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CHARACTERISTICS AND PERFORMANCE ANALYSIS OF DIFFERENT GRAIN SIZES BAMBOO-ACTIVATED CARBONS FOR MOTORCYCLE FLUE GAS ADSORPTION

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Abstract

The use of fossil fuels in human activities such as motorcycles has led to an increase in the concentration emitted in the atmosphere. Various efforts and methods such as adsorption using activated carbon have been developed and applied to reduce the emission. Therefore, this study focuses on the characteristics and performance of bamboo-activated carbons in the adsorption of motorcycle flue gases. This was carried out using different grain sizes (z) of activated carbons AC-M1, AC-M2, and AC-M3 for grain sizes of $z \leq 250$, $250 < z \leq 420$, and $420 < z \leq 590$ microns, respectively, which were derived from swat bamboo and carbonized at a temperature of 750 °C. Furthermore, physical activation was applied by heating the charcoal at the same temperature under a nitrogen flow rate of 150 mL/min nitrogen. The Thermogravimetric (TGA), scanning electron microscopy (SEM), and adsorption isotherm tests were employed for the characterization of activated carbons. Additionally, the performances of activated carbons for motorcycle flue gas adsorption (CO_2, CO, and HC) were carried out by a motorcycle emission test. According to the results, activated carbon AC-M1 produced the best characteristics and performance for adsorption of motorcycle flue gas, as it has a pore volume of 0.135 cm^3/g, a specific surface area of 244.69 m^2/g, and a nitrogen adsorption capacity of 87.047 cm^3/g. These characteristics prove to have good adsorption efficiencies at 100 %, 87.30 %, and 100 % for adsorption of CO_2, CO, and HC, respectively.

Keywords: activated carbon, adsorption, flue gas, emission, swat bamboo.

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1. Introduction

The use of fossil fuels in human activities such as motorcycles [1] and coal-fired power plants [2], has increase CO_2 concentration in the atmosphere. Furthermore, CO_2 in the air causes significant problems because it is the main factor that leads to ocean acidification, global warming [3], rising global temperature, the greenhouse effect, and climate change [4, 5].

Increasing human activity in the economic sector demands high mobilization that requires transportation facilities such as motorized vehicles. The Association of Indonesia Automotive Industries (based on Indonesia Statistics Agency data) stated that the number of motorized vehicles

reached 133,617,012 units in 2019, which is a 5.3 % increase from the previous year. Motorbikes are the most common vehicles in Indonesia and continue to grow yearly with their number reaching 112,771,136 units in 2019 [6]. Furthermore, the number of motorbikes in Bali Province of Indonesia reached 4,352,596 units in 2019 which almost has a ratio of 1:1 with its total population (4.362 Million) [7]. Therefore, motorbikes contribute to the CO_2 content in Bali with such a high number. In addition to CO_2, burning fuel from motorized vehicles also produces other harmful pollutants such as NOx (nitrogen oxides), SO_2 (Sulfur dioxide), CO (carbon dioxide), and HC (hydrocarbon) [8].

The CO_2 capture and storage (CCS) technology is one of the various efforts that have been adopted to reduce the CO_2 concentration in the air [9]. One of the methods in this technology is adsorption, in which CO_2 gas is adsorbed on the surface of porous materials. The advantages of this method are low energy consumption, less volatile degradation [10], and does not corrode the equipment as in the chemical absorption method. It has lower production costs compared to the membrane method [11]. Furthermore, it uses various types of adsorbents such as activated carbon, zeolite, silica, and activated alumina.

