

Engine Emission and Noise Reduction Using Organic Waste-based Activated Carbon Filters: A Case Study on Motorcycles

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Engine Emission and Noise Reduction Using Organic Waste-based Activated Carbon Filters: A Case Study on Motorcycles

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ABSTRACT

The increasing number of motorcycles in developing countries such as Indonesia has intensified air and noise pollution, while large quantities of agricultural waste remain underutilized. This study investigates the feasibility of converting agricultural residues into activated carbon filters for simultaneous reduction of motorcycle exhaust emissions and noise. Activated carbon filters were fabricated from three abundant biomass wastes, namely peanut shells, palm fiber, and durian peels, and installed on a 110 cc motorcycle exhaust system. The effects of biomass precursor and chemical activating agents (H_3PO_4 , KOH , and $NaCl$) on carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbon (HC), and exhaust noise were experimentally evaluated under idle operating conditions. The results demonstrate that all biomass-derived activated carbon filters reduced exhaust emissions and noise compared with the unfiltered exhaust. Peanut shell-based activated carbon exhibited the highest performance for reducing CO and HC emissions, whereas durian peel-derived activated carbon achieved the

greatest reduction in CO₂ emissions. Among the investigated activating agents, KOH produced the highest adsorption performance owing to its ability to generate a more developed porous carbon structure. In addition, palm fiber-based activated carbon provided the greatest reduction in exhaust noise due to its porous acoustic-damping properties. These findings demonstrate that agricultural waste-derived activated carbon can serve as a low-cost and environmentally sustainable alternative for simultaneous exhaust emission control and noise attenuation, while promoting the valorization of agricultural residues within a circular economy framework.

Keywords: Carbon Filter, Exhaust Gas Emission, Natural Waste Material, Noise Pollution

1. Introduction

The increasing use of technology, especially in the automotive sector, is a result of the country's economic development. As a result, the number of vehicles is rising every year, becoming a concern for all groups (Tran et al., 2021). The reason for this increase is the need for people to use motorized vehicles for their daily transportation. In 2020, Indonesia ranked 9th globally for the highest air pollution levels, with levels dangerous to sensitive groups (Air, 2021). The number of motorized vehicles that continues to increase has caused serious problems, including higher fuel consumption and the rise of air pollution from exhaust emissions. The percentage of air pollution caused by motorized vehicles is 70-80%, while pollution from industry and other sources accounts for only 20-30%. (Rao et al., 2017) showed that motor vehicle exhaust emissions are a form of air pollution. Exhaust emissions contain hazardous substances such as carbon monoxide (CO), various hydrocarbons (HC), nitrogen oxides (NO_x), sulfur (SO_x), and lead (Pb) (Saleem, Zaidi, Ismail, & Goh, 2022; W. Wang et al., 2022; Yewale et al., 2022). The effects of air pollution are a major public health concern, including pneumonia and respiratory infections, particularly in industrialized countries where factories and motor vehicles are prevalent and closely tied to daily human activities. High levels of air pollution make the air unsafe for people, leading to strokes, cardiovascular disease, heart problems, and serious health issues for vulnerable groups such as pregnant women, the elderly, and children (Hua et al., 2017; Shen, Wang, Lin, Wu, & Horng, 2014). In addition to producing air pollution, vehicles also provide noise pollution, which can negatively affect (Gwenzi, Chaukura, Wenga, & Mtisi, 2021). Noise can cause disturbances in comfort, health, and even deafness (Patella, Aletta, & Mannini, 2019). Noise can lead to psychological disorders such as irritation, anxiety, and fear. Psychological disturbance caused by noise depends on its intensity, frequency, duration, timing, and the complexity or irregularity of its spectrum. Health problems from noise include hearing loss, digestive issues, stress, headaches, increased blood pressure, and reduced work performance (Stansfeld & Matheson, 2003). Noise pollution occurs when excessive noise enters the human environment. Loud sounds from industrial machines, cars, and airplanes can harm human health and lead to permanent hearing loss if continuously exposed for extended periods (X. Deng, Chen, Wang, Zhen, & Xie, 2018).

The significant negative effects of vehicles, such as exhaust emissions and noise, still require reduction. However, solutions like emission control technology—including modifications to exhaust piping, engine tuning, and adjustments to fuel or fuel systems—can help address these issues (Morillas, Gozalo, González, Moraga, & Vélchez-Gómez, 2018; Rabe et al., 2022). To reduce emissions of harmful gases from vehicles, one approach is to modify

the exhaust system by adding a filter or filters. Filtering combustion gases before they are released into the environment helps lower the emission of harmful gases produced by the vehicle. Catalytic converters are commonly used to filter vehicle emissions, but they are expensive because they contain platinum and palladium. Besides reducing exhaust emissions, the filter can also help decrease noise. Synthetic polymer materials derived from petroleum residues still dominate the filters used in air filtration systems. However, the raw materials of these synthetic polymers contain many toxic chemicals, are not easy to process, and can potentially cause cancer (Bao et al., 2016). Therefore, there is potential to replace the filter material with natural materials readily available in Indonesia (Azis, Kristanto, & Purnomo, 2021). Examples of filters made from natural ingredients are activated carbon from natural fibers such as palm fiber waste, durian peel, and banana midrib (Bhatnagar & Sillanpää, 2010). Therefore, research using activated carbon remains encouraged. Activated carbon is carbon with an amorphous or polycrystalline structure whose main component is free carbon, which is usually obtained by unique processes and has a high absorption capacity (Marsh & Reinoso, 2006). In general, there are two types of activated carbon: liquid-phase activated carbon and gas-phase activated carbon. Liquid-phase activated carbon is made from low-density materials, such as charcoal from yellow bamboo, which is granular, brittle, and rich in silica ash. It removes odors, tastes, colors, and other organic pollutants; gas-phase activated carbon is made from high-density materials. The activated carbon process involves several steps, including drying (dehydration) and carbonation, which activate the carbon. The carbonation process helps remove volatile substances from the material (Sethupathi, Bashir, Akbar, & Mohamed, 2015; Soffian et al., 2022). Carbonation is performed using a furnace. Activated carbon is usually found in fibrous materials like wood and leather, but other carbon-containing materials such as bones, grains, coal, and others can also be used. Activated carbon has delicate pores on its surface to absorb gases. These pores open after the activation process (H.-J. Kim et al., 2017; X. Song, Ma, Li, Ding, & Jiang, 2019).

Variations of activators produce different absorption capacities. The activation process on activated carbon aims to remove substances that cover the pores on its surface, thereby increasing the volume of the carbon pores. Activation usually uses alkali metal hydroxides, carbonate compounds, sulfides, ZnCl_2 , sulfuric acid, phosphoric acid, and sodium chloride dehydrating agents. H_3PO_4 , NaCl , and KOH are chemical substances that can be used as activated carbon activators. H_3PO_4 , or phosphoric acid, is widely used as an activator for various lignocellulosic materials, such as agricultural waste and fruit peels. Research related to the use of H_3PO_4 as an activated carbon activator has been widely carried out because the

process of neutralizing activated carbon is easy enough to use water, and the nature of phosphoric acid, which does not pollute the environment (Foo & Lee, 2010). KOH is used as an activator of activated carbon because it can react with carbon and belongs to the strong base group, so it can remove substances that cover the carbon pores, opening and expanding them, thereby increasing its microporosity. NaCl can be used as an activator because it can act as a dehydrating substance on carbon, limiting the formation of tar during the carbonation process, which can close the carbon pores (J.-Y. Kim et al., 2016; Naveenkumar, Kumar, Pushyanthkumar, & Kumaran, 2020).

Building on this background, the goal of this research is to develop activated carbon filters using waste materials to reduce exhaust emissions and noise pollution in Indonesia. The focus is on creating filters with three waste materials: peanut shells, palm fibers, and durian peels. The aim is to lower exhaust emissions—specifically CO, CO₂, and HC. Additionally, this study will examine the effect of these activated carbon filters from peanut shells, palm fibers, and durian peels on noise levels. The production process will involve different carbon activators, and the study will explore how various activated carbon activators influence waste-based filters in reducing exhaust emissions (CO, CO₂, and HC), as well as how they affect noise levels from motor vehicle exhausts.

