalysts prepared from bismuth trinitrate pentahydrate: influence of bismuth concentration. Catal Today. 2004;93701–709; Yang Q, Li Y, Yin Q, Wang P, Cheng Y.-B. Hydrothermal synthesis of bismuth oxide needles. Mater Lett. 2002;55(1–2):46–9.
- [25] Levin EM, Roth RS. Polymorphism of bismuth sesquioxide.
   I. Pure Bi<sub>2</sub>O<sub>3</sub>. J Res Natl Bur Stand A Phys Chem. 1964 Mar-Apr;68A(2):189-95.
- [26] Zhang L, Wang G, Xiong Z, Tang H, Jiang C. Fabrication of flower-like direct Z-scheme β-Bi<sub>2</sub>O<sub>3</sub>/g-C<sub>3</sub>N<sub>4</sub> photocatalyst with enhanced visible light photoactivity for Rhodamine B degradation. Appl Surf Sci. 2018;436:162–71.
- [27] Rouquerol J, Avnir D, Fairbridge C, Everett D, Haynes J, Pernicone N, et al. Recommendations for the characterization of porous solids (Technical Report). Pure Appl Chem. 1994;66(8):1739–58.