In the CO_2 adsorption method, the proper characteristics of the adsorbent such as strong CO_2 selectivity, low affinity to impurities and moisture, and good regeneration ability [12], have a role in the optimization of CO_2 adsorption. Activated carbon, one of the adsorbents, is an amorphous material made from carbonaceous materials containing low ash and high carbon content [13]. Compared to zeolite, the activated carbon has higher adsorption capacity and energy density, and a lower affinity for water (hydrophobic material) [14], therefore it is commonly applied in CO_2 adsorption applications. The activated carbon has a high adsorption capacity due to its complex structure with high specific surface area and large pore volume. Furthermore, its quality is associated with the chemical composition of the precursor and the selection of proper parameters in its manufacturing processes. Basically, carbon-containing materials can be utilized as a source of activated carbon. Additionally, the cellulose and lignin contents of precursor have an important effect on the ultimate carbon content of activated carbon. Meanwhile, the manufacture of activated carbon typically consists of three steps: dehydration, carbonization, and activation. The dehydration aims to reduce the moisture content of precursor which can be carried out by drying under sunshine or in the furnace before being processed to the carbonization step. Subsequently, carbonization is conducted by heating at high temperatures (300−700 °C) [15] to release volatiles and increase fixed carbon of char by hydrolysis process of the biomass components in the absence of an oxygen environment. To obtain an activated carbon, the char from the carbonization process must go through an activation procedure, which can be done physically or chemically. In physical activation, the precursor is activated at an elevated temperature from 700−1000 °C [13] using nitrogen, carbon dioxide, or steam. The chemical activation is a process of impregnating the precursor with an activating agent such as H_3PO_4, H_2SO_4, KOH, and NaOH at the temperature range from 400–800 °C [13]. Furthermore, parameters such as the temperature, the heating rate and holding time during carbonization and activation, as well as the kind of activating agent used, all have a substantial effect on the activated carbon characteristics.

Generally, commercial activated carbons originate from coal and petroleum coke [16], unrenewable sources with decreasing availability. Therefore, studies have commenced investigation using alternative precursors such as biomass. Various studies described the use of biomass activated carbons for CO_2 adsorption before-mentioned as from sewage sludge [17], stevia residue [18], rice husk char [19], sugarcane bagasse [5], date palm tree [20], chestnut shell, walnut shell, and macadamia shell [21].

Furthermore, another promising biomass precursor is bamboo. Various publications that related the uses of bamboo as an activated carbon with varying applications have been released. These include supercapacitor electrodes [22–26], wastewater treatment [27], adsorption of benzene, toluene, o-xylene, and p-xylene [28], adsorption of nitrogen [29], and as a lithium-sulfur battery [30]. However, few references exploring the use of different grain size bamboo-activated carbon for simultaneous adsorption of motorcycle flue gases even though bamboos have a good chemical composition (20−26 percent lignin and 40−50 % percent alpha-cellulose) [31] and potency to produce a high quality of activated carbon. Therefore, in this work, the characteristics

of different grain size bamboo-activated carbons physically activated with nitrogen were investigated. Furthermore, the performances of the activated carbons in adsorption motorcycle flue gas (CO_2, CO, HC) were evaluated by motorcycle emission test.

2. Materials and methods

2. 1. Material

The swat bamboo (*Gigantochloa verticillata*) was used as a precursor and was obtained from Br. Pengaji, Melinggih Kelod Vilage, Payangan District of Gianyar Regency, Bali, Indonesia. As stated in a previous study, the chemical compositions of this bamboo consisted of 44.22 % cellulose, 22.99 % lignin, and 14.97 % hemicellulose [32]. Its proximate analysis contents were 7.93 % moisture, 87.80 % volatile, 2.02 % ash, and 2.25 % fixed carbon. Meanwhile, its ultimate analysis consisted of 43.42 % C, 6.14 % H, and 1.70 % N. Before the carbonization process, the bamboo was cut into small sizes, rinsed with distilled water, and dried in a muffle furnace until no weight change.

2. 2. Activated carbon production

2. 2. 1. Carbonization

The samples used in this study (small pieces of bamboo) were loaded into a stainless tubular reactor and entered into an electric programmable tubular furnace. Furthermore, they were carbonized at a temperature of 750 °C at a heating rate of 10 °C/min, maintained at that temperature for 1.5 hours, then cooled to a temperature of 30 °C. The chars produced were grounded in three different grain sizes (z) of $z \leq 250$, $250 < z \leq 420$, and $420 < z \leq 590$ microns.