2. Materials and Methods

2.1. Material Preparation

Figure 1 describes the processing of peanut shells, durian peels, and palm frond waste into powder form for making air filters using these waste materials as the main components. The process includes several steps. First, the raw materials, such as peanut shells, durian peels, and palm frond waste, are collected and sorted. They then go through a cleaning stage to remove impurities and foreign particles. After cleaning, the raw materials are processed with specialized machinery or techniques to grind them into fine powder. This powder is then used as the main material for making air filters. The selection of these waste because the waste contains ingredients that can be used to make activated carbon (Chandra, Mirna, Sunarso, Sudaryanto, & Ismadji, 2009; Martini et al., 2012; Raju, Kumarappa, & Gaitonde, 2012), The composition of the waste was shown below:

- a. Peanut shell waste contains 9.5 vol. % water, 35.7 vol. % cellulose, 18.7 vol. % hemicellulose, and 30.2 vol. % lignin.
- b. Palm waste contains 22.1 vol. % cellulose and 14.3 vol. % hemicellulose

- c. Durian peel waste contains 50% - 60 vol. % carboxymethylcellulose and 5 vol. % lignin.

These chemical components can absorb carbon from motorcycle exhaust gases. Besides containing various chemicals capable of binding carbon, this waste was chosen because of the buildup of peanut shell waste, palm sugar waste, and durian peel around the Surakarta city area. If this waste is allowed to accumulate, it could cause environmental pollution.

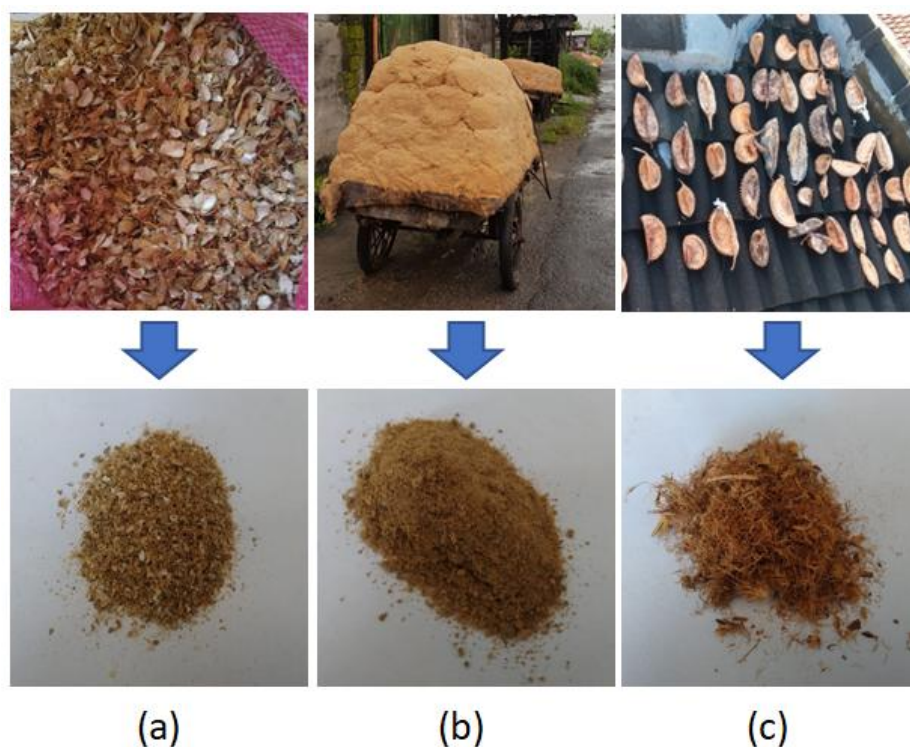


Figure 1. Waste material (a) peanut shell, (b) palm fiber waste, and (c) durian peel waste

This study used peanut, palm, and durian waste because these wastes contain substantial amounts of cellulose and lignin, which can be used to produce activated carbon. To make an activated carbon-based air filter, the material must be prepared and assembled into a filter. In this experiment, we used commercial phosphoric acid (H_3PO_4) at 10% concentration. There are 9 steps to activate the activated carbon in the waste material. This preparation to activate the carbon has also been studied by (Hayashi, Horikawa, Takeda, Muroyama, & Nasir Ani, 2002; Lillo-Ródenas, Cazorla-Amorós, & Linares-Solano, 2003; Lozano-Castelló, Lillo-Ródenas, Cazorla-Amorós, & Linares-Solano, 2001; Suhas, Carrott, & Ribeiro Carrott, 2007; Teng, Yeh, & Hsu, 1998; Yagmur, Ozmak, & Aktas, 2008) :

- a. Begin with chopping the filter material—peanut shells, palm fiber, and durian peel—into tiny grains. These grains are filtered through a 16-mesh screen to achieve a uniform grain size.

- b. Conduct the waste material carbonation process in a furnace set at a temperature of 350°C for 2 hours, utilizing air as the carrying gas (comprising 79% N₂ and 21% O₂). This process aims to convert the waste material into carbon while releasing volatile elements.
- c. Upon completion of the carbonation process, initiate the activation phase by soaking the carbon material in a 10% solution of phosphoric acid (H₃PO₄) for 24 hours. This activation process removes hydrocarbons, tar, and other organic materials from the carbon. H₃PO₄ is selected for its strong covalent bonds and its ability to increase the pore volume of the carbon material.
- d. After the 24-hour soaking period, rinse the activated carbon thoroughly with distilled water to neutralize its pH.
- e. Subsequently, dry the activated carbon in an oven at 110°C for 4 hours, maintaining ambient air conditions. This drying process aims to minimize the impact of water content on the carbon material (Yuliusman, Sinto, Nugroho, & Naf'an, 2018).
- f. Prepare the adhesive dough by combining tapioca flour and water in a mass ratio of 1:5 to create the adhesive that will bind the prepared waste material.
- g. Combine the sticky dough with the activated carbon charcoal obtained from the waste material in a mass ratio of 6:4 (Heidarinejad et al., 2020).
- h. Form the filter using a filter mold under a pressure of 50 kg/cm², shaping it with a diameter of 4.5 cm and a height of 2 cm. The filter design includes seven 4-mm-diameter holes, as depicted in Fig. 2.
- i. Dry the finished filter in the sunlight until it solidifies. This drying process occurs at temperatures around 29-32°C, with approximately 85% humidity and an average wind speed of 10 km/hr. The drying duration spans 3 days from 09:00 to 15:00 (GMT+7).

These meticulous steps outline the procedure for activating the carbon within waste materials to create effective filters that mitigate exhaust emissions and noise pollution. **Figure 2** illustrates the waste processing being fed into a molding apparatus. This molding device not only processes the waste material but also forms multiple air inlet passages by creating perforations. Furthermore, the image provides dimensional details of the finalized printed filter, including size, thickness, and other specific measurements relevant to the produced air filter.

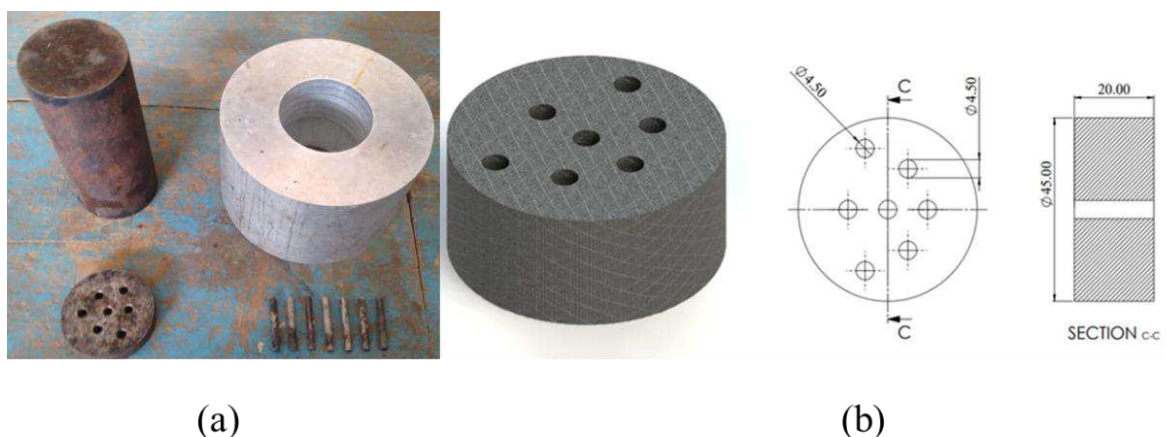


Figure 2. Design the active carbon filter (a) filter molds and (b) active carbon filter

Figure 3 depicts a waste-based activated carbon filter prepared for testing on motorcycles. While our experiment did not analyze the pore structure and size of our filter, previous research has examined the pore structure of activated carbon filters derived from waste materials. Researchers have used a scanning electron microscope (SEM) to examine the surface morphology of solid particles using an electron beam. The SEM provides high-definition imaging and precise particle-size measurements, enabling chemical and elemental analysis of the sample. Moreover, energy-dispersive X-ray spectroscopy (EDS) is used to analyze the obtained data. This method allows analysis of each element based on its peak in the X-ray emission spectrum resulting from X-ray excitation. **Figure 4** illustrates the SEM image results of the activated carbon filter, and **Table 1** shows the element analysis results from EDS. The elemental carbon active filter based on peanut shell raw materials was reported by (S. Wang, Nam, & Nam, 2020), palm fiber by (Daud & Ali, 2004), and durian peel by (Chandra et al., 2009). Subsequently, these activated carbon filters are assembled into a unified component, as depicted in **Figure 5**. Notably, this filtration system has been patented in Indonesia with the registration number S00202201196. Its key advantage lies in its ease of installation and removal for various types of motorcycle exhausts, facilitating straightforward filter replacements.

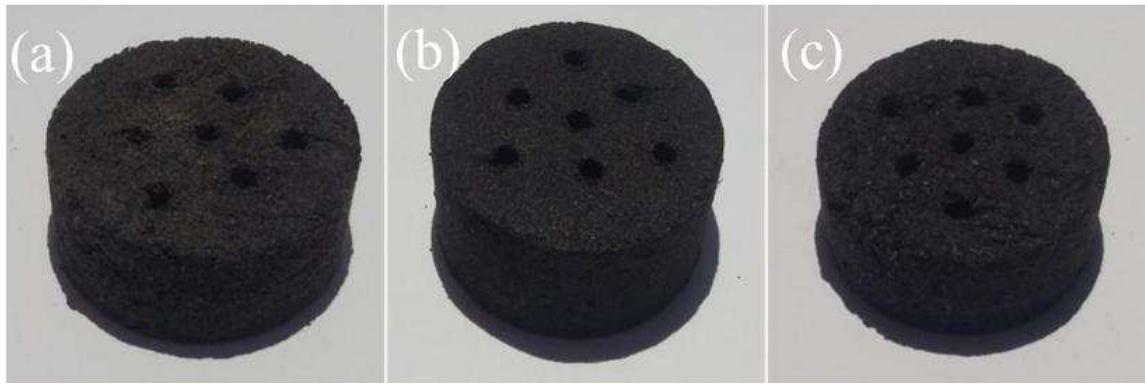


Figure 3. Active carbon filter (a) peanut shell, (b) palm fiber waste, and (c) durian peel

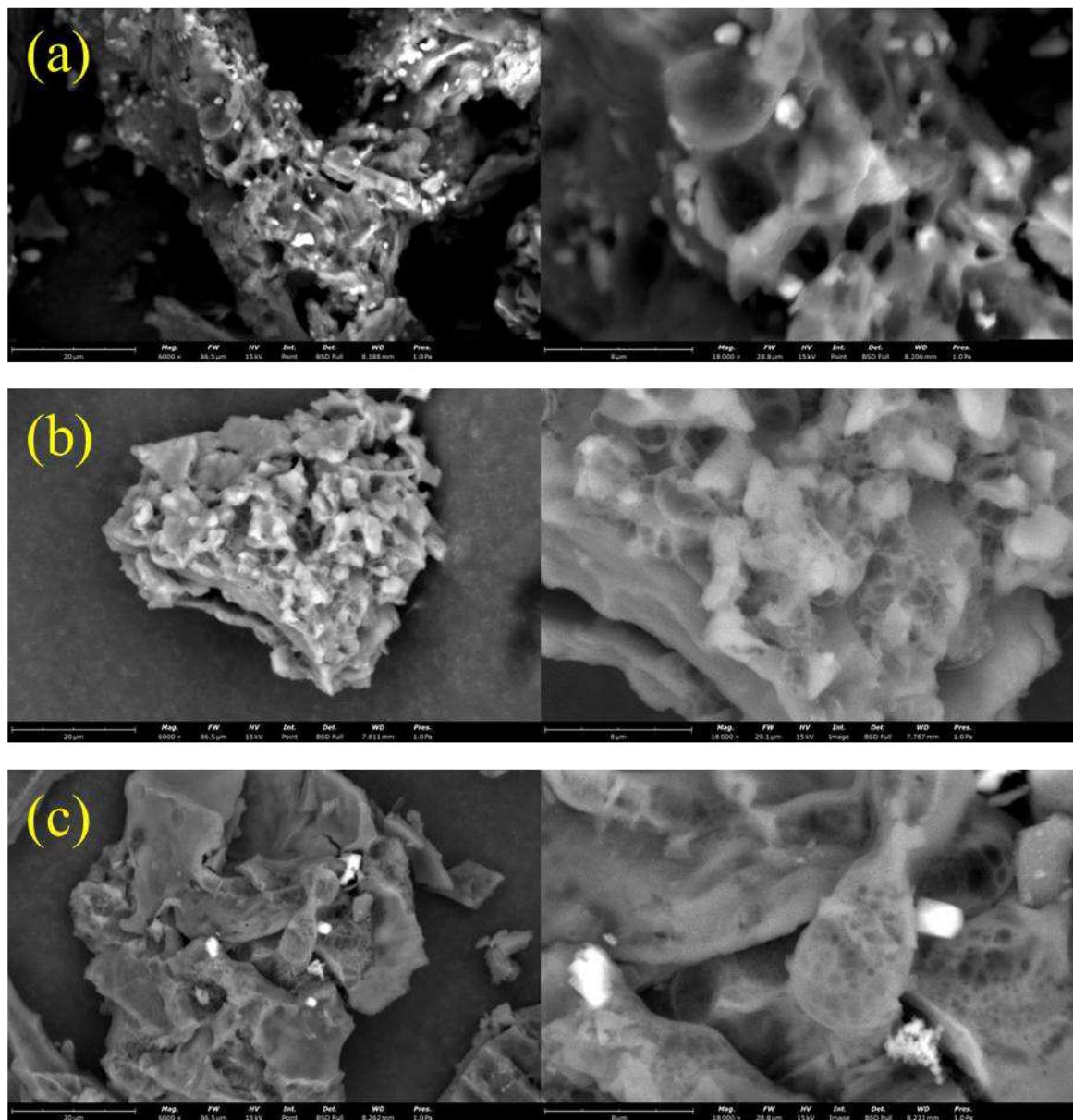
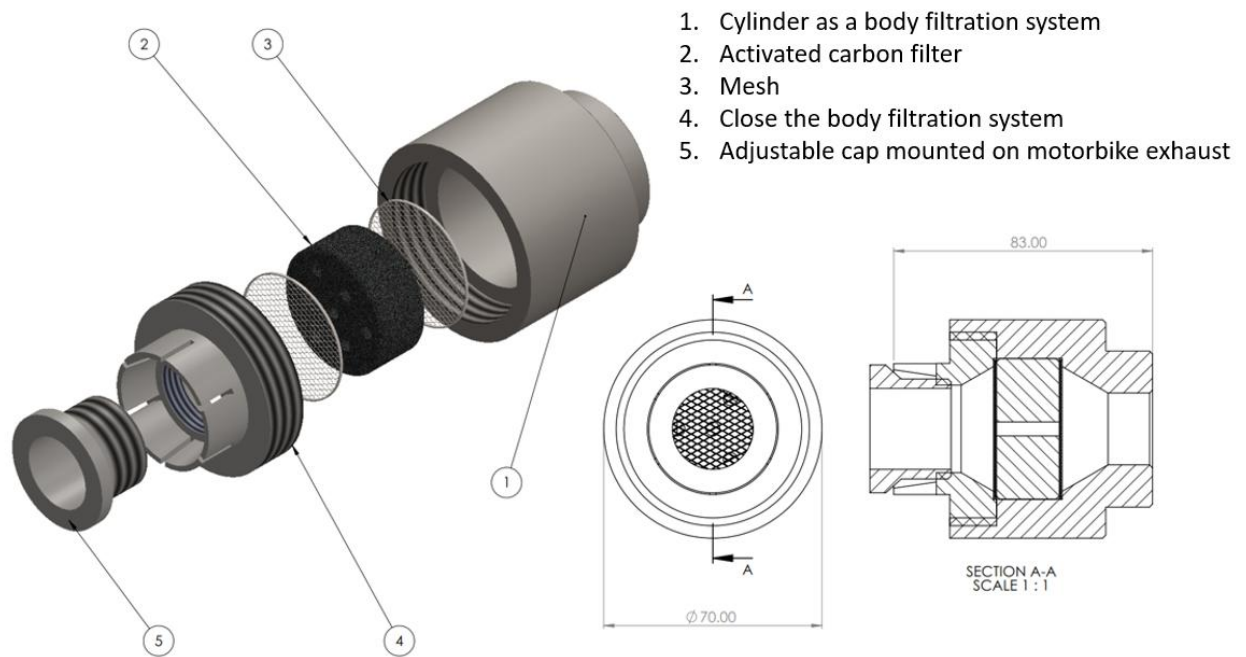