2. 2. 2. Activation

The powdered chars were physically activated in the same furnace by heating to 750 °C over 1.5 h. Simultaneously, a steady nitrogen flow rate of 150 mL/min was applied to the reactor, which was kept for 1 hour and cooled in the furnace until it reached room temperature. The activated carbons generated were labeled as AC-M1, AC-M2, and AC-M3 with grain sizes of (z) of $z \leq 250$, $250 < z \leq 420$, and $420 < z \leq 590$ microns, respectively.

2. 3. Activated carbons characterization

2. 3. 1. Surface characterization

The surface characteristics of activated carbon such as pore volume, pore diameter, and specific surface area were measured using a Quantachrome Nova Machine-version 11.0 through a nitrogen adsorption isotherm test at a temperature of −265.85 °C. The BET (Brunauer-Emmett-Teller) method was used to calculate surface areas (S_{BET}). The total pore volume and S_{BET} were obtained directly from the data recorded in the nitrogen adsorption isotherm test. By inputting the adsorption isotherm data (p/po vs amount of nitrogen adsorbed), the pore size distribution was analyzed using a demo version of SAIEUS software (www.nldft.com/download/) based on the Carbon-N2, 2D-NLDFT heterogeneous surface model. Furthermore, using the Scanning Electron Microscopy (SEM) instrument JSM-651OLA, the image surface morphologies of activated carbons were examined.

2. 3. 2. TGA and Ultimate analysis of activated carbons

Thermogravimetric Analysis (TGA) used to measure the volatile, ash, moisture, and fixed carbon contents of activated carbon were evaluated using a TGA 701, 0.02 % RSD Precision machine. Meanwhile, the C, H, and N contents of activated carbons (ultimate analysis) were detected using a CHN628S elemental determination machine.

2. 4. Experimental procedures

The procedure of the experiment is illustrated in **Fig. 1** which shows that gas emissions from motorcycle exhausts (4 strokes gasoline-fueled motorcycle 'XYZ' assembled in 2017), were stored in a gasbag. Gas is pumped through the flow meter and flows to the multi-gas analyzer (Capalec, Cap 3201 series, H-TECH) at a constant rate of 500 cm^3/min. The composition of flue gas

emissions detected and read in the multi-gas analyzer was recorded and stored. Furthermore, the sample (activated carbon AC-M1) was also put in a glass tube. By adjusting the valve, the gas was routed into the glass tube while recording the flue gas passing. The tests were repeated three times with the same steps on the activated carbons AC-M2 and AC-M3.

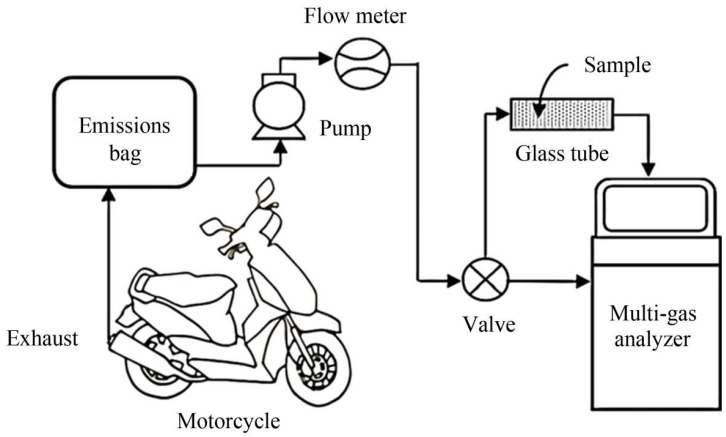


Fig. 1. Experimental set up

The adsorption performance of activated carbons on motorcycle exhaust gases is determined based on their adsorption efficiency. As shown in (1), the adsorption efficiency (Ads_{eff}) was calculated as the difference between the measured amount of gas without and with activated carbon (Ads_1) divided by the measured amount of gas without activated carbon (Ads_O) multiplied by 100 percent:

$$Ads_{eff} = \frac{Ads_O - Ads_1}{Ads_O} \times 100\,\%. \quad (1)$$

3. Result and discussions

3. 1. Proximate and ultimate analysis of precursor, char, and activated carbons

Tables 1, **2** show the results of the proximate and ultimate analyses of raw material, char, and activated carbon. It shows that fix carbon of bamboo increased from 2.25 % to 69.23 % after carbonization and 71.19 to 72.74 % after activation. Therefore, heating at high temperature during carbonization causes thermal decomposition where volatile gaseous of the precursor was released resulting in a significant increase in fixed carbon of char i.e. char with lower volatile and higher fixed carbon. The fixed carbon showed no gradual increase during activation because the most volatile was released during carbonization and small parts during activation, as shown in **Table 1**.

Table 1
Proximate analysis

Samples	Proximate composition (%)			
	Moisture	Volatile	Ash	Fix carbon
Swat bamboo	7.93	87.8	2.02	2.25
Char	7.88	8.56	14.36	69.23
AC-M1	8.82	6.59	13.40	71.19
AC-M2	9.04	6.99	11.23	72.74
AC-M3	8.03	7.06	13.41	71.50

The C content of swat bamboo is 43.42 %, with a close range to the carbon content of other bamboos as stated by various studies [29, 33–36]. The increase of the C content of bamboo after carbonization (char) and activation (activated carbons) is proportional to their fixed carbon contents. In this study, the different grain sizes of activated carbons did not gradually affect

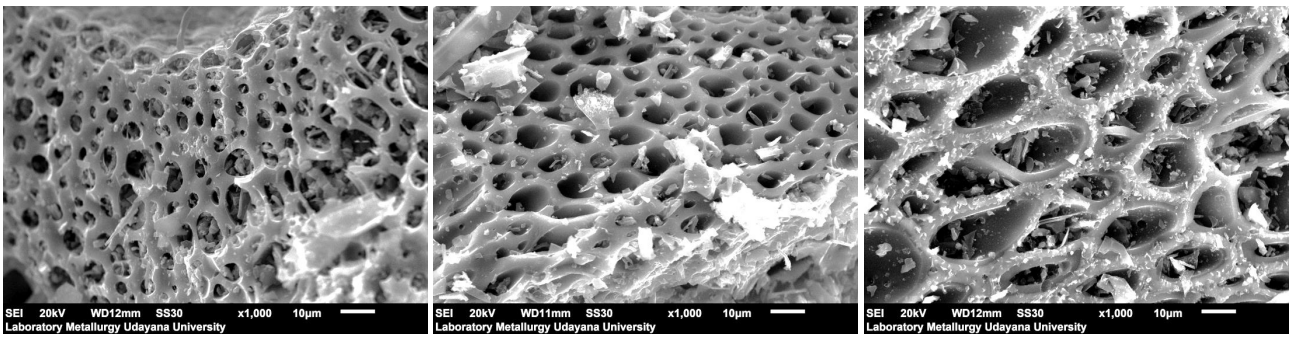
the contents of fixed carbon and carbon. The different grain sizes (small to bigger sizes) cause the fixed carbon and carbon contents of activated carbons to fluctuate. The highest fixed carbon (72.72 %) and carbon (74.14 %) contents were obtained by AC-M2.

Table 2
Ultimate analysis

Samples	Ultimate components (%)		
	C	H	N
Swat bamboo	43.42	6.14	1.70
Char	71.21	1.27	0.77
AC-M1	72.46	1.57	4.64
AC-M2	74.14	1.70	3.61
AC-M3	73.01	1.65	3.96

3. 2. Surface morphology of activated carbons

Fig. 2 shows SEM images that illustrated the surface morphology of three different grain sizes of activated carbons. These images show that the activated carbons porosities have been formed after carbonization and activation processes. Therefore, the smaller the grain size, the narrower the pore diameter of activated carbon. The activated carbon AC-M1 has more pores with smaller pores sizes compared to activated carbons prepared with the higher grain sizes (AC-M2 and AC-M3), indicating that AC-M1 releases more volatile gaseous [37] compared to AC-M2 and AC-M3, as shown in **Table 1** (AC-M1 has the lowest volatile content).