Figure 4. SEM image result for active carbon filter (a) peanut shell, (b) palm fiber waste, and (c) durian peel

Table 1. Element analysis from the carbon active filter

Waste Material	Element Analysis (%)			
	C	N	O	P
Peanut Shell	64.608	1.5	30.473	3.328
Palm Fiber Waste	62.638	7.546	28.295	1.52
Durian Peel	68.883	5.924	23.761	1.431

**Figure 5.** Filtration system and dimension

2.2. Experimental Setup

Figure 6 Show the experimental setup used to assess the impact of different waste-based active carbon filters on motorcycle emissions and noise levels. The experimental setup used a 4-stroke internal combustion engine with a 110 CC SOHC valve mechanism, featuring a compression ratio of 9:1. The motorcycle used a carburetor fuel system with a piston diameter of 50 mm and a stroke of 55.6 mm. Additionally, it operated at a maximum power of 8.46 HP at 7500 RPM and a maximum torque of 0.86 kg·m at 5500 RPM.

The research was conducted under idle conditions (1500 RPM). The filtration system, comprising three variations of active carbon filters derived from peanut shells, palm fiber waste, and durian peel, was installed on the motorbike exhausts. To measure emission levels, an Iyasaka AET-4000Q gas analyzer (Meter Toledo, Ohio, U.S.A.) was employed. The gas

emissions targeted for measurement in this study included carbon monoxide (CO), carbon dioxide (CO₂), and hydrocarbons (HC).

Exhaust emission levels were measured for 1 hour, with data collected at 5, 15, 30, 45, and 60 minutes. These exhaust gas measurements were taken approximately 75 mm from the motorcycle exhaust. Exhaust gas emissions testing was conducted at the Department of Transportation in Surakarta City, Indonesia. Furthermore, noise data was collected using a sound meter, specifically the Sound Level Meter GM1356 (PCE Instrument, Southampton, UK). Noise measurements were taken for a duration of 10 seconds at a distance of 30 cm from the downstream end of the exhaust tip. The objective of the noise testing was to determine whether the addition of filters made from waste materials affected the motorbike's exhaust noise.

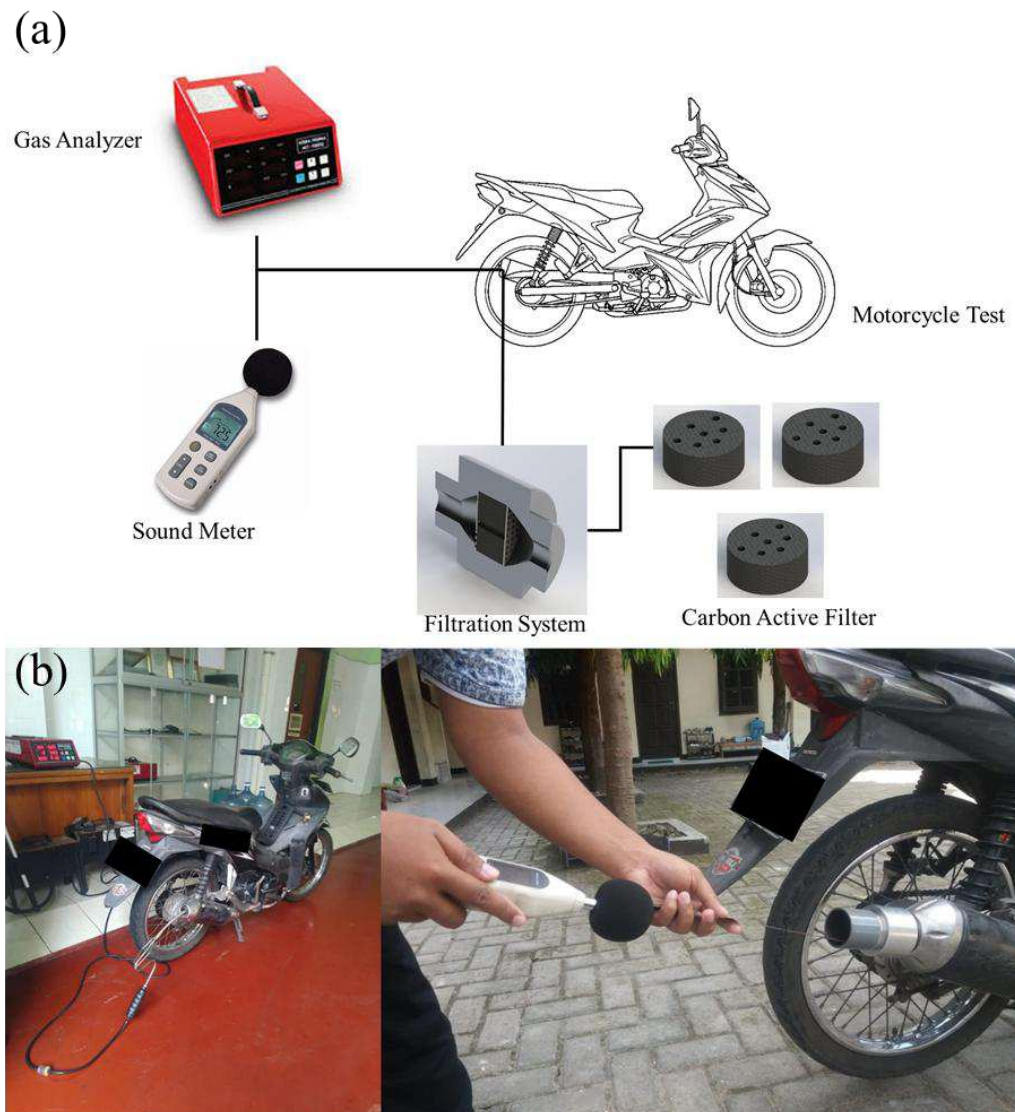


Figure 6. Experimental apparatus (a) schematic of the experimental apparatus and (b) measurement position of the exhaust gas emission and noise test

3. Results and Discussion

3.1. The effect of an active carbon filter with different materials

The experimental data were collected using various active carbon filters made from different materials, all connected to the motorcycle's exhaust outlet while in idle mode. Before conducting the experiment, a proximate analysis was performed to assess the quality of the active carbon. This analysis was carried out at the Integrated Research and Testing Laboratory, Universitas Gadjah Mada, Yogyakarta, Indonesia. **Table 1** presents the proximate analysis results for active carbon filters made from different materials. The study aims to determine the percentage composition of biomass, focusing on its chemical energy stored as fixed carbon and volatile chemicals, along with the inert fraction represented by ash and water content. Volatile matter, a component of the fuel, includes gases and vapors (such as hydrocarbons) released during the thermal decomposition of biomass (Perea-Moreno, Manzano-Agugliaro, Hernandez-Escobedo, & Perea-Moreno, 2018). Fixed carbon and ash are components that remain after volatile elements are released. Fixed carbon usually supports slow combustion after the volatiles are emitted. Ash refers to the inorganic residue left behind after burning fixed carbon, and its composition and amount can vary depending on the biomass source and collection method (Mata-Sánchez et al., 2013).

Table 2. Proximate analysis of active carbon filter

Proximate Active Carbon	Peanut Shell	Palm Fiber Waste	Durian Peel
Water Content (Wt. %)	5.89%	12.71%	10.67%
Ash Content (Wt. %)	21.67%	16.36%	12.32%
Volatile Content (Wt. %)	23.55%	26.33%	22.66%
Carbon Content (Wt. %)	48.85%	44.57%	54.32%

According to **Table 2**, the proximate analysis was performed following ASTM D3172–D3175, while the quality of the produced activated carbon was assessed based on the requirements outlined in SNI 06-3730-1995. The analysis showed that the produced activated carbons still contained moisture, ash, volatile matter, and fixed carbon, all of which are important indicators of activated carbon quality. The measured moisture contents were 5.89%, 12.71%, and 10.67% for peanut shell-, palm fiber-, and durian peel-activated carbons, respectively. These values are within the maximum moisture requirement of 15% as specified in SNI 06-3730-1995 (Indonesia, 1995). A low moisture content is preferred, as excessive water can occupy pore spaces, hinder pore development during activation, and limit access to

adsorption sites (Neme, Gonfa, & Masi, 2022). The ash contents of peanut shell-, palm fiber-, and durian peel-activated carbons were 21.67%, 16.36%, and 12.32%, respectively, exceeding the maximum limit of 10% outlined in SNI 06-3730-1995. Elevated ash content signifies the presence of inorganic minerals that may partially block pore openings, diminish the effective surface area, and consequently impair adsorption performance (Lemraski & Sharafinia, 2016).

The volatile matter contents of peanut shell-, palm fiber-, and durian peel-activated carbons were 23.55%, 26.33%, and 22.66%, respectively. Peanut shell and durian peel met the SNI limit of < 25%, but palm fiber slightly exceeded it. Volatile matter affects pore formation during carbonization, as the release of volatile compounds helps develop the pore network in activated carbon (Neme et al., 2022). The fixed carbon contents were 48.85%, 44.57%, and 54.32% for the three samples. While these values confirm successful carbonization, they are below the SNI minimum of 65%. Previous research indicates that higher fixed carbon and lower ash content improve sorbent properties by creating a stable carbon framework and well-developed porosity (Ogungbenro, Quang, Al-Ali, Vega, & Abu-Zahra, 2020). Overall, the activated carbons met the moisture content standard, and peanut shell and durian peel also satisfied the volatile matter requirement. However, all samples had high ash contents and lower fixed carbon than the Indonesian standards, suggesting that process optimization is necessary to enhance their physicochemical properties and adsorption capabilities.

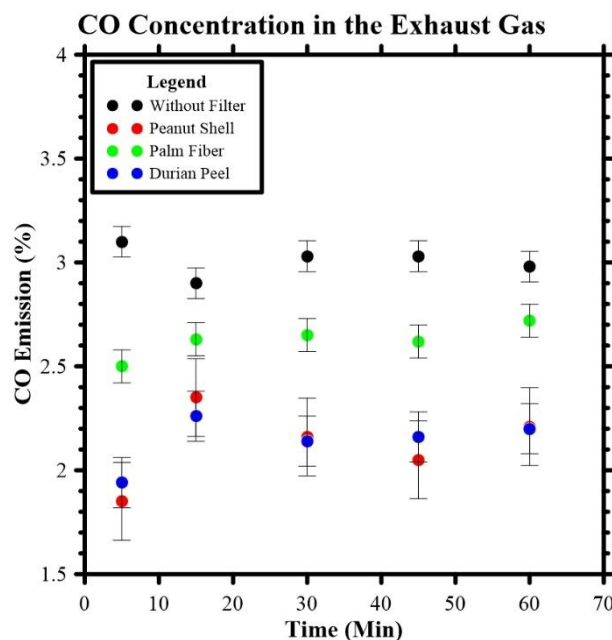


Figure 7. CO emission of the active carbon filter with different materials

Figure 7 illustrates the average CO emissions from the motorcycle over 60 minutes, with and without the active carbon filter. The findings demonstrate that without the active carbon filter, the CO emission level was approximately 3.01%. However, when utilizing the

active carbon filter, there was a notable reduction in CO emissions: 2.62% for the palm fiber filter, 2.14% for the durian peel filter, and 2.12% for the peanut shell filter. The results indicate that the peanut shell-based carbon filter outperforms the other filters in reducing CO emissions due to several factors. Primarily, the peanut shell filter exhibits the lowest water content among the three filters. This lower water content significantly influences CO absorption. Additionally, the peanut shell filter has larger pores, facilitating enhanced absorption of CO as it traverses them. Study from Lewicka (Lewicka, 2017) have highlighted the effectiveness of active carbon derived from peanut shell waste in absorbing carbon. Similarly, Deng et al. (S. Deng et al., 2015) Conducted experiments utilizing active carbon derived from peanut shell waste material for carbon capture, further supporting the efficient CO absorption capacity of peanut shell-based active carbon filters.

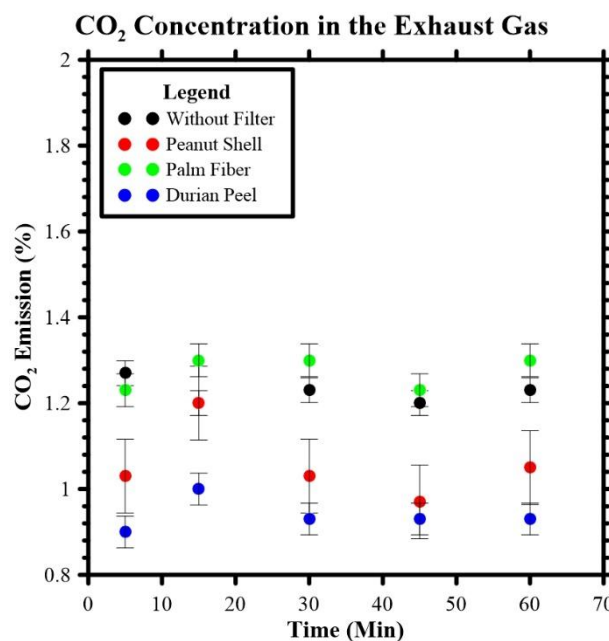


Figure 8. CO₂ emission active carbon filter with different materials

Figure 8 Shows the average CO₂ emissions from the motorcycle over a 60-minute period, comparing emissions with and without the active carbon filter. The results indicate that without the active carbon filter, CO₂ emission levels were around 1.23%. When using the active carbon filter, emissions rose to 1.27% for the palm fiber filter, dropped to 0.94% for the durian peel filter, and reached 1.06% for the peanut shell filter. The findings suggest that the durian peel-based carbon filter performs best in reducing CO₂ emissions. Although the reduction isn't significant, the decrease in CO₂ emissions linked to the activated carbon filter is related to the volatile levels and carbon content in the filter. These factors influence the filter's ability to absorb CO₂. Among the tested materials, the durian peel has the highest carbon content and the lowest volatile content. This characteristic helps reduce CO₂ levels in exhaust emissions.