a *b* *c*

Fig. 2. SEM image of activated carbons: *a* – AC-M1; *b* – AC-M2; *c* – AC-M3

The cross-sections of the activated carbon pores are irregular and non-uniform, as shown in **Fig. 2**. Some are oval or rectangular in shape, but the majority is irregular. Pore shapes are also irregular in the longitudinal direction. Some are cylindrical, some are bottlenecks, and the majority is irregular. The cylindrical pores outperform the bottle neck because the bottle neck can impede the smooth adsorption and desorption of adsorbate molecules into the pore due to the narrowing of the pore's neck. Based on this, AC-M1 has the potential to have pores that are mostly cylindrical in shape because it has the highest absorption ability compared to AC-M2 and AC-M3, as shown in **Tables 4**, **5**.

3. 3. Adsorption isotherm of activated carbons

Fig. 3 shows the adsorption isotherm curves of three different grain sizes of activated carbons representing the relationship between the quantity of nitrogen adsorbed and the relative pressure (p/po). According to the IUPAC classification of adsorption isotherms-1985 [38], the curves of AC-M1 and AC-M3 are close to Type I and the curve of AC-M2 is close to type II. Furthermore, at a relative pressure of 0.25, the shapes of the curves indicate the end of adsorption at the first layer. Therefore, the form of curves at the relative pressure less than 0.25 shows existing of micropores in the samples and conformed at the PSD, as shown in **Fig. 4**.