Studies conducted by Yuliusman et al. (Yuliusman, Ayu, Hanafi, & Nafisah, 2020a, 2020b) have indicated that activated carbon derived from durian peel is effective in absorbing CO₂ emissions from motorcycles. Furthermore, additional studies (Chandra, Mirna, Sudaryanto, & Ismadji, 2007; Chandra et al., 2009; Mohamad Nor, Lau, Lee, & Mohamed, 2013) have corroborated these findings, supporting the effectiveness of durian peel-based activated carbon in absorbing CO₂ emissions from the air.

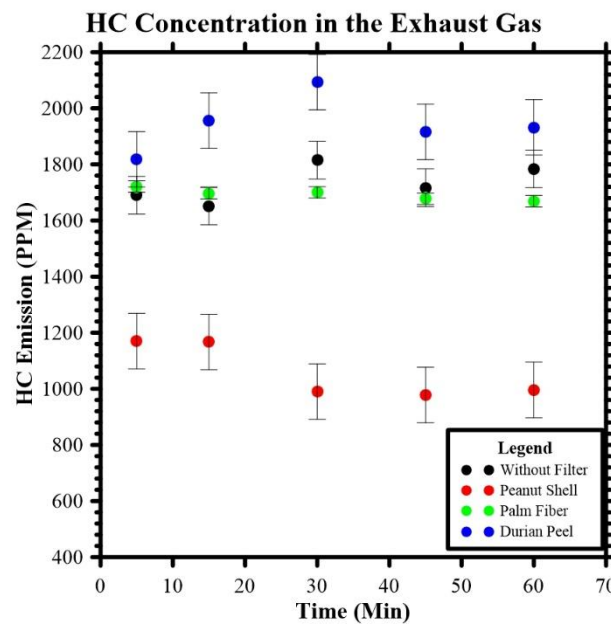


Figure 9. HC emission of the active carbon filter with different materials

Figure 9 displays the average HC (hydrocarbon) emissions from the motorcycle over a 60-minute period, comparing emissions with and without the active carbon filter. The findings show that without using the active carbon filter, the HC emission level was approximately 1731 ppm. However, when the active carbon filter was used, HC emissions decreased to 1692 ppm with the palm fiber filter and 1060 ppm with the peanut shell filter. Conversely, using the durian peel carbon filter increased HC emissions to 1943 ppm. As a result, the peanut shell-based carbon filter performs best in reducing HC emissions. Studies conducted by various researchers (Bedane, Guo, Eić, & Xiao, 2019; Lewicka, 2017; S. Wang et al., 2020) have indicated that peanut shell waste material has the capacity to reduce carbon emissions when used as an activated carbon filter material. This aligns with the observed reduction in HC emissions when using a peanut-shell-based carbon filter in the motorcycle exhaust system.

Table 3. Noise test of the active carbon filter

Filter	Noise Test			
	Test 1	Test 2	Test 3	Average
Without Filter	69.51	70.29	69.29	69.7
Peanut shell	64.95	66.78	65	65.58
Palm fiber Waste	60.57	61.89	59.88	60.78
Durian peel	62.16	62.92	62.48	62.52

Table 3 presents the results of noise measurements taken on motorcycles, comparing cases with and without an activated carbon filter. The measurements were taken three times for each filter type. Motorcycles without any filter had a noise level of 69.70 dB. However, adding activated carbon filters showed a clear reduction in noise levels. Among the different filters, the palm fiber waste-activated carbon filter achieved the greatest reduction, averaging 60.78 dB. The durian peel-activated carbon filter came in second, with an average noise level reduction of 62.52 dB. The peanut shell activated carbon filter showed an average reduction of 65.58 dB. This data indicates that adding activated carbon filters effectively reduces motorcycle noise, with varying levels of noise reduction across different filter types.

3.2. The effect of the activator of the active carbon filter in durian peel material

A subsequent experiment was conducted to examine the effect of different active carbon activators on the properties of the activated carbon filter. Phosphoric Acid (H_3PO_4), Potassium Hydroxide (KOH), and Sodium Chloride (NaCl) were chosen as activators for the carbon filter. These activators have been commonly used in previous studies as effective agents for activating waste-based carbon materials. (Hirunpraditkoon, Tunthong, Ruangchai, & Nuithitikul, 2011; Khalid, Meng, Akram, & Cao, 2016; J.-Y. Kim et al., 2016; Li, Han, Li, Li, & Lu, 2017; Martin-Gullon, Marco-Lozar, Cazorla-Amorós, & Linares-Solano, 2004; Teng et al., 1998; Yagmur et al., 2008). The durian peel was designated as the raw material for the carbon filter before the commencement of the experiment. **Table 4** presents the proximate analysis results of the active carbon filter with different activators, showcasing the variations in properties induced by these distinct activation agents. The proximate analysis was performed following ASTM D3172–D3175, while the quality of the produced activated carbon was assessed based on the requirements outlined in SNI 06-3730-1995

Table 4. Proximate analysis of active carbon filter

Proximate Active Carbon	H ₃ PO ₄	KOH	NaCl
Water Content (Wt.%)	10.677	50.422	75.587
Ash Content (Wt.%)	22.668	35.156	30.734
Volatile Content (Wt.%)	12.330	12.330	15.338
Carbon Content (Wt.%)	54.340	41.884	46.368

According to SNI 06-3730-1995 (Indonesia, 1995), the maximum allowable moisture content for technical activated carbon is 15%. The activated carbon prepared using H₃PO₄ exhibited a moisture content of 10.67%, satisfying the SNI requirement. In contrast, the moisture contents of KOH- and NaCl-activated carbons were 50.42% and 75.58%, respectively, which exceeded the specified limit. High moisture content is undesirable because residual water may occupy pore spaces, reduce the accessibility of adsorption sites, and adversely affect adsorption performance (Neme et al., 2022).

The ash contents of the H₃PO₄-, KOH-, and NaCl-activated carbons were 22.68%, 35.16%, and 30.74%, respectively, all exceeding the maximum ash content of 10% specified in SNI 06-3730-1995. Elevated ash content indicates the presence of inorganic mineral residues that may partially block pore openings, reduce the effective surface area, and consequently decrease the adsorption capacity of activated carbon (Lemraski & Sharafinia, 2016).

The volatile matter contents were 12.33%, 12.33%, and 15.33% for the H₃PO₄-, KOH-, and NaCl-activated carbons, respectively, all satisfying the SNI requirement of $\leq 25\%$. The release of volatile compounds during carbonization contributes to pore formation and influences the development of the porous structure of activated carbon (Neme et al., 2022). The fixed carbon contents were 54.34%, 41.88%, and 46.36% for the H₃PO₄-, KOH-, and NaCl-activated carbons, respectively. Although these values indicate successful carbonization of the biomass, they remain below the minimum fixed carbon content of 65% specified in SNI 06-3730-1995. Previous studies have reported that activated carbons with higher fixed carbon and lower ash contents generally exhibit superior adsorption performance because they provide a more stable carbon matrix and facilitate the development of well-defined porous structures (Ogungbenro et al., 2020).

Overall, the activated carbon prepared with H₃PO₄ exhibited the most favorable proximate characteristics among the three activating agents, particularly in moisture content. However, the relatively high ash contents and lower fixed carbon contents indicate that further

optimization of the activation conditions is necessary to improve the physicochemical properties and adsorption performance of the activated carbon.

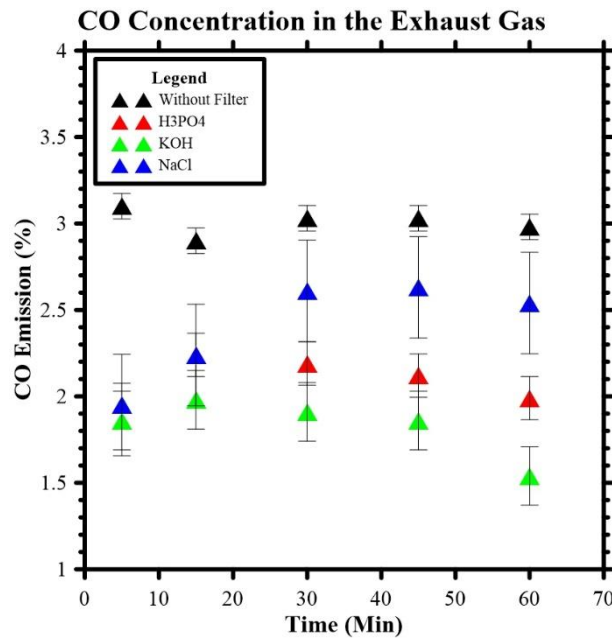


Figure 10. CO emission of active carbon filter with different carbon activation

Figure 10 illustrates the average CO emissions from the motorcycle over a 60-minute test. This experiment involved using a durian-based activated carbon filter treated with different carbon activators. Initially, without the filter, the average CO emission was recorded at 3.01%. When NaCl served as the activator, the CO emission decreased to 2.39%. Using H₃PO₄ as the activator further lowered CO emissions to 2.10%. Finally, with KOH as the activator, CO emissions dropped to 1.83%. The data show that the choice of activator significantly affects CO emissions from the durian peel-activated carbon filter. Notably, KOH use resulted in the greatest reduction in CO emissions. This can be linked to KOH's ability to effectively absorb carbon atoms. Alkaline activators like KOH are effective at enlarging pores and increasing carbon surface area, thereby improving their adsorption capacity compared to acidic activators. Additionally, alkaline activators like KOH are more reactive with materials rich in carbon, such as durian peel, which contains about 50-60% carboxymethylcellulose.

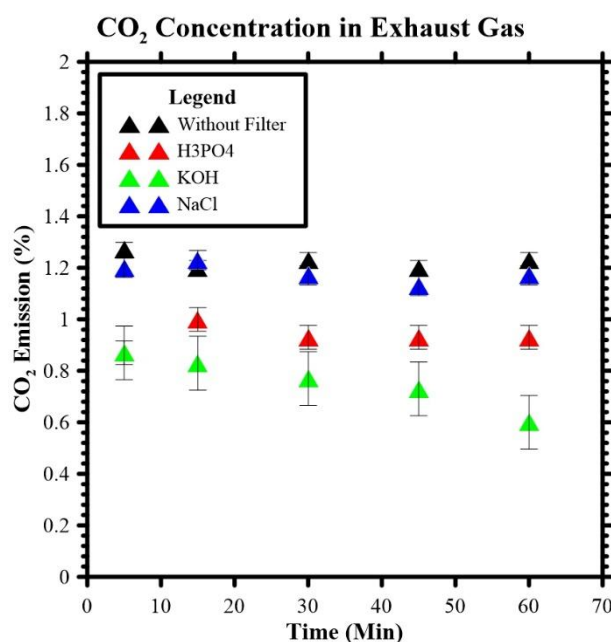


Figure 11. CO₂ emission of active carbon filter with different carbon activation

Figure 11 displays the average CO₂ emissions from the motorcycle observed during a 60-minute test. The experiment employed a durian-based active carbon filter treated with various carbon activators. Initially, without the filter, the average CO₂ emission was measured at 1.23%. Upon utilizing NaCl as the activator, CO₂ emissions reduced to 1.18%. With H₃PO₄ as the activator, CO₂ emissions further decreased to 0.93%. Finally, employing KOH as the activator resulted in the lowest CO₂ emissions of 0.76%. The data indicate that the choice of activator significantly impacts CO₂ exhaust emissions in the durian peel-activated carbon filter. Specifically, using KOH as the activator resulted in the greatest reduction in CO₂ emissions. This outcome is attributed to KOH's ability to effectively absorb carbon atoms. Alkaline activators like KOH are adept at enlarging pores and expanding the carbon surface area, enhancing their adsorption capabilities compared to acidic activators. Moreover, alkaline activators such as KOH exhibit heightened reactivity with materials containing high carbon content, such as durian peel, which contains approximately 50-60% carboxymethylcellulose.

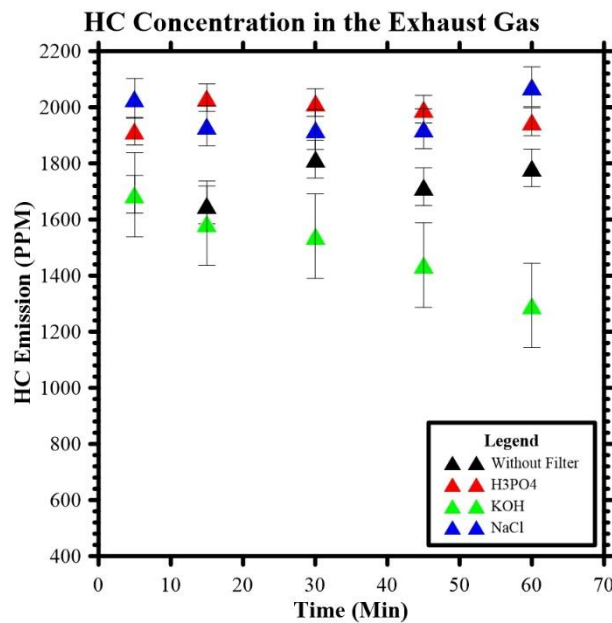


Figure 12. HC emission of the active carbon filter with different carbon activation

Figure 12 presents the average HC emissions from the motorcycle observed over a 60-minute test duration. The experiment involved utilizing a durian-based active carbon filter treated with various carbon activators. Initially, without the filter, the average HC emission was recorded at 1731.27 ppm. Upon employing NaCl as the activator, HC emissions increased to 1976.67 ppm. When H₃PO₄ served as the activator, HC emissions further rose to 1981.47 ppm. Finally, using KOH as the activator resulted in a 1509.40 ppm decrease in HC emission. These results suggest that the choice of activator significantly influences HC exhaust emissions in the durian peel-activated carbon filter. Notably, using KOH as the activator resulted in a significant reduction in HC emissions. This effect can be attributed to KOH's efficient capacity to absorb carbon atoms. Alkaline activators like KOH excel in enlarging pores and expanding the carbon surface area, enhancing their adsorption capabilities compared to acidic activators. Additionally, alkaline activators, particularly KOH, exhibit greater reactivity with materials rich in carbon content, such as durian peel, which contains approximately 50-60% carboxymethylcellulose. The superior performance of KOH activation observed in this study agrees well with previous investigations. KOH reacts with the carbon matrix via carbon etching, generating abundant micropores and significantly increasing the accessible surface area (Chiang, Yeh, & Weng, 2019). In contrast, H₃PO₄ mainly promotes dehydration and structural stabilization, whereas NaCl primarily functions as a dehydrating agent with relatively limited pore development. Consequently, KOH-activated carbon generally exhibits superior adsorption capacity because of the greater number of accessible adsorption sites (Singh, Bhunia, & Basu, 2019).

Table 5. Noise test of the active carbon filter

Filter type	Noise Test			
	Test 1	Test 2	Test 3	Average
Without Filter	69.51	70.29	69.29	69.7
Phosphoric Acid (H ₃ PO ₄)	62.16	62.92	62.48	64.32
Potassium Hydroxide (KOH)	65.56	64.84	62.56	62.52
Sodium Chloride (NaCl)	59.80	59.87	59.51	59.73

Table 5 presents the results of the noise test conducted on the active carbon filter. Before employing the activated carbon filter, the motorcycle emitted a noise level of 69.70 dB. After applying the filter, the noise level was reduced to 64.32 dB. Specifically, for filters treated with a KOH activator, the noise level decreased to 64.32 dB, a 7.7% reduction. For filters using the H₃PO₄ activator, the noise level reached 62.52 dB, indicating a 10.3% reduction. Lastly, filters employing NaCl as the activator showed the greatest noise reduction, at 59.73 dB, corresponding to a 14.3% reduction. These noise level measurements were obtained using a decibel meter. The data underscores that the use of a durian peel-activated carbon filter, treated with different activators (H₃PO₄, KOH, and NaCl), effectively reduces noise levels emitted by motorcycles. Notably, NaCl emerged as the activator resulting in the most substantial reduction compared to other activators.