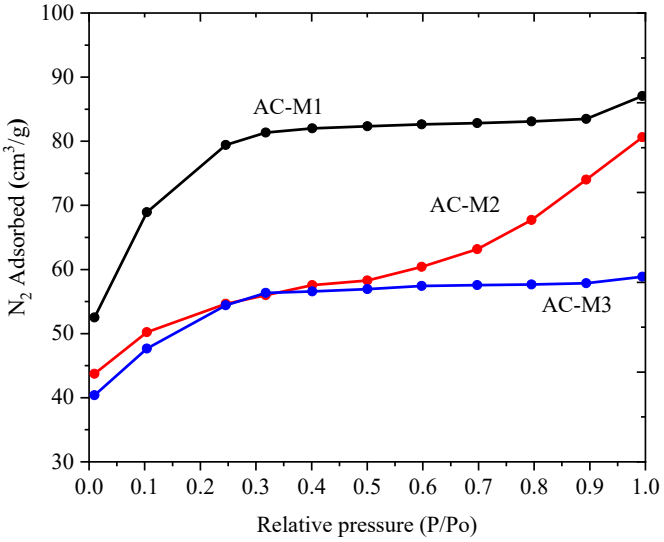


Fig. 3. The activated carbon adsorption isotherm

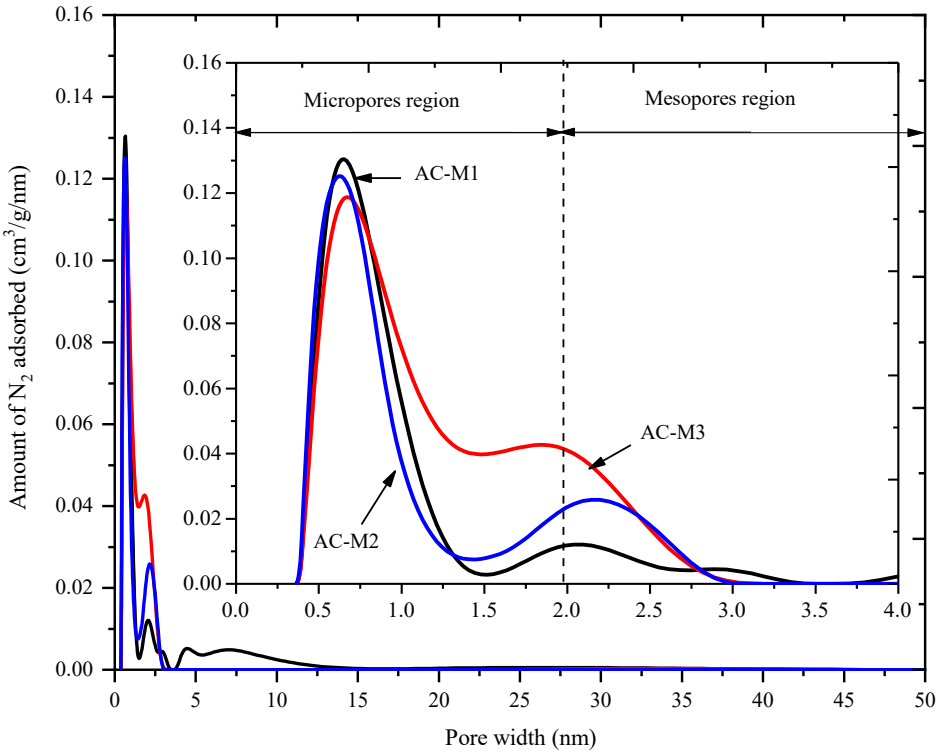


Fig. 4. Pore size distribution of activated carbons

Adsorption on micropores is a full filling process, and when the pore surface is covered by adsorbate molecules, a single layer of adsorption forms, as shown in **Fig. 3** below a relative pressure of 0.025. Following that, a multilayer adsorption process takes place, which is characterized by a flat curve on the AC-M1 and AC-M3 curves and a concave line on the AC-M2 curve. This suggests that adsorption takes place in the mesopore.

3. 4. Pore size distribution

Fig. 4 shows the pore size distribution of different grain size activated carbons which are represented by curves showing the volume of nitrogen adsorbed at different pores sizes. This indicates that activated carbons have heterogeneous structures and constitute one of the factors

influencing the characteristic adsorption of activated carbon [39]. Adsorption only occurs if the molecule size of adsorbate is the same or less than the diameters of the pores of activated carbon. AC-M1 has bimodal pores distribution pattern (the curve has two adsorption peaks), AC-M2 and AC-M3 have multi-modal distribution patterns (the curves have more than two adsorption peaks) and spread in micropores region with pores less than 2 nm and mesopores region with pores size between 2−50 nm. Therefore, PSD in both areas is associated with the molecule movement and the adsorption efficiency on activated carbon [40].

3. 5. Surface structures of activated carbons

Table 3 depicts the surface structure of activated carbon, with specific surface area, pore volume, and pore width ranging from 110.389–244.692 m^2/g, 0.085–0.013 cm^3/g, and 2.201−6.201 nm, respectively. In this case, the different grain size of activated carbons influences the pore volume, specific surface area, pore diameter of activated carbon. The smaller the grain size, the higher the specific surface area and pore volume but the lower pore diameter of activated carbons. This shows that AC-M1 with the smallest grain size has the highest surface area of 244.692 m^2/g and pore volume of 0.135 cm^3/g. Therefore, it has the highest capacity for nitrogen adsorption.

Table 3

Surface structures of activated carbons

Activated carbons	Specific surface area, S_{BET}, (m^2/g)	Pore volume, *Vp*, (cm^3/g)	Pore width, *Dp*, (nm)	Amount of N_2 adsorbed, (cm^3/g)
AC-M1	244.692	0.135	2.201	87.048
AC-M2	209.282	0.093	3.347	80.645
AC-M3	110.389	0.085	6.560	58.874

3. 6. Adsorption performance of activated carbon

Table 4 shows the composition of motorcycle flue gases with (AC-M1, AC-M2, AC-M3) and without activated carbons (N-AC). It shows that the use of activated carbons reduces CO, CO_2, and HC contents, indicating that the adsorption of flue gases works well on the activated carbons. Furthermore, the smaller the grain size of activated carbons, the higher capacity in the flue gases adsorption. The AC-M1 is capable of reducing the content of CO, CO_2, and HC from 0.21 % to 0.03 %, from 0.87 % to 0 %, and from 26.33 ppm to 0 ppm, respectively. The adsorption efficiencies of this activated carbon are 87.03 %, 100 %, and 100 % for adsorption of CO, CO_2, and HC, respectively as shown in **Table 5**. This indicates a strong relationship between the surface characteristic and the adsorption capacity of activated carbons. Therefore, activated carbon with a smaller grain size has a higher surface area, pore-volume, nitrogen adsorption capacity, and capacity for adsorption of CO, CO_2, and HC, as shown in **Tables 3**, **5**.