3.3 Proposed adsorption and acoustic attenuation mechanism

According to the literature, the reduction in CO emissions observed in this study is mainly due to activated carbon's physical adsorption mechanism. During exhaust flow, CO molecules diffuse through macropores and mesopores before reaching micropores, where adsorption predominantly occurs through van der Waals interactions (Abd, Othman, & Kim, 2021). Macropores primarily function as gas transport channels; mesopores facilitate diffusion; and micropores provide the majority of adsorption sites due to their exceptionally large internal surface area (T. Song, Liao, Xiao, & Shen, 2015). CO₂ adsorption primarily occurs via a pore-filling mechanism because the kinetic diameter of CO₂ molecules closely aligns with ultramicropore sizes. As a result, adsorption depends heavily on micropore volume, pore-size distribution, and oxygen-containing functional groups rather than on total carbon content (T. Song et al., 2015; Tangsathitkulchai, Naksusuk, Wongkoblap, Phadungbut, & Borisut, 2021; Yin, Liu, Liu, & Wu, 2013). The current study found that durian peel-activated carbon achieved

the highest CO₂ reduction, indicating that its pore structure and surface chemistry provide suitable adsorption sites for CO₂. Similar findings were reported by (Maniarasu, Rathore, & Murugan, 2022), who showed that biomass-based activated carbon effectively captures CO₂ from diesel exhaust, with pore features significantly impacting performance. In contrast, hydrocarbon adsorption is more complex because HC molecules are considerably larger than CO molecules. Previous studies have demonstrated that mesopores primarily function as diffusion channels, whereas micropores act as adsorption sites (Pui, Yusoff, & Aroua, 2019). Furthermore, adsorption performance is enhanced by oxygen-containing functional groups through van der Waals interactions, hydrogen bonding, and π - π interactions between aromatic hydrocarbons and the graphitic carbon surface (Jia et al., 2024; Ma, Zhang, Wu, Li, & Yang, 2019), the proposed mechanism shown in **Figure 13**.

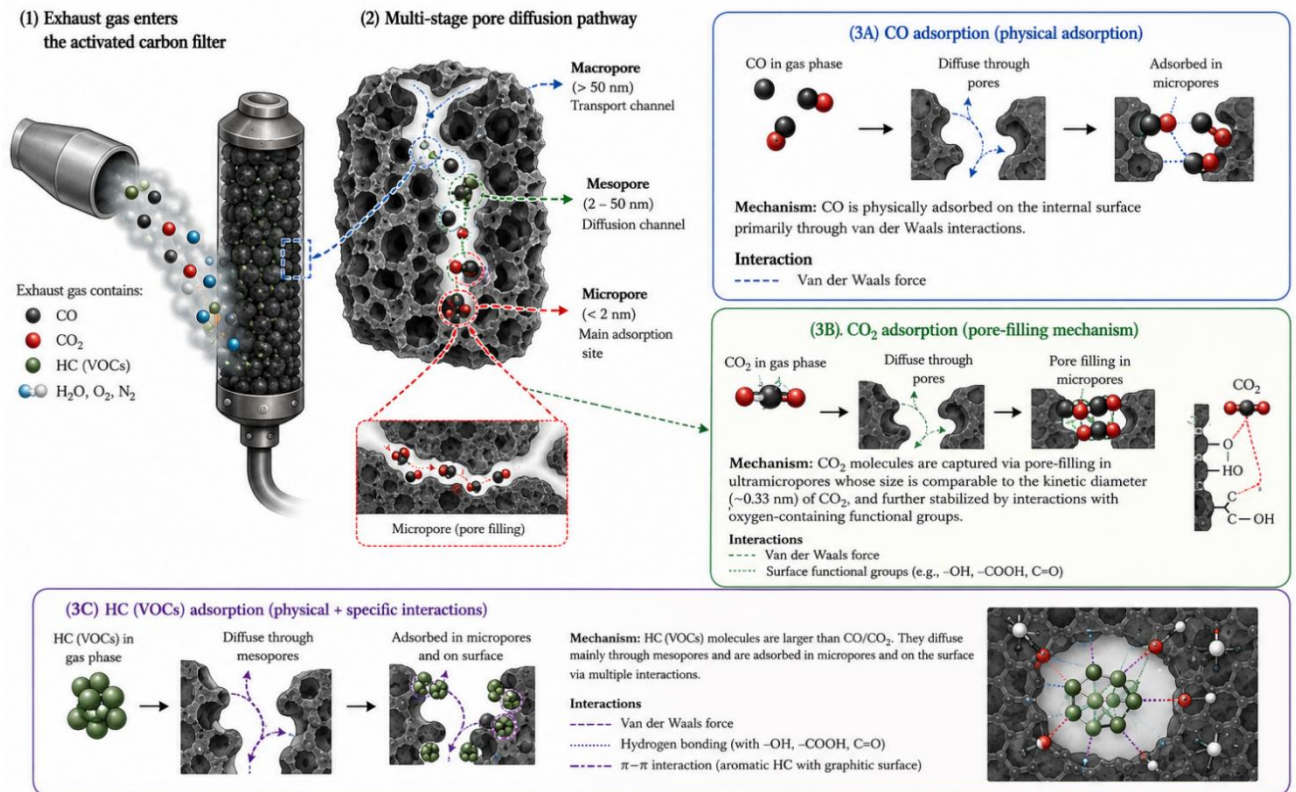


Figure 13. Exhaust gas emission absorption mechanism

4. Conclusions

This study aimed to evaluate the effectiveness of an active carbon filter made from waste materials in reducing motorcycle exhaust emissions and noise pollution. The study used peanut shells, palm fiber, and durian peel as materials for the active carbon filter. Additionally, an investigation was conducted to assess the effect of carbon activators on durian peel as an active carbon source. The 110 CC motorcycle was tested for 60 minutes, during which exhaust gas components (CO, CO₂, and HC) were monitored. The main conclusions from this study are as follows:

- a. Waste materials rich in cellulose, hemicellulose, and lignin demonstrate potential in absorbing carbon-based emissions from motorcycles.
- b. The utilization of waste materials in developing active carbon filters effectively mitigates motorcycle exhaust gas emissions (CO, CO₂, and HC) while addressing natural waste concerns associated with peanut shells, palm fiber, and durian peel.
- c. The active carbon filter derived from peanut shell exhibits superior performance in reducing CO and HC emissions, whereas the durian peel material demonstrates better efficacy in reducing CO₂ emissions.
- d. The active carbon filter derived from palm fiber demonstrates optimal performance in reducing noise pollution emitted by the motorcycle.
- e. Among various activator materials, KOH shows superior effectiveness in reducing CO, CO₂, and HC emissions, and NaCl proves to be the most effective activator in lowering noise pollution from the motorcycle.

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Author's Contributions

Herman Saputro: conceptualization, funding acquisition, supervision, project administration, writing-review, and editing; **Laila Fitriana:** funding acquisition, supervision; **Aris Purwanto:** data curation, methodology, formal analysis, writing-original draft; **Riyadi Muslim:** data curation, methodology; **Rusdan Aditya Aji Nugroho:** data curation, methodology; **Fudhail Bin Abdul Munir:** supervision, writing review and editing; **Wei Cheng Wang:** supervision, writing review and editing; **Mohd Sayuti Ab Karim:** supervision, writing review and editing. All authors contributed to the interpretation of the results, reviewed and approved the final version of the manuscript, and agreed to be accountable for all aspects of the work.

Declarations

Ethical Approval Not applicable. The research did not involve human participants, human biological materials, or animals.

Consent to Participate Not applicable. This study did not involve human participants.

Consent to Publish Not applicable. This study does not contain any individual person's identifiable data or information requiring consent for publication.

Competing Interests Not applicable. The authors declare that they have no competing interests.

Clinical trial number Not applicable.

Data Availability Statement

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) and Grammarly Pro solely to improve language quality, grammar, and readability. All scientific content, data

analysis, interpretation, and conclusions were developed and verified by the authors, who take full responsibility for the final manuscript.

Patents

This filtration system has been registered as a patent in Indonesia with the registration number S00202201196.

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