Table 4

The measured of motorcycle flue gases

Flue gases	Activated carbons			
	N-AC	AC-M1	AC-M2	AC-M3
CO (%)	0.21	0.03	0.15	0.17
CO_2 (%)	0.87	0	0.50	0.63
HC (ppm)	26.33	0	8.00	12.33
CO_2 (%)	20.77	22.47	19.50	17.90

Table 5
Adsorption Efficiency of motorcycle flue gases

Flue gases	Adsorption efficiencies (%)		
	AC-M1	AC-M2	AC-M3
CO	87.30	26.98	17.46
CO_2	100	42.53	27.20
HC	100	69.62	53.16

Previous studies show that bamboo activated carbon physically activated with a nitrogen flow rate of 350 mL/min (AC-350N_2) had an adsorption efficiency of 100 %, 85.71 %, and 83.41 % each for adsorptions of CO_2, CO, and HC, respectively [41]. Various studies state the adsorption efficiency of motor vehicle flue gases as shown in **Table 6**.

Table 6
Various study of adsorbents performance for adsorption of motor vehicle flue gases

Samples	Adsorption efficiencies (%)				References
	CO	CO_2	HC	SO_2	
Swat bamboo Activated Carbon (AC-M1)	87.3	100	100	–	This work
Swat bamboo (AC-350N_2)	85.71	100	83.41	–	[41]
Banana peels activated carbon	100	–	–	100	[42]
Activated alumina	–	7.6	–	–	[43]
Activated alumina	–	9.26	–	–	[44]
Cocos nucifera-activated carbon	60.9	–	67.03	–	[45]
Mauritia flexuosa-activated carbon	54.3	–	63.5	–	[45]
Durian peel activated carbon (with a 70:30 MgO:AC ratio)	99.14	–	87.73	–	[46]

It can be seen that activated carbon produced in this study (AC-M1) has a higher adsorption capacity for CO_2 and HC than all activated carbons except activated carbon from swat bamboo (AC-350N_2). However, it has a lower CO absorption capacity than activated carbon derived from banana peels and durian peels.

3. 7. Limitations and direction for further development of the research

Activated carbon is known to have a complex pore structure and a high level of imperfection, making it difficult to characterize using chemical analysis or structural formulation. To obtain suitable characteristics for a particular application, experimentation is required. This research is still on a laboratory scale and has practical limitations [47]. An activated carbon container with a special design is required to avoid interfering with the vehicle's function and aesthetics, which will be interesting to research in the future. Furthermore, more research on life time and ways to regenerate activated carbon easily and cheaply is required, so that technical, service life, and economic aspects are thoroughly investigated before being applied.

4. Conclusions

This study found that the different grain sizes of activated carbons possess various surface characteristics and adsorption capacity. The smaller the grain sizes of activated carbons, the better their properties and adsorption capacity. AC-M1, with a grain size of fewer than 250 microns, has the best characteristic, with a specific surface area of 244.692 m^2/g, pore volume of 0.135 cm^3/g, a pore diameter of 2.201 nm, and nitrogen adsorption capacity of 87.048 cm^3/g. Due to these

characteristics, AC-MI has the best performance in the adsorption of flue gases (CO, CO_2, and HC) of a motorcycle compared to activated carbons (AC-M2 and AC-M3) which have a greater grain size. The adsorption efficiencies of AC-M1 were 100 % for CO_2 and HC and 87.5 % for CO. Therefore, indicating clearly that smaller grain sizes swat bamboo activated carbon has promising potency for flue gas motorcycle adsorption.

Conflict of interest

The authors declare that there is no conflict of interest in relation to this paper, as well as the published research results, including the financial aspects of conducting the research, obtaining and using its results, as well as any non-financial personal relationships.

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